

# Advanced Communication Techniques for Next-generation Cognitive Wireless Networks

by

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This is to certify that I have examined this copy of a doctoral dissertation by

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*To my parents Fatma and Ahmet Özger*

## ABSTRACT

As wireless devices become ubiquitous, demand for the electromagnetic spectrum has increased to a level that leads to two problems in wireless communications. First problem is spectrum scarcity problem. Since most of the spectrum is allocated to licensed users, unlicensed users are facing with the problem of insufficient spectrum bands. Electromagnetic spectrum band is scarce, hence, it must be utilized efficiently. Although unlicensed spectrum bands are overcrowded, licensed ones are underutilized. Second problem is inefficient spectrum utilization. Cognitive radio technology stands as a promising approach to overcome these problems and to enable next-generation cognitive wireless networks, which are the wireless networks with spectrum-awareness. This technology enables using the licensed spectrum bands in an opportunistic manner with limited interference to the licensed users. In this thesis, cognitive radio is adopted in different types of wireless networks to realize next-generation cognitive wireless networks. Due to greatness of the domain of next-generation cognitive wireless networks, this thesis focuses on a subset of these networks. Hence, this thesis investigates four different wireless networks with cognitive radio capability for next-generation cognitive wireless networks. Advanced communication techniques are proposed and analyzed in these four main pillars of wireless networks.

First pillar of next-generation cognitive wireless networks is cognitive radio ad hoc and sensor networks. Spectrum opportunity characterization is performed, mobility-aware clustering protocol is proposed, clustering in multi-channel spectrum-aware environment is investigated, energy optimal transmission range is found, network coding is studied for multicast communication in this type of networks.

Second pillar of them is wireless networked control systems with cognitive radio capability. Maximum coverage area and maximum energy-efficiency under Kalman

filter convergence with maximum cost-efficiency are studied.

Third pillar is cognitive wireless multimedia networks. Challenges and requirements are analyzed to enable spectrum-aware communications in cognitive wireless multimedia networks. Existing solutions are investigated and open research issues are determined.

Last pillar is Internet of Things. Spectrum scarcity problem is worsened by this paradigm, and nodes within Internet of Things are resource-constrained. Hence, it benefits from cognitive radio technology to overcome these challenges. Hence, network coding application is utilized to decrease transmission efforts, and energy harvesting in the domain of smart grid and smart cities is investigated to overcome limited energy supply challenge.

The analysis and studies in this thesis help realization of next-generation cognitive wireless networks. The thesis also points out open research issues and how cognitive radio can be applied in next-generation wireless networks.

## ÖZETÇE

Kablosuz araçlar yaygınlaştıkça elektromanyetik tayfa olan talep kablosuz haberleşmede iki soruna yol açacak şekilde artmıştır. Bunlardan ilki tayf kıtlığı sorunudur. Tayfın büyük bölümü lisanslı kullanıcılara ayrıldığı için, lisansı bulunmayan kullanıcılar yetersiz tayf bandı problemi ile karşı karşıya kalmaktadır. Elektromanyetik tayf yetersiz olduğundan etkili kullanılmalıdır. Lisanslı olmayan tayf bantlarının kullanımı çok yoğunken, lisanslı olanlar yeterince kullanılmamaktadır. İkinci sorun verimsiz tayf kullanımı sorunudur. Bilişsel radyo bu sorunları aşmak ve tayf-bilinçli gelecek nesil kablosuz ağları gerçekleştirmek için gelecek vaadeden bir teknolojidir. Bu teknoloji lisansı olmayan kullanıcıların lisanslı tayfa fırsatçı bir şekilde erişebilmelerine sınırlı olarak lisanslı kullanıcılara girişim koşuluyla olanak sağlar. Bu tezde gelecek nesil bilişsel kablosuz ağları gerçekleştirebilmek için bilişsel radyo benimsenmiştir. Gelecek nesil bilişsel kablosuz ağların alanı çok büyük olduğundan, bu tez bu ağların alt kümesine odaklanmaktadır. Bu yüzden, bu tez gelecek nesil bilişsel kablosuz ağlar için bilişsel radyo özelliğine sahip olan dört farklı kablosuz ağı incelemektedir. Bu dört önemli ağda gelişmiş haberleşme teknikleri önerilmiş ve analiz edilmiştir.

İlk olarak bilişsel radyo tasarsız ve algılayıcı ağlar çalışılmıştır. Bu ağlarda, tayf fırsatı karakterizasyonu sağlanmış, hareket-bilinçli kümeleme protokolü önerilmiş, çok kanallı tayf bilinçli ortamlarda kümeleme incelenmiş, enerji eniyileyerek haberleşme uzaklığı bulunmuş ve ağ kodlaması çoklu iletişimde kullanılarak incelenmiştir.

İkinci olarak bilişsel radyo özellikli kablosuz ağı kontrol sistemleri incelenmiştir. Azami kapsama alanı ve azami enerji verimliliği Kalman süzgeci yakınsaması ve azami masraf verimliliği ile birlikte incelenmiştir.

Üçüncü olarak bilişsel kablosuz çoklu ortam ağları çalışılmıştır. Zorluklar ve gereklilikler bu tarz ağlarda tayf-bilinçli haberleşmeyi gerçekleştirebilmek için analiz

edilmiştir. Varolan çözümler incelenmiş, ve açık araştırma konuları belirlenmiştir.

Dördüncü olarak nesnelerin interneti incelenmiştir. Bu paradigma tayf ktlığı sorununun çözümlünü daha zor hale getirmiştir. Ayrıca nesnelerin internetinde bulunan düğümlerin kaynakları kısıtlıdır. Bu nedenle bilişsel radyo kullanılarak bu sorunların üstesinden gelinebilir. Ağ kodlaması kullanılarak haberleşme teşebbüslerini en aza indirmek için kullanılmış, enerji toplama işlemi akıllı şebeke ve akıllı şehir uygulamalarında kullanılarak kısıtlı enerji problemi giderilmiştir.

Bu tezdeki analizler ve çalışmalar gelecekteki nesil bilişsel kablosuz ağların gerçekleştirilmesine yardımcı olmuştur. Ayrıca bu tez açık araştırma problemlerini ortaya çıkarmış ve bilişsel radyonun gelecek nesil haberleşme sistemlerinde nasıl uygulanabileceği ortaya konulmuştur.

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## NOMENCLATURE

|                |                                                        |
|----------------|--------------------------------------------------------|
| <b>BER</b>     | Bit Error Rate                                         |
| <b>C_REP</b>   | Clustering Reply                                       |
| <b>C_REQ</b>   | Clustering Request                                     |
| <b>CH</b>      | Cluster-head                                           |
| <b>CIoT</b>    | Cognitive Internet of Things                           |
| <b>CRAHN</b>   | Cognitive Radio Ad Hoc Networks                        |
| <b>CR</b>      | Cognitive Radio                                        |
| <b>CRN</b>     | Cognitive Radio Network                                |
| <b>CRSN</b>    | Cognitive Radio Sensor Networks                        |
| <b>DSA</b>     | Dynamic Spectrum Access                                |
| <b>EFC_REP</b> | Eligibility for Clustering Reply                       |
| <b>EFC_REQ</b> | Eligibility for Clustering Request                     |
| <b>EFEH</b>    | Electric Field Energy Harvesting                       |
| <b>EH</b>      | Energy Harvesting                                      |
| <b>EH-CR</b>   | Energy Harvesting Cognitive Radio                      |
| <b>ESAC</b>    | Event-driven Spectrum-Aware Clustering                 |
| <b>ESDC</b>    | Event to Sink Directed Clustering                      |
| <b>IoT</b>     | Internet of Things                                     |
| <b>mESAC</b>   | mobility-aware Event-to-Sink Spectrum-Aware Clustering |
| <b>NC</b>      | Network Coding                                         |
| <b>NCS</b>     | Networked Control System                               |

|             |                                     |
|-------------|-------------------------------------|
| <b>OSA</b>  | Opportunistic Spectrum Access       |
| <b>PU</b>   | Primary user                        |
| <b>QoS</b>  | Quality of Service                  |
| <b>RF</b>   | Radio Frequency                     |
| <b>RLNC</b> | Random Linear Network Coding        |
| <b>SG</b>   | Smart Grid                          |
| <b>SNR</b>  | Signal-to-Noise Ratio               |
| <b>SOC</b>  | Spectrum Opportunity Clustering     |
| <b>SOP</b>  | Spectrum Opportunity                |
| <b>SU</b>   | Secondary User                      |
| <b>USOP</b> | Utilization of Spectrum Opportunity |
| <b>WMSN</b> | Wireless Multimedia Sensor Networks |
| <b>WNCS</b> | Wireless Networked Control System   |
| <b>WSN</b>  | Wireless Sensor Networks            |

## Chapter 1

# INTRODUCTION

### 1.1 *Next-generation Cognitive Wireless Networks*

Demand for wireless communication has increased unprecedentedly over a decade. This demand causes electromagnetic spectrum shortage since the spectrum is a limited resource. Furthermore, most of the spectrum is allocated to the licensed users, and the licensed spectrum bands are not utilized efficiently. To overcome the spectrum scarcity and inefficiency problems, cognitive radio technology has been proposed.

Cognitive radio has three key functionalities, which are spectrum sensing, spectrum decision and spectrum hand-off. These functions help wireless node to detect and use the vacant licensed spectrum bands. Also, they can vacate the licensed spectrum band if the licensed user arrives. These functionalities increase the spectrum utilization.

Cognitive radio technology is applied to a number of wireless networks. In this thesis, we apply cognitive radio to wireless ad hoc networks, wireless sensor networks, wireless networked control systems, wireless multimedia networks, and newly emerged paradigm Internet of Things. In this thesis, these type of networks with cognitive radio capability are termed as *next-generation cognitive wireless networks*.

According to the challenges posed by the cognitive radio in different types of wireless networks. To this end, the thesis is structured into three main areas:

- *Cognitive radio ad hoc and sensor networks* - Clustering, optimal transmission range, interference, network coding, etc.
- *Cognitive wireless networked control systems* - Coverage, energy-efficiency, cost-

efficiency.

- *Cognitive wireless multimedia networks* - Investigation of wireless multimedia sensor networks, open issues for the application of cognitive radio technologies in wireless multimedia sensor networks.
- *Cognitive Internet of Things* - Energy harvesting, cognitive radio networking, network coding application

## 1.2 Contributions

The contributions of this thesis on next-generation cognitive wireless networks can be listed as:

- Characterization of the utilization of vacancies in the licensed spectrum
- Proposing a mobility-aware event-driven clustering protocol
- Investigation of the state-of-the-art clustering approaches that can be utilized in cognitive radio networks and open research issues
- Investigation of optimal transmission range providing energy-efficiency
- Examination of network coding effects in multicast communication
- Maximum coverage area and energy-efficiency under Kalman filter convergence and cost-efficiency constraint
- Analysis of multimedia communication in spectrum-aware environment and outline of open research issues
- Investigation of network coding application in cognitive radio capable Internet of Things and integration of cognitive radio sensor networks with the Internet

- Design of energy harvesting cognitive radio networking to enable IoT-enabled Smart Grid
- Investigation of merger of energy harvesting and cognitive radio in Smart Cities

### 1.3 Thesis Outline

The rest of the thesis is organized as follows.

**Chapter 2:** Cognitive radio (CR) is proposed to use the spectrum opportunistically. Spectrum opportunity (SOP) can be defined as the possibility of a spectrum-aware communication between a CR transmitter and a CR receiver. Successful spectrum-aware communication between the communicating CRs, which is utilization of SOP (USOP), depends on the SOP detection and the correct transmission of a packet. Spectrum sensing performance, physical channel, and network parameters affect the probability of USOP. In this chapter, we characterize the probability of the USOP under different network topologies [7]. The network topology is due to the relation between transmission ranges of licensed users and CRs. We numerically study this probability for different network parameters and topologies. We find that the characteristics of USOP highly depend on the network topology, CR sensing performance and licensed users' activities.

**Chapter 3:** Cognitive Radio (CR) enables dynamic spectrum access to utilize licensed spectrum during its idle time. CR technology is applied to wireless ad hoc and sensor networks, to form Cognitive Radio Ad Hoc Networks (CRAHNs) and Cognitive Radio Sensor Networks (CRSNs), respectively. Clustering is an efficient technique to manage such networks and is crucial to support CR-enabled protocols in physical, medium access and network layers. In this chapter, we thoroughly investigate clustering as a tool to manage key requirements in multi-channel CRAHNs and CRSNs. In this context, we overview motivations for and challenges of clustering in CRAHNs and CRSNs, and factors affecting clustering. Functionalities of clustering such as topology, spectrum and energy management in these networks are studied,

and the existing clustering schemes are reviewed in detail. We conclude by revealing key considerations for efficient and effective clustering in realistic multi-channel CRAHNs and CRSNs.

**Chapter 4:** Cognitive radio sensor networks (CRSNs) are event-based systems such that sensor nodes detect events and the event readings of the sensors are collaboratively conveyed in a multi-hop manner through vacant channels from event regions to a sink. Hence, the event-to-sink communication and the dynamic radio environment require a coordination scheme in CRSNs. In this chapter, we propose a spectrum-aware clustering protocol to address the event-to-sink communication coordination issue in mobile CRSNs. Our clustering scheme consists of two phases. The first phase is the determination of nodes eligible for clustering, and the second phase is to form clusters among those nodes according to vacant spectrum bands. Clusters are temporary and they are not preserved after the end of events. Furthermore, we find average re-clustering probability, expected cluster coverage area, and find maximum event generation frequency for energy-efficient operation of our protocol. We study performance of our protocol in terms of control and data packet exchange, time steps required for clustering, connectivity of clusters, energy consumed for clustering, and re-clustering ratio due to the mobility. Performance comparison simulations show that our algorithm has better performance in terms of connectivity and energy consumption.

**Chapter 5:** The dynamic radio environment in cognitive radio ad hoc networks (CRAHNs) affects the success of the communication and, hence, the energy consumption. The CRAHN nodes do not have battery replacement option and power control capability. Hence, transmission range, which is set before the deployment, is one of the most critical parameters in CRAHNs. The main contribution of our chapter is to present a mathematical optimization model for the transmission range of CRAHN nodes. To the best of our knowledge, no attempt has yet been made on this topic. In this chapter, we firstly find an average advance in distance of a source packet towards the destination at one hop in a dynamic radio environment. Accord-

ing to this advance in distance and the energy consumption at each hop, we define a cognitive hop advance-energy function under reliable and unreliable link conditions. Using this function, we optimize the transmission range of the CRAHN nodes for energy-efficiency. The numerical analyses show that the dynamic radio environment and CRAHN node parameters highly affect the optimal transmission range.

**Chapter 6:** Wireless ad hoc network nodes with cognitive radio (CR) capability access the licensed spectrum bands in an opportunistic manner via spectrum sensing functionality. However, imperfections in the spectrum sensing and arrival of licensed users during CR communications cause interference to the licensed users, which is highly undesirable. Considering these cases, we apply random linear network coding (RLNC) in a multicast session within a cluster, where a clusterhead sends its file to its members by dividing it into packets. We study the number of these packets, i.e., coding window size, in the multicast session, which provides minimum interference and maximum multicast throughput. Hence, we find successful packet transmission probability, expected multicast session completion time, multicast throughput and upper bound on expected interference to primary user during the session. In numerical evaluation, we observe a trade-off between coding window size and throughput/interference depending on primary user activities, file length, field size, and number of multicast receivers. The results can be used to propose spectrum-aware network coding schemes for throughput enhancements and interference mitigation.

**Chapter 7:** In this chapter, we addressed the maximum coverage problem under convergence constraint of the Kalman filter with maximum cost-efficiency in wireless networked control systems. This system has cognitive radio capability and consists of  $N$  subnetworks. We formulate an optimization problem under convergence constraint. We study the maximum coverage area of the system for different network parameters.

**Chapter 8:** Wireless networked control system (WNCS) is a control system that a wireless network closes the control loop. WNCS estimator, i.e., Kalman filter, estimates the system state according to the observations of sensors. These observations which are from  $N$  independent subnetworks are conveyed to the Kalman filter

through vacant bands opportunistically with cognitive radio capability of the nodes. We characterize the successful packet delivery probability and study the maximization of energy-efficiency of overall system under the convergence constraint of the Kalman filter by defining an optimization problem. We also find a lower bound on maximum total coverage area. Furthermore, we perform numerical analysis to observe the effects of system parameters such as number of subnetworks, average ON probability of primary users, transmission ranges and densities of sensor nodes and primary users, and false alarm probability.

**Chapter 9:** In this chapter, we surveyed the existing literature on multimedia communication in WSN, CRN, CRSN and WMSN. We also investigate the protocols proposed for wireless networks and point out their advantages and disadvantages to realize the multimedia communication in cognitive radio ad hoc and sensor networks. Existing approaches are scrutinized from the perspective of network layers. The challenges posed by multimedia communication and cognitive radio ad hoc and sensor network paradigm are clearly indicated for each network layer. Open research avenues for realizing multimedia communication over cognitive radio ad hoc and sensor networks are determined.

**Chapter 10:** The Internet of Things (IoT) enables to connect every electronic device to the Internet. This paradigm causes deployment of excessive number of IoT devices, which are mainly sensors and RFID tags. These devices creates a large volume of traffic due to their pervasiveness and transmission of their observation about the environment. These transmissions intensifies problem of spectrum scarcity. The cognitive IoT (CIoT) overcomes this problem by using cognitive radio (CR) in the devices of the CIoT. Furthermore, network coding (NC) is a technique for efficient data transmission and throughput maximization with robustness to network failures. In this chapter, we state technical challenges posed by NC and CR technology to realize the CIoT. Then, we investigate integration approaches of CR-capable sensor networks with the Internet and the NC applications for the CIoT. We also state open issues for the application of NC in the CIoT.

**Chapter 11:** The Internet of Things (IoT) provides connectivity to the objects that monitor and sense the environment to integrate physical world with digital world. If IoT is enabled in the Smart Grid (SG), it can benefit from advantages of the IoT such as interoperability, connectivity, etc. By combining the IoT with energy harvesting (EH) and cognitive radio (CR) techniques, the problems of SG, such as harsh channel conditions and limited battery power, may be resolved. Hence, incorporation of EH and CR reveals a new networking paradigm for IoT-enabled SG. To this end, we first introduce CR usage in the IoT-enabled SG, and explain the advantages and challenges of CRs. Furthermore, we propose EH approaches for the resource constraint of wireless devices in the IoT-enabled SG. Operation and node architecture of energy harvesting cognitive radios, and network architecture of the IoT-enabled SG are described to explain details of our networking paradigm. Open issues and future research directions are discussed to enable this new paradigm.

**Chapter 12:** In this book chapter, we combine two important techniques, which are cognitive radio (CR) and energy harvesting (EH) to realize Smart City. We first study solutions to overcome the challenges for Smart City and investigate cognitive radio sensor networks (CRSNs), their Internet connection and application of harvesting methods in CRSN domain. Furthermore, we reveal the motivations for spectrum-aware and self-sustaining communications in Smart City. In the light of these discussions, we study a networking architecture of Internet of Things (IoT) consisting of energy harvesting cognitive radios (EH-CRs), i.e., Energy Harvesting Cognitive Internet of Things. By using this architecture, we also propose a general implementation framework for EH-CRs for the Smart City concept.

## Chapter 2

# ON THE UTILIZATION OF SPECTRUM OPPORTUNITY IN COGNITIVE RADIO NETWORKS

### 2.1 Introduction

Inefficient utilization of licensed channels and overcrowded unlicensed spectrum bands lead to opportunistic use of licensed bands by unlicensed users [8]. The enabling technology of the opportunistic spectrum use is cognitive radio (CR). Nodes with CR capability can form ad hoc networks [9], named as cognitive radio networks (CRNs). Spectrum sensing and decision are the cognitive cycle functions.

Primary users (PUs) and secondary users (SUs) share the licensed spectrum band. While PUs have the privilege to utilize the spectrum band at any time, SUs use it opportunistically. We represent the SUs as CRs throughout the chapter since SUs are cognitive radio nodes. CRs have spectrum opportunity (SOP) if there is no communication activity by PUs. The establishment of a communication link depends on not only the physical distance of the CRs but also the SOP occurrence [10]. Hence, the spectrum opportunity is viewed as a finite delay connectivity due to temporal dynamics of the channel in CRNs without considering the spectrum sensing performance of CRs in [10]. The authors in [11] consider only the spatial properties of successful communication in CRN. However, SOP experiences both spatial and temporal variation. Furthermore, the key point is the sensing of the spectrum vacancy correctly. Spectrum sensing performance can be enhanced by exploiting the spatial diversity of sensors and temporal diversity between the slots in a cooperative sense. The spectrum sensing performance can be increased by an improved energy detector and CRs with multiple antenna [12]. CRs with multiple antenna are costly for resource con-

strained networks. The authors in [13] investigate the detection of spatial-temporal opportunity. However, they do not consider successful utilization of SOP during a packet transmission. To our knowledge, there is no study in literature that jointly characterizes the SOP detection by a CR with a single radio having imperfections in the channel sensing and SOP utilization during a packet transmission.

In this chapter, we investigate the probability of successful joint idle channel detection and packet transmission, which is defined as the utilization of SOP (USOP). The contribution of our chapter is the determination the probability of USOP in a dynamic radio environment under imperfections in the channel sensing for different network topologies. The topologies can be categorized according to the relative transmission distance of PUs and CRs. As USOP probability defines the characteristics of the spectrum-aware communication, it can be used for developing solutions for medium access control, resource management, power control and routing in CRN.

## 2.2 Network Topology

Network topology affects the interaction between CRs and PUs, which also has impact on USOP. Two network topologies can be realized in CRNs [11], which we denote as  $T1$  and  $T2$ .

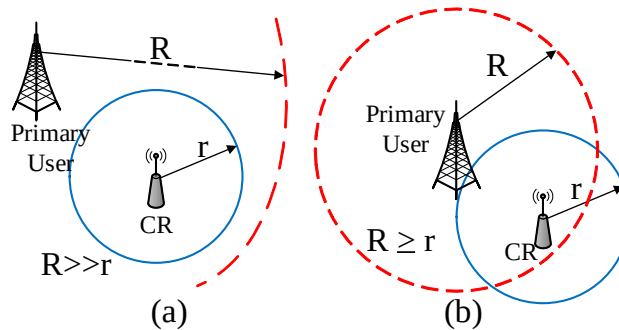


Figure 2.1: Network topologies: (a)  $T1$ , (b)  $T2$ .

The relationship between the transmission ranges of PUs and CRs is the cause of topology difference in the network. Fig. 2.1 shows two different network topologies.

$T1$  is the topology, in which the transmission range of PU is much greater than that of CRs, hence, no spatial variation of SOP is present. There is only time variation due to the activities of the PU.  $T2$  is the topology, in which the transmission range of CRs is comparable with the transmission range of PUs. Hence, there is a spatial variation due to random deployment of PUs in the network in  $T2$ . Temporal activities of the PUs cause variations in time domain. Hence,  $T2$  has spatial-temporal SOP variations.

We characterize the probability of USOP between two CRs for  $T1$  and  $T2$ . The spatial and temporal variation effects are considered to fully capture the dynamics of the USOP.

### 2.3 Utilization of Spectrum Opportunity

The first step of SOP utilization is the correct sensing of the spectrum. Hence, the SOP utilization depends on the performance of the spectrum sensing and network topology. We analyze the SOP under the imperfect channel sensing and the different network topologies. The second step of the utilization is to send the packet to the receiver without error.

#### 2.3.1 Imperfect Spectrum Sensing

Energy detection is the most common method for the spectrum sensing due to its simplicity and easy implementation. However, it comprises imperfections due to channel shadowing and fading [14]. There are two types of errors, which are false alarm (FA) error and mis-detection (MD) error. FA error is due to sensing an idle channel as an occupied one. MD error is due to assuming the occupied channel as an idle one.

The SOP detection probability is the probability of sensing the channel as idle given that the channel is actually idle. We first explain the temporal activity of channel to characterize SOP. To this end, we define random variables defining the idle and busy times of PUs which are denoted as  $T_I$  and  $T_B$ , respectively.  $T_I$  and  $T_B$  follow exponential distributions whose means are  $\alpha$  and  $\beta$ , respectively [15, 16, 17]. Hence, the probability distribution functions are defined for  $T_I$  and  $T_B$  as  $f_{T_I}(t) = \frac{1}{\alpha}e^{-\frac{t}{\alpha}}$ ,

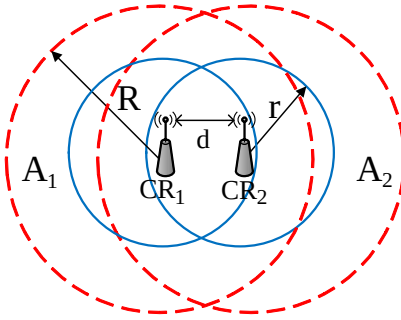


Figure 2.2: A communication link between  $CR_1$  and  $CR_2$ .

and  $f_{TB}(t) = \frac{1}{\beta}e^{-\frac{t}{\beta}}$ , respectively. The probability that PU is idle (PU is OFF) is  $P_{OFF} = \frac{\alpha}{\alpha+\beta}$ . The probability that PU is busy (PU is ON) is  $P_{ON} = \frac{\beta}{\alpha+\beta}$ .

The determination of the probability of FA,  $P_{FA}$ , is vital to find the probability of SOP detection. If we define the event that the non-existence and existence of the PU signal as  $\mathcal{H}_0$  and  $\mathcal{H}_1$ , respectively,  $P_{FA}$  is defined as [16],  $P_{FA} = Pr[Busy|\mathcal{H}_0] = P_{OFF}\mathcal{Q}(\frac{\delta-2\tau_S B\sigma_n^2}{\sqrt{4\tau_S B\sigma_n^2}})$ , where  $B$  is the bandwidth of the channel,  $\delta$  is the signal detection threshold,  $\sigma_n$  is the noise variance, and  $\tau_S$  is the sensing time, and  $\mathcal{Q}$  is Q-function [18]. The detailed information about  $P_{FA}$  and  $\delta$  selection is found in [16]. In this chapter, we directly consider  $P_{FA}$ , however, we provide the equation of  $P_{FA}$  for the coherence of the chapter. Vacant spectrum detection probability correctly,  $P_V = Pr[Idle|\mathcal{H}_0]$ , is defined as [16]

$$P_V = P_{OFF} - P_{FA} = P_{OFF}\mathcal{Q}\left(\frac{2\tau_S B\sigma_n^2 - \delta}{\sqrt{4\tau_S B\sigma_n^2}}\right). \quad (2.1)$$

### 2.3.2 USOP characterization in Network Topology T1

The temporal variation of PU activity is the only cause of the SOP change in T1. There is no spatial variation since PU covers the CR in the network as seen in Fig. 2.1(a). The existence of SOP and its utilization between a CR transmitter and a CR receiver depend on the activity of the PU, the sensing performance of the transmitter and the successful reception at the receiver. Furthermore, the packet size,  $N_b$ , and

the data rate of the link,  $R_b$ , are important for USOP since there must be no PU activity during the use of the licensed spectrum band. Hence, the PU must not be active during the packet transmission interval, and it can be defined as

$$P_{NP} = Pr[T_I > \frac{N_b}{R_b}] = \int_{N_b/R_b}^{\infty} \frac{1}{\alpha} e^{-\frac{t}{\alpha}} dt = e^{-\frac{N_b}{R_b \alpha}}. \quad (2.2)$$

The successful communication at the CR transmitter is realized when the transmitter detect the vacancy of the spectrum band correctly, and there is not any PU activity during the transmission activity. Hence, the USOP probability at the transmitter side can be described as

$$P_{tx} = Pr[\text{No PU during transmission} | \text{SOP detection}] \quad (2.3)$$

$$= P_{NP}(P_{OFF} - P_{FA}) = P_{NP}P_V. \quad (2.4)$$

(2.3) describes the USOP at the transmitter, and (2.4) shows that the USOP at the transmitter is the intersection of the event that there is no PU activity during the transmission, and the event that the transmitter successfully detects the SOP.

The probability of USOP at the receiver,  $P_{rx}$ , is the same as the probability of USOP at the transmitter side. The receiver must not be exposed to PU activities during the reception and it must detect SOP correctly. Furthermore, the communication link is unreliable due to the properties of the physical channel. Hence, the successful probability is given as [19]  $P_S(\gamma) = (1 - \Gamma(\gamma))^{N_b}$ , where  $\gamma$  is the signal-to-noise ratio (SNR) between the transmitter and the receiver which depends on the power control,  $\Gamma$  is the bit error rate (BER). The expression of BER in Rayleigh fading channel for  $\gamma \geq 5$  can be written as [18, 19]

$$\Gamma_f(\gamma) \approx \frac{\sigma_m}{2\beta_m \gamma}, \quad (2.5)$$

where  $\sigma_m$  and  $\beta_m$  depend on the modulation type.  $\sigma_m = 1$  and  $\beta_m = 2$  for binary phase shift keying modulation [18], which is used in our network. Hence, we can

characterize the USOP probability as the USOP probability at the transmitter side and the receiver side without packet error. The probability of USOP can be described as

$$P_{USOP}^{T1} = P_{tx}P_{rx}P_S = ((P_{OFF} - P_{FA})P_{NP})^2 P_S. \quad (2.6)$$

### 2.3.3 USOP characterization in Network Topology T2

The spatial-temporal variations in the spectrum availability affect the characterization of USOP in  $T2$ . The transmission ranges of PUs and the CRs in  $T2$  are comparable as seen in Fig. 2.1(b), hence, there is a more dynamic radio environment. Let  $R$  be the transmission range of a PU, and  $r$  be the transmission range of the CRs. Fig. 2.2 shows a communication link between a transmitter and a receiver. The distance between the communicating nodes,  $d$ , is smaller than  $r$ .  $A_1$  and  $A_2$  are the regions that no PU activities must be present for  $CR_1$  and  $CR_2$ , respectively.

There are two cases for USOP in  $T2$ . The union of these cases includes the conditions, which do not violate the spectrum-aware communication among CRs. These cases can be outlined as follows.

**Case 1:** In the first case, there must be no PUs located in the union of regions  $A_1$  and  $A_2$ . As there are not any PUs in the union of these regions, the CRs must correctly detect the spectrum vacancy. Let PUs in the network be randomly deployed with a uniformly distribution whose density is  $\lambda_{PU}$  [11]. The probability that there is not any PU located in the region  $S(d, R) = A_1 \cup A_2 = 2\pi R^2 - 2R^2 \cos^{-1}(\frac{d}{2R}) + \frac{d}{2} \sqrt{4R^2 - d^2}$  can be defined as

$$P_1 = Pr[\text{No PUs in } A_1 \cup A_2] = e^{-\lambda_{PU} S}. \quad (2.7)$$

The probability that  $CR_1$  successfully detects the spectrum vacancy can be written as  $P_{OFF} - P_{FA}$ .  $CR_2$  must sense the vacant channel correctly, and this probability is the same as the probability of correct spectrum vacancy detection for  $CR_1$ . Furthermore, the packet must be received without error, and this probability is  $P_S$ . Hence,

the probability of Case 1 is written as

$$P_{C1}^{T2} = P_1(P_{OFF} - P_{FA})^2 P_S. \quad (2.8)$$

**Case 2:** In the second case, there may be PUs located in the region  $S(d, R)$ , and the number of PUs located in the region  $S(d, R)$  is denoted by  $N_{PU,S}$ . The PUs located in region  $S(d, R)$  affect the communication since the communication activity of a PU in this region interferes with the transmitter or the receiver or both. Hence, all the PUs located in this region must be in OFF state during the transmission of packet. The probability that there are  $k$  PUs in region  $S$  can be given as  $Pr[N_{PU,S} = k] = e^{-\lambda_{PU}S} \frac{(\lambda_{PU}S)^k}{k!}$ . PUs are distributed uniformly in the network, and the density of PUs is denoted by  $\lambda_{PU}$ . Hence, the probability that there are  $k$  PUs in the region  $S$  is given according to a Poisson distribution. We can assume that the network size is infinity, and the number of PUs in the network can be approximated as infinity.

Let  $Q_{PU,S}$  be the state of the PUs in the region  $S$ . If  $Q_{PU,S} = 0$ , the PU nodes in the region  $S$  are in OFF state during the packet transmission. Hence, we can denote the USOP probability in Case 2 as

$$P_2 = Pr[N_{PU,S} > 0 \cap Q_{PU,S} = 0] \quad (2.9)$$

$$= Pr[N_{PU,S} > 0] Pr[Q_{PU,S} = 0 | N_{PU,S} > 0] \quad (2.10)$$

$$= \sum_{k=1}^{\infty} \frac{e^{-\lambda_{PU}S} (\lambda_{PU}S)^k}{k!} P_{NP}^k \quad (2.11)$$

$$= e^{-\lambda_{PU}S} \left( \sum_{k=0}^{\infty} \frac{(\lambda_{PU}S P_{NP})^k}{k!} - 1 \right) \quad (2.12)$$

$$= e^{-\lambda_{PU}S(1-P_{NP})} - e^{-\lambda_{PU}S}. \quad (2.13)$$

The probability of no active PUs for Case 2 in  $T2$  is written in a conditional form as in (2.10). As in (2.11), the uniform distribution of PUs in the network causes a Poisson distribution for possible PUs in the region  $S$ , where  $k$  represents the number of PUs in the region  $S$ , and its range is from one to infinity since we are considering

the case that there are one or more PUs in the region  $S$ . Furthermore, the number of PUs in the network may increase to infinity as the network size is assumed to be infinity. We use the Taylor expansion of exponential number in (2.12) and (2.13). For a successful SOP detection and its utilization, the PUs in the region  $S$  must be OFF during the communication. The transmission must also be carried without error in Rayleigh fading channel, whose probability is  $P_S$ . The probability of USOP in  $T2$  for Case 2 can be written as

$$P_{C2}^{T2} = P_2(P_{OFF} - P_{FA})^2 P_S \quad (2.14)$$

since both the transmitter and the receiver should sense SOP and utilize the idle channel successfully. The overall USOP probability for  $T2$  is found by the summation of the probabilities of cases  $C1$  and  $C2$  as follows,

$$P_{USOP}^{T2} = P_{C1}^{T2} + P_{C2}^{T2} = P_S(P_1 + P_2)(P_{OFF} - P_{FA})^2. \quad (2.15)$$

## 2.4 Numerical Results

In this section, we study the probability of USOP under different conditions and network topologies. As explained in Section 2.3,  $P_{USOP}$  depends on the network system parameters according to the network topology. Unless otherwise stated, we set the system parameters as  $R_b = 100 \text{ Kbps}$ ,  $N_b = 500 \text{ bits}$ ,  $P_{OFF} = 0.9$ ,  $P_{FA} = 0.1$ ,  $\alpha = 100 \text{ msec}$ ,  $d = 10 \text{ m}$ ,  $R = 20 \text{ m}$ ,  $\gamma = 30 \text{ dB}$ , and  $\lambda_{PU} = 0.0001 \text{ PU/m}^2$ , which are on the order the values in [15, 16, 19, 17]. In our first study, we investigate the USOP probability for different system parameters which are  $N_b$ ,  $R_b$ ,  $\alpha$ ,  $\gamma$  and  $P_{OFF}$  as seen in Fig. 2.3. These parameters are selected due to their ability to change the channel characteristics and the network as in [16, 17].

We first investigate the effects of  $R_b$  and  $N_b$ . As  $N_b$  increases,  $P_{NP}$  in (2.2) decreases, and also  $P_S$  decreases. Hence,  $P_{USOP}^{T1}$  in (2.6) decreases. For  $R_b = 50 \text{ kbps}$ , 25% decrease occurs as the greatest change for a 750 bits change in  $N_b$ .  $P_{USOP}^{T2}$

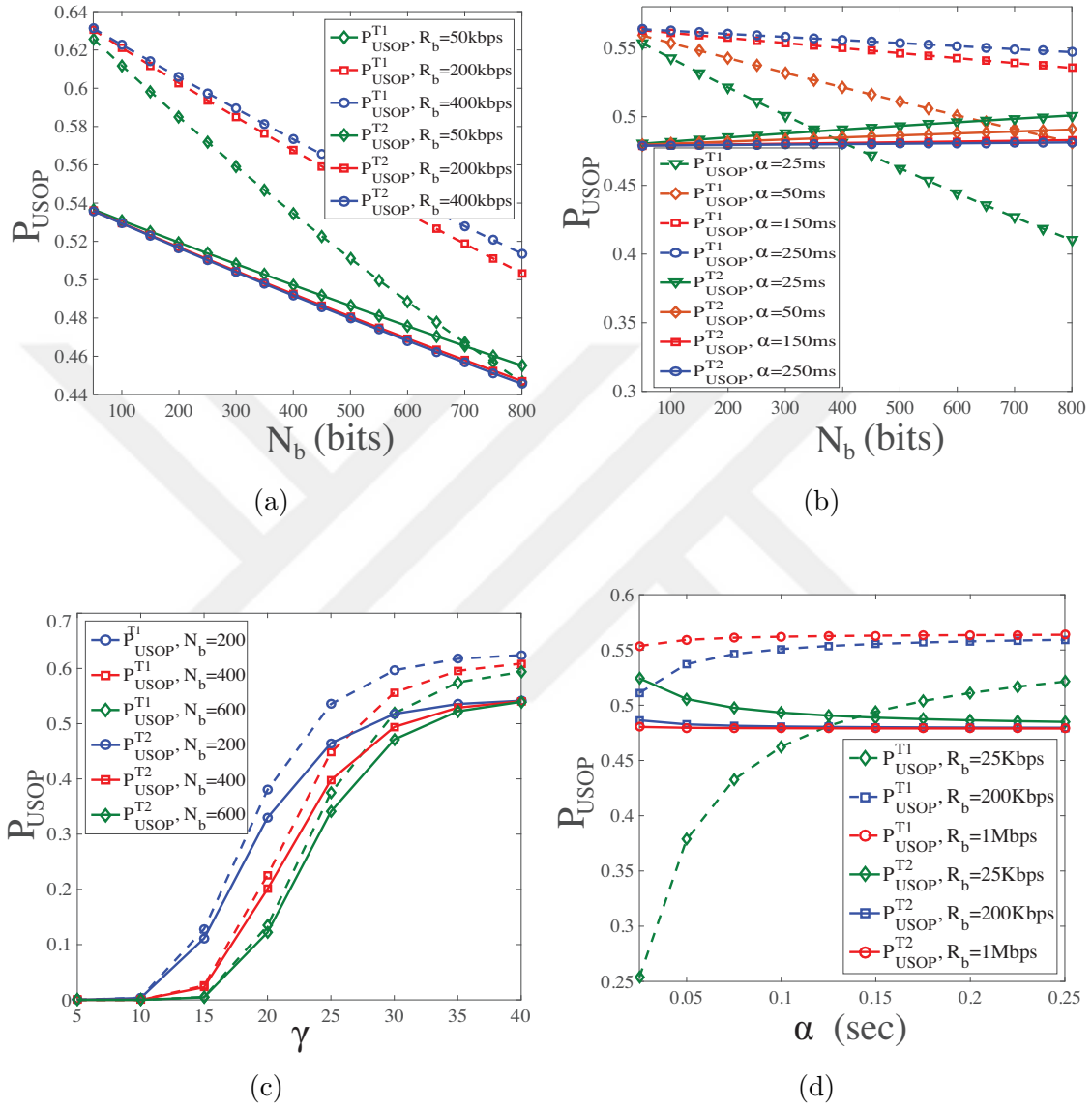


Figure 2.3: Probability of USOP under different topologies vs. (a)  $N_b$ , (b)  $N_b$ , (c)  $\gamma$ , and (d)  $\alpha$ .

decreases due to the increase in  $N_b$  in (2.13) for  $T^2$  as seen in Fig. 2.3(a). This decrease is due to the increase in  $N_b$ . The approximate change is 18% for  $P_{USOP}^{T^2}$  for all  $R_b$ . Also, as  $\alpha$  increases,  $P_{NP}$  in (2.2) increases. Hence,  $P_{USOP}^{T^1}$  decreases as seen in Fig. 2.3(b). However, the effect of  $\alpha$  is at most 5% for  $T^2$ . However,  $\alpha$  has positive effect on  $P_{USOP}^{T^2}$  due to (2.13).  $\alpha$  is the mean inactive time of PUs, and an increase in

$\alpha$  increases the probability of no PU activity during the communication effort. OFF state of PU is actually means an opportunity for a CR. It has power control to change their SNR,  $\gamma$ . For SNR values smaller than 15 dB, the channel is in deep fade and the communication is almost impossible. However,  $P_{USOP}^{T1}$  and  $P_{USOP}^{T2}$  reach almost 0.5 for 30 dB as seen Fig. 2.3(c). The quality of channel increases and the fading effects become negligible. An increase in  $R_b$  decreases the communication time, hence, the probability that communicating nodes expose to PU activity decreases, which also increases  $P_{NP}$ . This increase causes an increase in  $P_{USOP}^{T1}$  for  $T1$  due to (2.2) and a decrease in  $P_{USOP}^{T2}$  for  $T2$  due to (2.13).

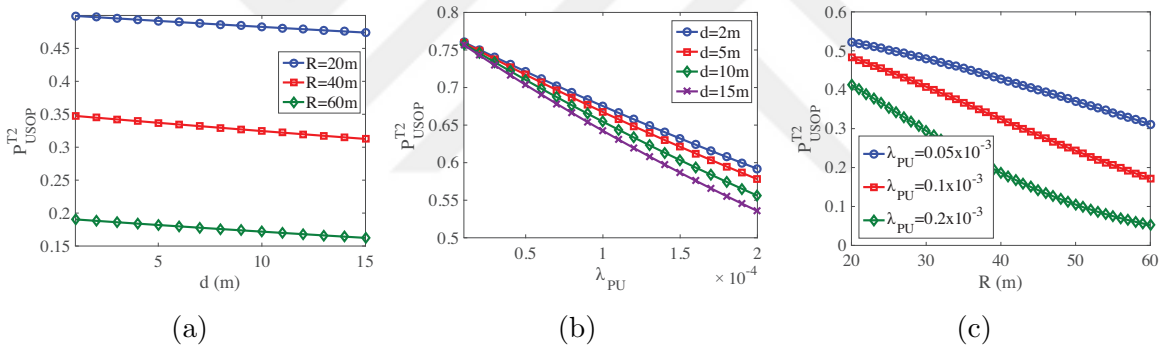


Figure 2.4: Probability of USOP under network topology  $T2$ ,  $P_{USOP}^{T2}$ , vs. (a)  $d$ , (b)  $\lambda_{PU}$ , (c)  $R$ .

The network parameters such as  $R$ ,  $\lambda_{PU}$  and  $d$  affect the SOP probability only in  $T2$ . Hence, we study the effect of these parameters on  $P_{USOP}^{T2}$ . As we increase  $R$ , the CRs become more exposed to the activities of PUs. Hence, this effect decreases  $P_{USOP}^{T2}$ . The effect of  $d$  is small since  $R$  is much greater than  $d$ . The effects of  $d$  and  $R$  can be seen in Fig. 2.4(a).  $\lambda_{PU}$  is a significant parameter since it affects the number of PUs located in the communication area of the CRs. As we increase  $\lambda_{PU}$ , there would be more PU activity in the communication area. Hence, it decreases  $P_{USOP}^{T2}$  as seen Fig. 2.4(b). For instance,  $P_{USOP}^{T2}$  decreases nearly 30% when  $\lambda_{PU}$  increases from  $25 \times 10^{-6}$  to  $200 \times 10^{-6}$ . The effect of  $R$  can be seen in Fig. 2.4(c) in a more profound way. The increase in  $R$  causes an increase in  $S(d, R)$ .  $P_{USOP}^{T2}$  decreases as  $S(d, R)$

increases in (2.15). Nearly 85% decrease in  $P_{SOP}^{T2}$  is seen when  $\lambda_{PU} = 200 \times 10^{-6}$ . Hence,  $R$  highly affects  $P_{USOP}^{T2}$ .



## Chapter 3

# CLUSTERING IN MULTI-CHANNEL COGNITIVE RADIO AD HOC AND SENSOR NETWORKS

### 3.1 Introduction

Proliferation of wireless devices resulted in spectrum scarcity problem, considering the fact that spectrum is not efficiently utilized in traditional fixed spectrum assignment policy. Cognitive Radio (CR) stands as the solution to overcome this problem by enabling Dynamic Spectrum Access (DSA) to licensed bands in an opportunistic manner [9, 20].

CR technology is applied to different types of wireless networks, called as CR-enabled wireless networks in general. CR-enabled networks can be segregated in two dimensions, as seen in Fig. 3.1. Firstly, a CR-enabled network may be exploiting a single licensed channel or multiple licensed channels for its use. Secondly, CR-enabled networks can be centralized or distributed, depending on their architecture. Centralized CR-enabled networks, i.e., Cognitive Radio Networks (CRNs), have base stations that regulate cognitive cycle functions of spectrum sensing, spectrum decision, and spectrum hand-off. On the other hand, in distributed CR-enabled networks, i.e. Cognitive Radio Ad Hoc Networks (CRAHNs) [9] and Cognitive Radio Sensor Networks (CRSNs) [20], there is a flat architecture without a strict central entity. These distributed CR-enabled wireless networks can be termed as *Cognitive Radio Ad Hoc and Sensor Networks*. Our focus in this chapter is multi-channel CRAHNs and CRSNs as seen in Fig. 3.1.

Despite the fact that numerous solutions are offered for CRAHNs and CRSNs, coordination in these networks remains one of the key challenge for their realization.

Clustering can be utilized as a functional tool that can be used to manage and regulate operations in such distributed networks [21]. Clustering divides these distributed networks into different logical groups, depending on the functionality that clustering is employed for. In a cluster structure, there is a cluster-head that organizes the inter- and intra-cluster communication, and cluster members send packets to their corresponding cluster-heads. Apart from physical proximity, common channels should be present between cluster members in CRAHNs and CRSNs. Hence, this type of clustering is called *spectrum-aware clustering*. Due to this feature, clustering is used as a functional tool for DSA functions, medium access control, routing, and managing multi-channel communications. Despite its advantages, some key challenges such as heterogeneous licensed channels, mobility and dynamic change in vacant channels in the networks must be carefully considered to propose clustering solutions.

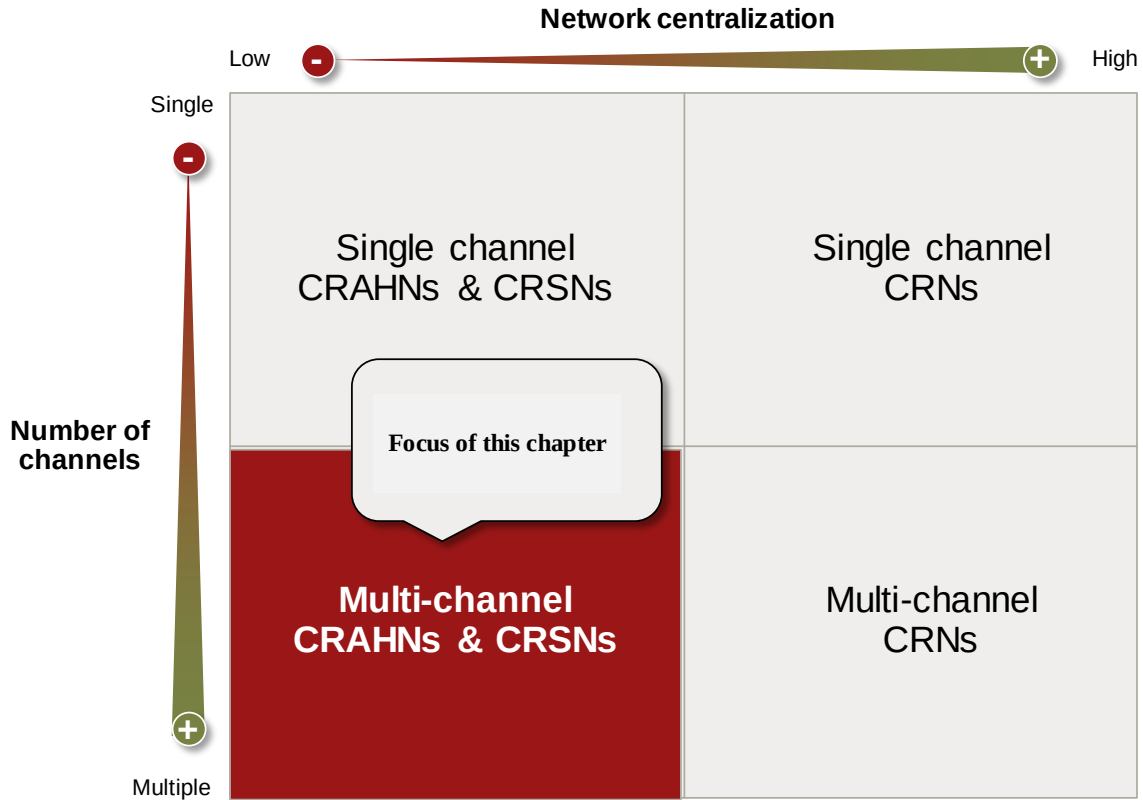


Figure 3.1: Domain of clustering in cognitive radio wireless networks.

In this chapter, we investigate factors that affect clustering, which are network types, models and objectives. In terms of network types, we consider CRAHNs and CRSNs. Nodes in CRSNs are generally have limited energy and computational capability. Hence, proposed clustering solutions should be energy-efficient and simple. In terms of network topology, we consider network topologies in CRAHNs and CRSNs. The topologies differ according to the relative communication ranges of PUs and CRs. In terms of network objectives, we consider support for mobility, channel heterogeneity, sensing imperfections, etc. Existing spectrum-aware clustering schemes are studied. Although, there are some studies to form clusters in dynamic radio environment, there are some unrealistic assumptions. Hence, we study how a distributed clustering approach should be designed for CRAHNs and CRSNs by taking inherent challenges into account to overcome difficulties of multi-channel cognitive radio ad hoc and sensor networks.

This chapter is organized as follows. Section 3.2 motivates the clustering and explains challenges. Section 3.3 overviews factors that affect clustering. Functionalities of clustering are explained in detail in Section 3.4. Existing clustering schemes are presented and their comparisons are made to observe their differences in clustering in Section 3.5. We present how a clustering approach should be in CRAHNs and CRSNs for a realistic scenario in Section 3.6.

### **3.2 Motivations and Challenges**

Dynamic radio environment and non-existence of central entity require efficient spectrum management and communication techniques. One of the most important technique is the clustering since it has the ability to organize ad hoc network. Apart from the advantage of organization, it imposes local coordinators so that spectrum-aware communications can be performed in a structured way. Hence, we describe motivations for and challenges of clustering in cognitive radio ad hoc and sensor networks in detail.

### 3.2.1 Motivations for Clustering

Clustering forms groups to better utilize the resources in ad hoc networks. It becomes more beneficial for ad hoc networks with DSA since spectrum-aware communication necessitates some form of decentralized structure that clusters can offer. We itemize the motivations for clustering in our domain.

- **Coordination between nodes:** In each cluster, there is a cluster-head that controls the communication in its group. Furthermore, it performs communication between clusters, which is inter-cluster communication. There is an additional constraint for communication between neighboring CRs, which is the existence of common vacant licensed channels. This fact further motivates the clustering approach in our domain to enable virtual backbones in these networks.
- **Scalability:** Ad hoc and sensor networks have high network density so that protocols and the solutions in these networks may not be scalable. Furthermore, the dynamic change in the spectrum availabilities of the nodes jeopardizes the proper functioning of the devised solutions. On top of homogeneous network, clustering imposes virtual nodes to improve scalability of the network by reducing communication overheads [21].
- **Improvement in network performance:** Cluster are organized according to their spectrum availability so that they are immune to PU arrivals on their operating channels due to spectrum-aware clustering.
- **Cooperation between the nodes:** Spectrum management, which consists of spectrum sensing, spectrum decision and spectrum handoff, can be managed more easily and in a more structured way. These complex tasks, i.e., cognitive cycle functions, are performed in a cooperative manner between the cluster members. Furthermore, the cooperation between the cluster-heads results in better communication among the nodes in our domain.

- **Imposing local control channels:** The most important problem in spectrum-aware communication is to assume a common control channel in whole network. However, this assumption is not realizable due to dynamic behavior of the PUs. Clusters form local common control channels to regulate the communication between the cluster members.
- **Multi-channel communication support:** Cluster-heads can construct multiple channels in an efficient way to support higher level of quality of service.

The above mentioned motivations trigger spectrum-aware clustering schemes for CRAHNs and CRSNs. Efficient clustering protocols and algorithms boost network performance and organize the communication within these type of ad hoc networks, in which the operation of CRs highly depends on licensed users.

### 3.2.2 Challenges of Clustering

Despite the various motivations of clustering in CRAHNs and CRSNs, there exist challenges posed by the ad hoc nature of these types of networks and dynamic radio environment. The following outlines these challenges.

- **Dynamic change in availability of licensed bands:** In dynamic radio environment, the most important factor that threatens the stability of clusters is dynamic change in vacant spectrum bands of the clusters. If there is no common channel among the cluster members, these nodes should be re-clustered. Hence, the clustering scheme should be robust to the changes in the available spectrum bands. Furthermore, frequent re-clustering causes energy consumption due to control messages for the formation of new clusters.
- **Mobility of CRs and/or PUs:** Another challenges posed by these type of networks is the mobility. The clusters are formed in the local vicinity of the cluster-heads. Hence, if the cluster-heads lose their connection with the cluster members, the cluster structure changes and the association and disassocia-

tion mechanisms should be performed for the incoming and outgoing nodes to the clusters. Furthermore, the mobility of PUs causes more dynamic spatio-temporal changes in spectrum availability of the CRs. Hence, the mobility poses challenge to form and preserve the clustering structures in CRAHNs and CRSNs.

- **Imperfect channel sensing:** In order to form clusters, correct detection of the spectrum opportunities is of utmost important. The common method for spectrum sensing is energy detection due to its simplicity [9]. However, this method has imperfections in the sensing process. The most important criteria for the formation of clusters is vacant spectrum bands of CRs. Hence, the probabilities of mis-detection and false alarm are important for the stability of clusters.
- **Maintenance of clusters:** Due to the dynamic radio environment, the maintenance of the clusters pose a challenge. Effects of PUs increases the cost to preserve the clusters. Due to these dynamic effects, some nodes may leave their current clusters or join another one.
- **Heterogeneity in licensed channels:** Channel characteristics of licensed channels may differ in a realistic scenario in a multi-channel CRSNs and CRAHNs. This difference may result in different bit rate, transmission range, etc. It decreases efficiency of the communication due to the dynamic arrival of PUs operating in these heterogeneous channels.

### **3.3 Factors Affecting Clustering**

In this section, we investigate the factors that affect clustering. We elaborate on these factors in the following subsections.

### 3.3.1 Network Types

We have two network types, which are CRAHNs and CRSNs. The most important consideration for these network types is energy-efficiency since CRSNs consist of nodes having limited battery power. The key difference between these two types of network is energy limitation of CRSN nodes.

### 3.3.2 Network Objectives

For multi-channel CRAHNs and CRSNs, the clustering is highly affected by the objectives of the network. Clustering maintenance, correct channels sensing, managing heterogeneity in multi-channel system, and mobility support are important objectives of the networks, which directly alter the clustering approaches in multi-channel CRAHNs and CRSNs.

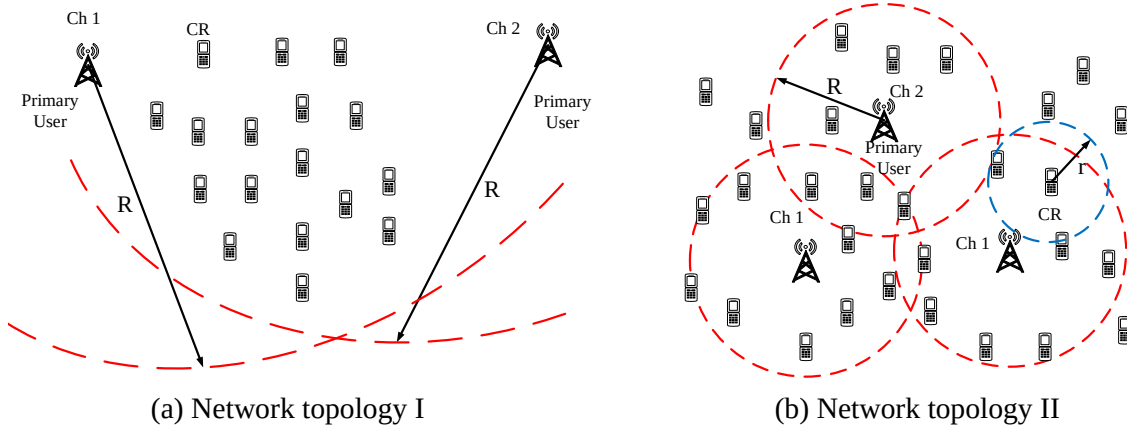


Figure 3.2: Network topologies: (a) Topology I, (b) Topology II.

### 3.3.3 Network Models

The spectrum opportunity for CRs depends on communication activities of PUs. Depending on features of PUs, the opportunity to access the spectrum changes both spatially and temporally. The most important factor resulting in the dynamic change in spectrum opportunity is relative transmission range of PUs with respect to that

of CRs. Depending on this fact, we model CRAHNs and CRSNs as two topologies, which are Topology I and Topology II as in [22]. We explain these two topologies and their effects for clustering.

#### *Topology I*

In Topology I, there are PUs in the network operating in different licensed channels. However, the transmission range of PUs is larger than that of SUs such that PU network covers secondary network ( $R \gg r$ ) as seen in Fig. 3.2(a). According to license channel usage activities of PUs, there would be temporal variations in spectrum opportunity. Also, there would be spatial variation in vacant licensed bands due to the effects of shadowing and fading. Hence, there would be spatio-temporal variations in the available licensed spectrum bands of CRs. For instance, the vacant channel lists of CRs may differ although two PUs using channels 1 and 2 in Fig. 3.2(a) covers all the CRs.

#### *Topology II*

In Topology II, the transmission range of PUs is comparable with the transmission range of CRs ( $R > r$ ) as seen in Fig. 3.2(b). Hence, even if the all PUs use their licensed spectrum, there would be spectrum opportunities for the CR nodes located outside of the transmission ranges of PUs. Furthermore, the variations in the channel use of the PUs result in the temporal changes in the spectrum availability of CRs located inside the transmission range of them. This model causes a very dynamic radio environment, which requires coordination scheme for the communication between the CR nodes in a distributed manner.

### **3.4 Functionalities of Clustering**

The method of clustering is used in different functionalities for CRAHNs and CRSNs due to its potential benefits. Coordination, performance improvement, cooperation

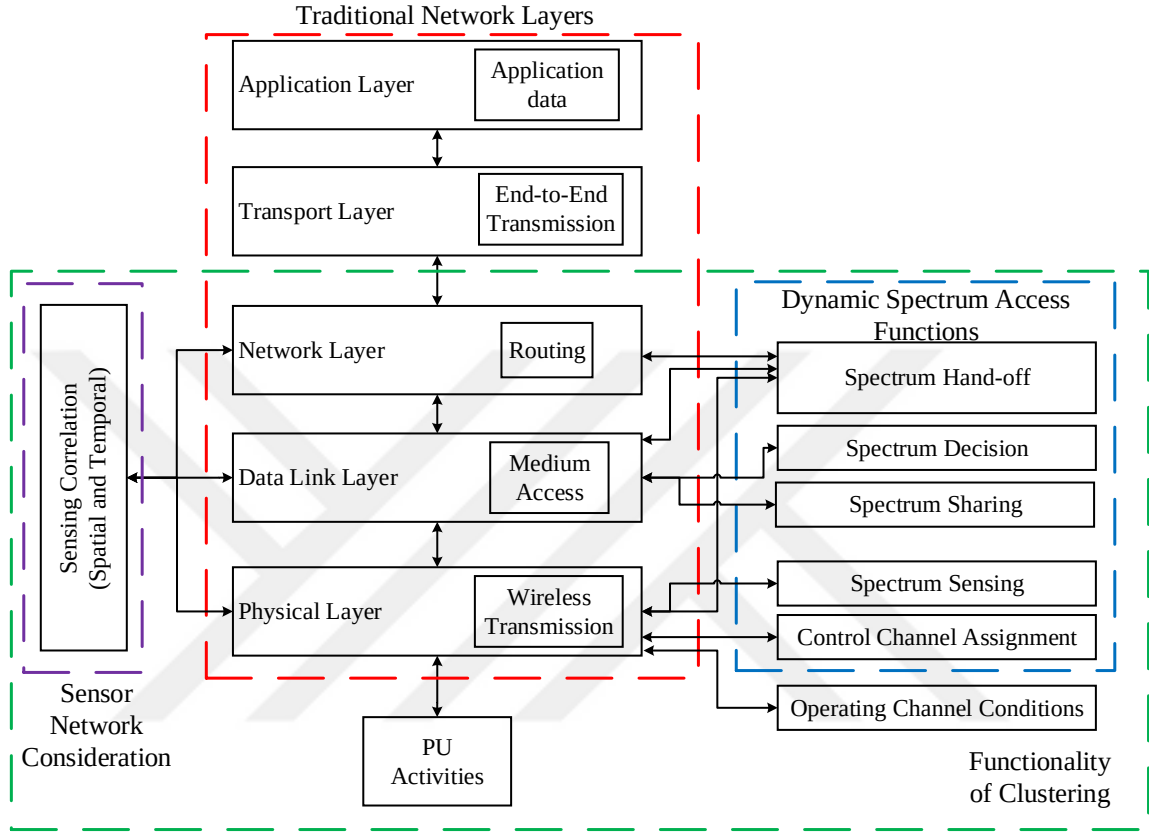


Figure 3.3: Functionalities of clustering and their relations with traditional network layers and dynamic spectrum access functions.

and scalability gains are the main motivations for its applications in different domains of CR-enabled ad hoc networks. These applications are summarized in the following.

- Spectrum Sensing:** The nodes in a cluster send their observation about the spectrum to the cluster-head to make local decision about the vacancy in licensed channels. The cluster-head behaves as a fusion center to determine PU presence. The nodes in the cluster cooperate to reach a consensus for more reliable spectrum sensing. This application is more suitable for the networks with Topology I. Due to shadowing, fading and imperfections of spectrum sensing, CRs cooperate to determine vacancy of the spectrum bands in Topology I by clustering.

- **Topology Management:** Apart from devising protocols for ad hoc networks, the topology should be managed efficiently in these type of networks. Dynamic radio environment makes it more challenging. Hence, imposing virtual backbones such as cluster-heads in the network helps better management of topology of the network. There are two issues in CRAHNs for topology management, which are topology changes and common control channel [23]. Cluster-based approaches by exploiting spatio-temporal variations in vacant licensed bands can be utilized to manage topologies in CRAHNs and CRSNs. This functionality can be utilized in both topologies.
- **Control Channel Assignment:** The most important problem in dynamic radio environment is availability of common control channel throughout the network. Hence, clustering forms small groups with common control channels among each of them. They are utilized to organize the spectrum-aware communication inside clusters. Control messages among cluster members are transmitted through these control channels [24]. Control channel assignment can be performed by clustering in both topologies.
- **Spectrum Sharing and Decision:** Allocation of resources in an ad hoc network with opportunistic spectrum access is a tough task due to contention towards vacant licensed bands and PU arrivals. Clustering can be utilized to decrease the interference among SUs by power and sub-channel allocations [25]. Cluster-head decide the operating communication channels for intra-cluster communication that contributes to spectrum decision. The clustering is beneficial for both of the topologies while sharing and decision of the spectrum.
- **Routing:** Clustering forms a hierarchical structure in ad hoc networks. Hence, it makes routing more easier since nodes are grouped according to their neighborhood, and the nodes in different clusters communicate with each other via cluster-heads. For instance, clustering is utilized to route multimedia packets

in CRSNs according to dynamic spectrum access and quality of service requirements [26]. Routing with clustering is applicable in both topologies.

- **Medium access:** Cluster-heads can behave as a coordinator for accessing spectrum after sensing for the vacant channels collaboratively. A medium access scheme can be designed such that every node in a cluster can access the idle channel without contention [27]. The cluster-based medium provides higher throughput and smaller delays with less energy consumption. Dynamic spectrum access with clustering is possible in both topologies.
- **Managing sensing correlation:** In sensor networks, clustering can benefit from the exploitation of the spatial and temporal correlation of sensor nodes' observations. The nodes in a cluster have correlated observations in time and spatial domains, hence, the aggregation at the cluster results in less packet transmission and hence energy consumption. Correlation can be exploited by clusters in both topologies.

The functionalities of clustering cover physical, data link and network layers. Clustering approaches help realizing dynamic spectrum access functions such as spectrum hand-off, decision, sharing, and sensing as seen in Fig. 3.3. Furthermore, each of these functions affect the operations in the corresponding layer, which are shown by the arrows in Fig. 3.3. Another functionality of clustering is exploitation of spatio-temporal correlation, which affects physical, data link and network layers.

### 3.5 Spectrum-aware Clustering Schemes

The most important consideration of clustering in CRAHNs and CRSNs is the available spectrum bands in a neighborhood. Hence, clustering protocols in literature have this attribute in common. However, they have different approaches apart from the spectrum availabilities in neighborhood while forming clusters. We overview recent existing approaches for clustering in dynamic radio environment.

- **ROSS [28]:** This clustering schemes aims robustness of clusters, which means ultimate sustainability of them in case of increased PU activity. The authors in [28] propose a distributed clustering algorithm, which enables the cluster formation by interactions among neighbors of CR nodes. It consists of two cascaded phases, which are cluster formation and membership clarification. Firstly, cluster-heads are selected according to connectivity vector, which consists of individual connectivity degree and neighborhood connectivity degree. In this phase, common channels between cluster members are guaranteed and the cluster size is controlled. The second phase is for the clarification of cluster membership. The process of membership clarification is realized as a congestion game. The debatable nodes, which are overlapping nodes with different clusters, choose the cluster with highest common channels after joining them.
- **Affinity Propagation (AP) [29]:** This algorithm applies affinity propagation so that CR nodes are data points and the cluster-heads are exemplars. The main aim is to minimize the number of clusters in the whole network. Similarity measure is the common channels shared by CRs. The objective of the clustering is to have as high number of available channels as possible with other nodes in the cluster. The cluster-heads are chosen with a probability that is determined by the node degree of the CRs.
- **SOC [24]:** Spectrum Opportunity Clustering (SOC) is a cluster first algorithm. There are three steps for the formation of clusters. In the first step, the nodes know its neighbors and their vacant channels, and they forms bicliques which are maximum edge biclique or maximum one-sided edge biclique. The formed bicliques are broadcast to the neighbors and best biclique is selected according to largest cluster size or edges in the biclique as the second step. In the last step, the nodes with more than one cluster affiliation are removed. The cluster-head is the node with one hop communication distance with the cluster members.
- **CogLEACH [30]:** In this clustering method, expected number of cluster-

heads is fixed and the nodes with higher number of channels more likely to become cluster-heads. According to these conditions, every node is assigned a probability to become a cluster-heads. Non-cluster-head nodes send join request to the cluster-head with minimum communication cost based on the received signal strength.

- **DSAC [31]:** Distributed Spectrum-Aware Clustering (DSAC) scheme tries to minimize total energy consumption, which is sum of energy consumed for intra-cluster and inter-cluster communications. Optimal number of clusters are determined according to the average consumed energy. For the distributed algorithm, locally closest pairs are merged for clustering with group-wise available channel constraint.
- **Combo [32]:** In this clustering scheme, nodes know their  $k$ -hop neighbors and their corresponding vacant channels. All CRs calculate minimum number of common channels with their  $k$ -hop neighbors. According to this information, a weight is assigned to each CR for cluster-head selection process. The node with highest weight in its neighborhood becomes a cluster-head. These nodes send membership request for their clusters. If a node receives more than one request, it selects the one with the highest weight.

Table 3.1 summarizes the above discussions and gives overall comparison of existing clustering schemes according to the factors affecting clustering.

Table 3.1: Overall comparison of existing clustering schemes.

| <i>Protocols</i> | <i>Approach</i>             | Network Type             |             | Network Model   | Network Objectives  |                         |                         |                  |
|------------------|-----------------------------|--------------------------|-------------|-----------------|---------------------|-------------------------|-------------------------|------------------|
|                  |                             | <i>Energy-Efficiency</i> | <i>Type</i> | <i>Topology</i> | <i>Clus. maint.</i> | <i>Channels sensing</i> | <i>Heter. Mult.-Ch.</i> | Mobility Support |
| ROSS [28]        | Game Theory                 | x                        | CRAHN       | II              | x                   | Perfect                 | x                       | x                |
| AP [29]          | Affinity Propagation        | x                        | CRAHN       | II              | x                   | Perfect                 | x                       | Low mobility     |
| SOC [24]         | Bipartite Graphs            | x                        | CRAHN       | I and II        | ✓                   | Imperfect               | x                       | x                |
| CogLEACH [30]    | Weighing # of Idle Channels | ✓                        | CRSN        | I and II        | x                   | Perfect                 | ✓                       | x                |
| DSAC [31]        | Groupwise constraint        | ✓                        | CRSN        | II              | x                   | Perfect                 | x                       | x                |
| Combo [32]       | Adaptive Clustering         | x                        | CRAHN       | II              | x                   | Perfect                 | x                       | x                |

### **3.6 Distributed Clustering in CRAHNs and CRSNs**

Clustering is studied extensively in the domain of wireless ad hoc network. However, there are many open research issues for clustering in CRAHNs and CRSNs. Spectrum management, medium access control and routing solutions mainly assume that there exists a clustering scheme supporting these solutions. However, there are not enough clustering studies to satisfy inherent requirements of CRAHNs and CRSNs. The existing clustering solutions in CRAHNs and CRSNs do not fully cover the requirements of CRSNs and CRAHNs.

#### *3.6.1 Network Requirements*

CRAHNs have unique challenges, one of which high fluctuations in spectrum availability with different quality of service (QoS) requirements. For instance, multimedia applications require limited delay and jitter. Satisfaction of CRs is of utmost important with avoidance of interference to PUs. Furthermore, they need efficient spectrum management in a distributed multi-hop architecture. Topology management is another requirement since mobility of CRs and/or PUs causes very dynamic network topology. The most important requirement of these networks is the fragmentation of available spectrum and construction of multiple available channels in an efficient way.

Apart from the requirements of CRAHNs, there are additional ones for CRSNs. First of all, sensor nodes have limited battery power. Hence, the clustering must be energy-efficient. Since clustering requires control signaling, it may degrade the energy levels of the CRs. Furthermore, the sensor nodes have limited computational power. Hence, the proposed clustering approaches should be simple. Energy-efficiency and low computational overhead are two additional requirements for clustering in CRSNs.

#### *3.6.2 Clustering Design Considerations*

Design considerations of clustering in CRSNs and CRAHNs differ due to their unique requirements. They are briefly explained as common design considerations, and design

considerations specific to CRAHNs and CRSNs, which must be taken into account for a realistic communication scenario.

**Common design considerations:** The most important common constraint of the clustering approach in dynamic spectrum environment is that there needs to be at least one mutual vacant channel among the formed clusters. Furthermore, the results of spectrum sensing is also important since the clustering is performed according to the vacant spectrum bands. It is highly affected by the imperfections of CRs. The clusters can be formed according to erroneous vacant channel lists of CRs because of the sensing performance. Mobility of the nodes highly affects the heterogeneity in spectrum availability, which directly alters the cluster formation. It also causes some changes in the cluster topology such that member nodes disassociate, and a non-member node may associate itself with that cluster. Another consideration for clustering is heterogeneous licensed channels cause different characteristics such as transmission range and bit rate.

**Design considerations specific to CRAHNs:** The flows in an ad-hoc networks have different QoS levels, which poses a challenge to support these diverse communication setups. This is fortified by the dynamic spectrum access. Clustering must take them into account to support different QoS levels.

**Design considerations specific to CRSNs:** CRSNs have event-driven type of communication. The nodes report their observations after detection of an event. Clustering solutions should consider these unique property of CRSNs. Energy-efficiency is another consideration for CRSNs since the nodes have limited power. Despite the fact that clustering provides energy savings, PU activities may degrade the energy-efficiency by clustering if it is not properly designed.

### *3.6.3 Distributed Clustering Approach for CRAHNs*

Absence of centralized entity in CRAHNs necessitates cooperation between CRs. Clustering provides hierarchical structure on top of ad hoc networks. Hence, clustering is an efficient approach to manage CRAHNs. Cooperation is performed with

a distributed clustering approach, which may have different functionalities such as routing and medium access. To this end, we explain how a distributed clustering approach should be for CRAHNs.

Firstly, there is a general assumption about the existence of common control channel in the whole network. However, this is quite unrealistic due to PU activities. To make it more realistic, this channel is assumed to be a very narrow band channel, which may get congested easily. Hence, the proposed protocols must not rely on the existence of such channel. Channel hopping or rendezvous approaches could be adopted to overcome this difficulty and to cooperate with each other to form clusters in a distributed manner.

Existing clustering schemes form robust clusters against dynamic available channel variations. However, every cluster needs re-clustering due to non-existence of common channels during network operation. Apart from proposing robust clustering schemes, a re-clustering procedure should be designed for efficient operation of the network.

Different from the dynamic radio environment, mobility of network nodes makes the cooperation between them more challenging. The proposed clustering algorithms should be mobility aware. For instance, the node with higher mobility in its neighborhood should not be a cluster-head since it is highly possible for it to become disconnected from its members. This results in re-clustering, which an efficient clustering approach should avoid. Furthermore, the cluster should manage incoming and outgoing CRs to update cluster memberships. Apart from the formation of clusters, their maintenance is another issue to be considered in a realistic scenario.

Intra-cluster communication management should be also taken into account due to spectrum mobility. The operating frequency band of the cluster may become occupied, hence, the cluster members should organize intra-cluster communication accordingly to a new vacant channel without limited delay.

Fast convergence of clustering structures is of utmost importance to decrease communication overhead of clustering. Preference on cluster-head or cluster first for designing the clustering algorithm may affect the convergence.

Existing clustering schemes assume homogeneous licensed channels such that their channel characteristics are the same. However, in a realistic multi-channel CRAHN scenario, their bandwidth and center frequencies may be different. Hence, characteristics of these channels vary. For instance, spectrum sensing results for the licensed channels differ in such a case. Furthermore, the bit rate of the licensed channels become different. The characteristics of PUs on different channels may vary significantly, which results in very vigorous channel availability.

The above issues need to be carefully considered to fulfill the objectives of clustering in a multi-channel dynamic radio environment. The performance of clustering should be optimized according to these multiple objectives.

#### *3.6.4 Event-driven Approach for CRSNs*

CRSNs have event-driven traffic such that the resources are utilized when event occurs. Hence, event-driven clustering approach is shown to be energy efficient in [7]. Furthermore, this approach solicits clustering in the area between event and the sink since the nodes locating in this region will take part in forwarding event packets to the sink.

The observations by cluster members are aggregated by exploiting spatial and temporal correlation of them. Furthermore, the mobility-aware Event-to-sink Spectrum Aware Clustering Protocol (mESAC) [7] considers the mobility of the CR nodes to maintain the clusters. However, a definitive re-clustering procedure is not studied. Maintenance of the clusters during the event should be considered carefully by contemplating energy constraint of CRSN nodes.

Most importantly, heterogeneous multi-channel is not addressed in CRSN domain. It affects the clustering performance and energy consumption. Channel switching may occur frequently to use channels becoming idle with better characteristics.

Cluster connectivity is also important consideration while clustering since transport of event packets to the sink depends on connectivity of the clusters. Hence, the design of clustering algorithm should consider the inter-cluster communication

by arranging cluster-heads that can communicate via common channels among them. Furthermore, imperfect spectrum sensing may degrade the clustering performance since communication within a cluster may collide with PU due to the imperfection.



## Chapter 4

# EVENT-TO-SINK SPECTRUM-AWARE CLUSTERING IN MOBILE COGNITIVE RADIO SENSOR NETWORKS

### 4.1 Introduction

Cognitive radio technology has been proposed as a solution for the electromagnetic spectrum scarcity problem. Wireless nodes with cognitive radio (CR) capability can utilize the idle licensed bands opportunistically without any interference on primary users (PUs) [33, 8]. Wireless sensor networks (WSNs) can benefit from this advantage of CR technology to overcome the spectrum scarcity challenge. To this end, a new wireless networking paradigm, cognitive radio sensor networks (CRSNs), has been proposed by enabling dynamic spectrum access (DSA) schemes in WSNs [20].

Different from the fixed frequency allocation approach in WSNs, CRSN nodes opportunistically utilize the idle licensed bands. The opportunistic usage of the spectrum is provided by the cognitive cycle operations. CRSN nodes sense the spectrum to determine vacant bands by the spectrum sensing, choose their operating frequencies by the spectrum decision, and change the frequency by the spectrum hand-off according to the licensed user activities [20]. CRSNs are distributed networks such that they do not depend on any central entity to regulate the communication. Packets generated by the event detecting nodes are transmitted in a multi-hop manner from the event region to the sink in a dynamic radio environment. Technological advances and research efforts make the deployment of CRSNs realizable. To this end, the requirements of cognitive radio and sensor networks and their unique challenges are addressed by a growing number of studies on CRSN. Some of recent works focus on channel assignment according to residual energy [34], energy-efficient channel

management scheme [35], packet size optimization [17], power and rate adaptation for maximization of information theoretical capacity [36], and performance analysis in terms of delay [37].

Although CR capabilities offer the flexibility on wireless communication by using different spectrum bands, they also pose some important challenges. First of all, the routing in a dynamic radio environment is performed with an additional constraint of the spectrum availability. Also, the transmission between the sensor nodes can be interrupted by the cognitive cycle operations. The fluctuating nature of available channels due to the PU activity deteriorates the success of the wireless communication. The flat structure of CRSN also causes scalability issues due to an increase in the network size [38]. Furthermore, these challenges are amplified if the sensor nodes are mobile. The mobility of the nodes causes frequent topology changes. Spectrum management and dynamic topology change must be taken into consideration together to satisfy the requirements of the spectrum-aware communication and the management of the mobility. Furthermore, the event-driven communication nature injects bursty traffic which causes channel contentions and packet drops. Hence, these energy consuming operations must be handled.

Event-to-sink communication may be handled by a clustering approach due to following reasons. First of all, the event routing problem necessitates a cooperation scheme since the network is decentralized, and the channel availabilities of nodes and the topology of the network change dynamically. The event packets must be conveyed from the event region to the sink in such a dynamic environment. Clusters group nodes to cooperate with each other for the event packet routing, the channel assignment and sharing the channel sensing results reliably. Data channel can be determined by the cluster-head and cluster members for intra-cluster communication [21]. Clustering also provides network performance guarantees by organizing the nodes with respect to the dynamic channel availabilities. Cluster-heads and gateway nodes form a backbone for distributed CRSNs such that routing, cognitive cycle operations and mobility management become more manageable.

In a mobile and dynamic radio environment, keeping cluster structure before any event-to-sink communication may lead to excessive energy consumption. Hence, we propose forming clusters after event occurrences in CRSNs. The formed clusters are spectrum-aware such that the clustering criteria do not only depend on physical proximity but also available channels of the nodes and their positions in the network relative to the sink. In this chapter, we present mobility-aware Event-to-sink Spectrum-Aware Clustering (mESAC) protocol for mobile CRSNs. The contributions of our chapter are itemized as follows.

- Re-clustering probability and expected cluster coverage area are calculated.
- Maximum event generation frequency achieving energy-efficiency with respect to the whole network clustering is studied.
- The effects of mobility and the weight of the mobility in the cluster-head selection process are investigated.

## 4.2 Problem Motivation

We first describe the network model for CRSN. Afterwards, we give the motivation for the event-driven clustering.

### 4.2.1 Network Model

PUs utilize the licensed bands without any restrictions. CRSN nodes are the secondary users (SU) which can opportunistically access licensed channels if there is no primary user activity [8]. CRSN nodes can move according to random waypoint mobility model [39]. The nodes form a graph denoted by  $G = (V, E)$  where  $V$  is the set of nodes and  $E$  is the set of edges connecting the nodes. Two neighboring CRSN nodes are connected if they have a common channel.

There are  $M$  non-overlapping orthogonal channels having unique IDs. CRSN nodes can detect vacant spectrum bands by wideband spectrum sensing. The trans-

mission ranges of PUs and SUs are comparable such that the sensing results of SUs are correlated for the same neighborhood.

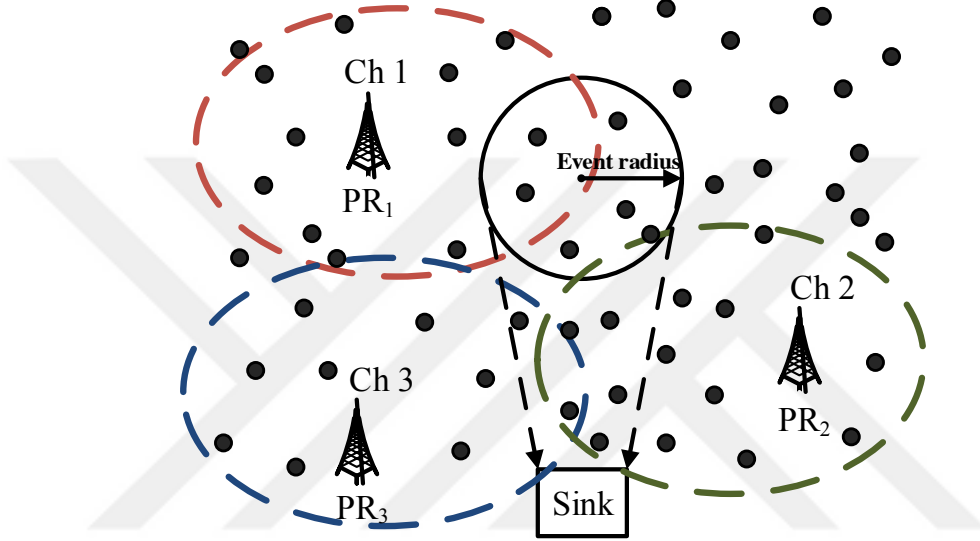


Figure 4.1: A typical CRSN topology with an event and the sink.

The communication is event-driven, and CRSN nodes located within the event radius detect the event. These nodes generate packets to be delivered to the sink. Many-to-one traffic pattern from the event detecting nodes toward the sink node is generated in a CRSN as illustrated in Fig. 4.1. There are 3 primary radios (PRs) and the coverage areas of them are shown by the circles with dashed lines and their operating channels are shown. Inside these circles, SUs can not use those channels if PUs are active.

Clustering needs the exchanges of control messages. The exchanges of these messages are provided via a common control channel with a very small bandwidth. It is available for SUs at any time [40]. Time is slotted and CRSN nodes can transmit their control information in these time synchronized slots. The time synchronization is not in the scope of the chapter. Overlay spectrum sharing is used as an interference avoidance model, i.e., SUs use portions of the spectrum not used by the PUs [8]. SUs know their location by utilizing localization algorithms. Neighbor discovery is provided by

Table 4.1: Notations For Clustering Protocol

| Notation  | Explanation                                  |
|-----------|----------------------------------------------|
| $C_i$     | Available channel list of node $i$           |
| $E_i$     | Remaining energy of node $i$                 |
| $d_{i,j}$ | Euclidean distance between nodes $i$ and $j$ |
| $d_i^e$   | Eligible node degree of node $i$             |
| $v_i$     | Speed of node $i$                            |
| $\mu$     | Mean of the distribution of node speed       |
| $P_i$     | Weight for cluster-head selection            |
| $R$       | Event radius in meters                       |
| $D_{es}$  | Distance between event and sink in meters    |
| $r$       | CRSN node transmission range in meters       |

the periodic common control channel signaling. All nodes know one-hop neighbors and their vacant channels by this signaling [41]. Table 4.1 shows the notations and their explanations which are useful for explaining the clustering protocol.

As in [42], the traffic of primary channel  $m$  is modeled as semi-Markov ON-OFF process where channel  $m$ 's state changes with probabilities  $p_{on,m}$  and  $p_{off,m}$ . OFF state of channel  $m$  is considered as a spectrum opportunity for SUs in the communication range of PU using channel  $m$ . SUs can use this channel for the communication and the cluster formation. This is the temporal variation of the spectrum availabilities. Also, PUs can be assumed to be distributed uniformly over the network area [11]. This may be interpreted as the spatial variation of the spectrum availabilities.

The free space path loss model is adopted such that  $\epsilon_{fs} = 10 \text{ pJ/bit/m}^2$  and  $E_{elec} = 50 \text{ nJ/bit}$  [43]. We also assume that the control packets for clustering are 200 bits [44]. We do not take into account the energy for spectrum sensing since it is a common and periodic process for each CRSN node. Our focus is the extra energy consumption due to the channel switching during the event packet transport. The energy consumption for the channel switching is assumed to be  $J_{sw} = 40 \text{ mJ}$  [45].

### 4.2.2 Problem Motivation

Multi-channel sensor networks and CRSNs utilize multiple channels for the communication. The most advantageous aspect of utilizing multiple channels in CRSNs and multi-channel WSNs is empowering parallel transmissions [46]. This aspect of the multi-channel communication alleviates the contentions and the collisions in these type of dense sensor networks. Multi-channel sensor networks are closely akin to CRSNs in this aspect but there is a fundamental difference. In case of the channel degradation and the interference, sensor nodes in multi-channel WSNs change the operating frequency band without any limitation by a licensed user. However, the channels CRSN nodes opportunistically utilize are the licensed channels and they can be used only when these channels are idle in CRSNs. The CR capabilities of sensor nodes provide the adaptability to the dynamic radio environment. Hence, the solutions for CRSNs must take into account the PU activities.

Although multi-channel WSNs and CRSNs have similar challenges such as channel switching and channel coordination, the realization of CRSNs poses some extra challenges due to the specific properties of CR and sensor networks, and the challenges are amplified by their unique union. The limited battery capability requires energy-efficient and low cost solutions as in the case of multi-channel WSNs. On the other hand, the spectrum management is a result of CR capability of CRSN nodes. The dynamic radio environment due to CR capabilities requires spectrum-awareness. Furthermore, the operation over multiple channels also poses challenges which are also experienced by multi-channel sensor networks. One of these challenges is channel switching which causes energy consumption. Channel coordination is another challenge faced by CRSNs and multi-channel WSNs. Two neighbor nodes must be on the same channel if they intend to communicate. However, solutions proposed for multi-channel WSNs are not spectrum-aware since they do not consider licensed user activities [47, 48]. On the other hand, cognitive radio network (CRN) solutions discard the hardware and the energy limitations. The solutions for multi-channel WSN and CRN do not address energy-efficiency and spectrum-awareness simultaneously.

The event-driven communication nature of CRSN causes a burst packet injection towards the sink. This yields a communication corridor from the event region to the sink [49]. There exist communication activities only when events occur and there are unique challenges of spectrum-aware communications and the mobility of the nodes. Hence, we propose an event-driven spectrum-aware clustering scheme in the corridor between event and sink to overcome these challenges. The main motivations for proposing clustering technique to this ephemeral event routing problem can be itemized as follows.

- Data aggregation is one of the most important features of the clustering technique. The nodes closer to each other make correlated observations [50]. This decreases the number of data packet transmission which is the most energy consuming part of event reporting. Furthermore, these nodes make correlated spectrum sensing observations [11]. Correlated spectrum sensing logically partitions the nodes in the network into groups with similar spectrum availabilities. Hence, the clustering fulfills the need for the data aggregation, and also the coordinate the spectrum-aware communication.
- The spectrum mobility and the node mobility pose a significant challenge on communication. The channel on which the sensor nodes decide to communicate may become occupied and a new communication channel must be decided. A node may lose its contact with its communicating neighbor due to the mobility of nodes and a new neighbor node must be decided for the event data routing. However, the clusters can deal with the spectrum mobility and the node mobility since the cluster may switch to another data channel among its cluster channels and the communicating node find easily another node in the cluster to route its event packets. Once, the clustering proposes redundancy against spectrum mobility and node mobility.
- A node must exchange control packets with all other neighbors to establish a communication link if the clustering is not utilized [21]. The constraint of having

at least a common channel and mobility may be very energy-consuming for the communication in CRSN without clustering since the nodes exchange control packets at each hop. However, clustering forms a communication structure keeping some neighbor nodes tuned to the same channel. The cluster structure may reduce the channel switching during transmissions of event packets.

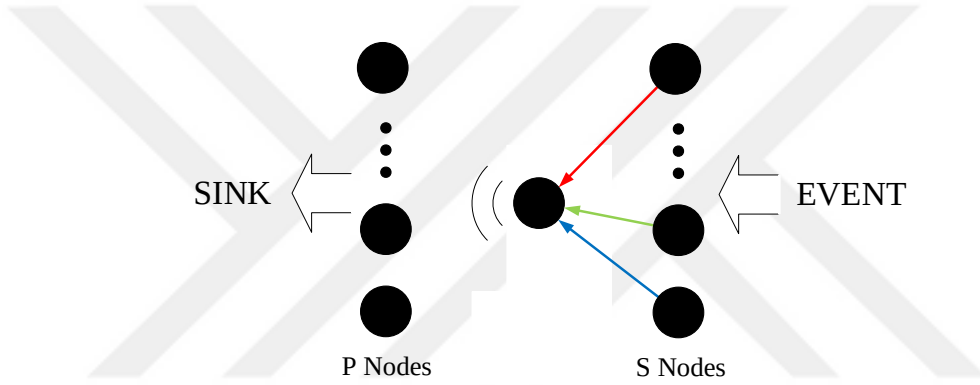


Figure 4.2: A communication scenario in a one hop neighborhood during an event to sink communication.

These advantages can be shown with an example for an event-to-sink communication scenario shown in Fig. 4.2. For clustering case,  $S$  nodes and  $P$  nodes are the cluster members, and the bottleneck node is the cluster-head.  $S$  transmissions on the same channel which causes  $SE_{ept}$  energy consumption where  $E_{ept}$  is the energy for one-hop transmission. The cluster-head aggregates these packets into one packets and transmits that packet to the nodes closer to the sink. The total energy consumption for the clustering case is  $(S + 1)E_{ept}$ . If the clustering is not used for this scenario,  $S$  nodes send their packets to the bottleneck node and  $W_1$  transmissions require channel switching where  $0 \leq W_1 \leq S$ . The bottleneck node sends all the received packets without aggregation which requires  $S$  transmissions and  $W_2$  channel switching where  $0 \leq W_1 \leq S$ . The total energy consumption is  $2SE_{ept} + (W_1 + W_2)J_{sw}$ . This simple scenario shows the advantage of the clustering scheme in spectrum-aware communication.

### 4.3 Related Work

There is a substantial amount of work on the clustering for cognitive radio networks (CRNs) and WSNs in literature. We classify some of the important works as those which have spectrum-awareness and not. For instance, in one of the spectrum-aware clustering approach in [51], the authors propose a distributed coordination architecture to overcome the spectrum heterogeneity challenge and the scalability issues. The proposed scheme groups nodes according to the selection of coordination channels adaptively and forms clusters in CRN. The scheme tries to maintain the groups during the network operation. Users are clustered in the same group if they have at least one common channel and two nodes in the same cluster can communicate via multiple hops. The aim is to minimize the number of clusters in the network. However, it decreases the number of common channels in clusters. Consequently, this feature of the protocol increases re-clustering probability since it causes less common channels among the cluster members. In [52], the network is partitioned into clusters by grouping neighbor nodes sharing local common channels. The network is formed by interconnecting the clusters gradually. Furthermore, it provides mechanisms for neighbor discovery, cluster formation, network formation, and network topology management. [53] uses graph theory for spectrum opportunistic clustering (SOC) and assigns control channel to each cluster so that each node in a cluster can communicate within the cluster by local common channels. The recent work [11] presents network topology and spectrum availability as bipartite graphs. Every node constructs bipartite graphs with its one-hop neighbors and available channels. Biclique graphs are obtained from these bipartite ones according to metrics such as maximum edge, maximum node and maximum edge one sided cardinality. These approaches do not use common channel over the entire network, however, a control channel is assigned to each cluster in the network by the clustering technique. The approaches in [53, 11] are not applicable to CRSN since there are three steps to form clustering which needs excessive energy consumption. The authors in [54] construct minimal number of clusters in cognitive radio networks using affinity propagation

(AP) message-passing technique. ROSS-DGA and ROSS-DFA are two distributed clustering approaches offered in [55]. They form robust clusters by providing inter-cluster and intra-cluster connectivity using the game theory. These approaches are not compatible with the resource-constrained nature of CRSN nodes. They do not consider the event-driven communication paradigm which is essential for CRSNs.

A clustering scheme is proposed for multi-channel WSNs to achieve power-efficiency [47]. It proposes a backbone by clustering and decreases the amount of packet forwarded to the sink by data aggregation by cluster-heads. However, clustering in [47] does not take into account the PU activities. The recent work in [31] suggests a spectrum-aware clustering protocol to enable energy-efficient communication in CRSN by intra-cluster aggregation and inter-cluster relaying. It also finds the optimal number of nodes in a cluster. However, the authors do not consider the connectivity between cluster-heads for inter-cluster communication. On the other hand, the clustering approaches proposed for WSNs consider energy-efficiency but lack spectrum-awareness. The clusters are formed by first selecting cluster-heads in WSN clustering schemes. Optimal cluster-head selection is an NP hard problem [56]. A novel cluster-head selection algorithm, Weighted Clustering Algorithm (WCA) [57], is proposed based on the combined weight metric. This metric is calculated by taking into account several system parameters. Despite vast amount of clustering approaches in WSN, the idea of clustering between event and sink, namely Event-to-Sink Directed Clustering (ESDC), is proposed in [49]. It suggests forming clusters in the corridor between the event and the sink in WSNs. However, this clustering scheme is not applicable to CRSN since WSN nodes are not aware of CR functionalities and ESDC does not address spectrum heterogeneity.

Although there exists significant amount of clustering approaches on CRNs, they do not address the challenge of limited energy resource and hardware capacity of sensor nodes. Thus, energy-efficient clustering solution is required to address the limited energy resource challenge as well as opportunistic spectrum access challenges. In this chapter, we provide energy-efficiency by exploiting the event-driven communication

nature, and perform the spectrum-aware clustering for the coordination in a dynamic radio environment.

#### **4.4 mobility- aware Event - to - sink Spectrum - Aware Clustering (mESAC)**

Our clustering protocol, mESAC, provides an on-the-fly coordination scheme for the communication in CRSN. We propose a two phase clustering protocol to establish the coordination between the event and the sink. The first phase is for the determination of the intermediate eligible nodes between the event and the sink, i.e., the formation of an eligibility routing corridor for clustering. In the second phase, the nodes in this corridor form the spectrum-aware clusters with their one-hop neighbors. Clusters are maintained until the end of the event. These phases are explained individually in the following subsections.

##### *4.4.1 Eligibility Corridor Determination*

The communication in CRSN starts with event occurrences, i. e., resources are used in the network for event occurrences. Hence, we designed our protocol according to communication needs of CRSN. The first step of our protocol is to determine the corridor between event and sink. This step is performed in a distributed fashion since the network is decentralized. We specify this corridor by changing the status of the nodes in this region. The first step of determining the eligible nodes is the event detection in our distributed approach. The event detecting nodes become eligible for clustering directly. Afterwards, Eligibility For Clustering REQuest (EFC\_REQ) messages are sent by these nodes to their one-hop neighbors through a common control channel by piggybacking it to the spectrum sensing packets through cooperative diversity mechanism [11, 41]. Each node receiving this message becomes an eligible node if it is located closer to the sink than the EFC\_REQ sender. The new eligible nodes send EFC\_REQ to their non-eligible one-hop neighbors and the process continues until EFC\_REQ reaches the sink. Non-eligible nodes do not send EFC\_REQ

messages, hence, the corridor can not be expanded further in the directions other than the direction towards the sink. Finally, the eligibility corridor is determined by these messages. Algorithm 1 outlines the eligibility process for the clustering. mESAC determines the eligible nodes in a distributed manner by Algorithm 1. In this phase, we assume that the sensor node density is sufficient to not terminate the formation of eligibility corridor due to routing towards the sink.

---

**Algorithm 1** Determination of the Eligible Nodes for Clustering

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```

1: Consider node  $i \in V$  where  $V$  is set of nodes in the network
2: if Node  $i$  detects event then
3:   It is eligible for clustering
4:   State( $i$ ) = "Eligible Ordinary Node"
5:   Start sending EFC_REQ to one-hop neighbors other than event detecting
   neighbors
6: else
7:   if It receives EFC_REQ from its neighbor then
8:     Compare the distance
9:     if  $d_{i,sink} \leq d_{EFC\_REQ-sender,sink}$ 
        $\wedge d_{i,event} \geq d_{EFC\_REQ-sender,event}$  then
10:      Node  $i$  is eligible for clustering
11:      State( $i$ ) = "Eligible Ordinary Node"
12:      Send EFC_REQ to one-hop neighbors
13:    else
14:      Not eligible
15:    end if
16:  else
17:    Node  $i$  is not eligible
18:  end if
19: end if

```

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If a node receives an EFC\_REQ message by one of its neighbors, the sender already knows if the request receiver is eligible due to the neighbor discovery. However, the nodes that are eligible or non-eligible for clustering inform their neighborhood by Eligibility For Clustering REPLY (EFC\_REP) message upon receiving an EFC\_REQ message. Due to the mobility, some nodes leave or enter the eligibility region, the topology changes in the eligibility region are tracked by the neighbor discovery process which is not in the scope of this chapter. These nodes become eligible or non-eligible

according to the eligibility condition by the requests from their eligible neighbors. After this process, a new subnetwork is generated which is denoted by  $G' = (V', E')$  where  $V'$  is the set of eligible nodes and  $E'$  is the set of edges connecting eligible nodes.  $V'$  is a subset of  $V$ .

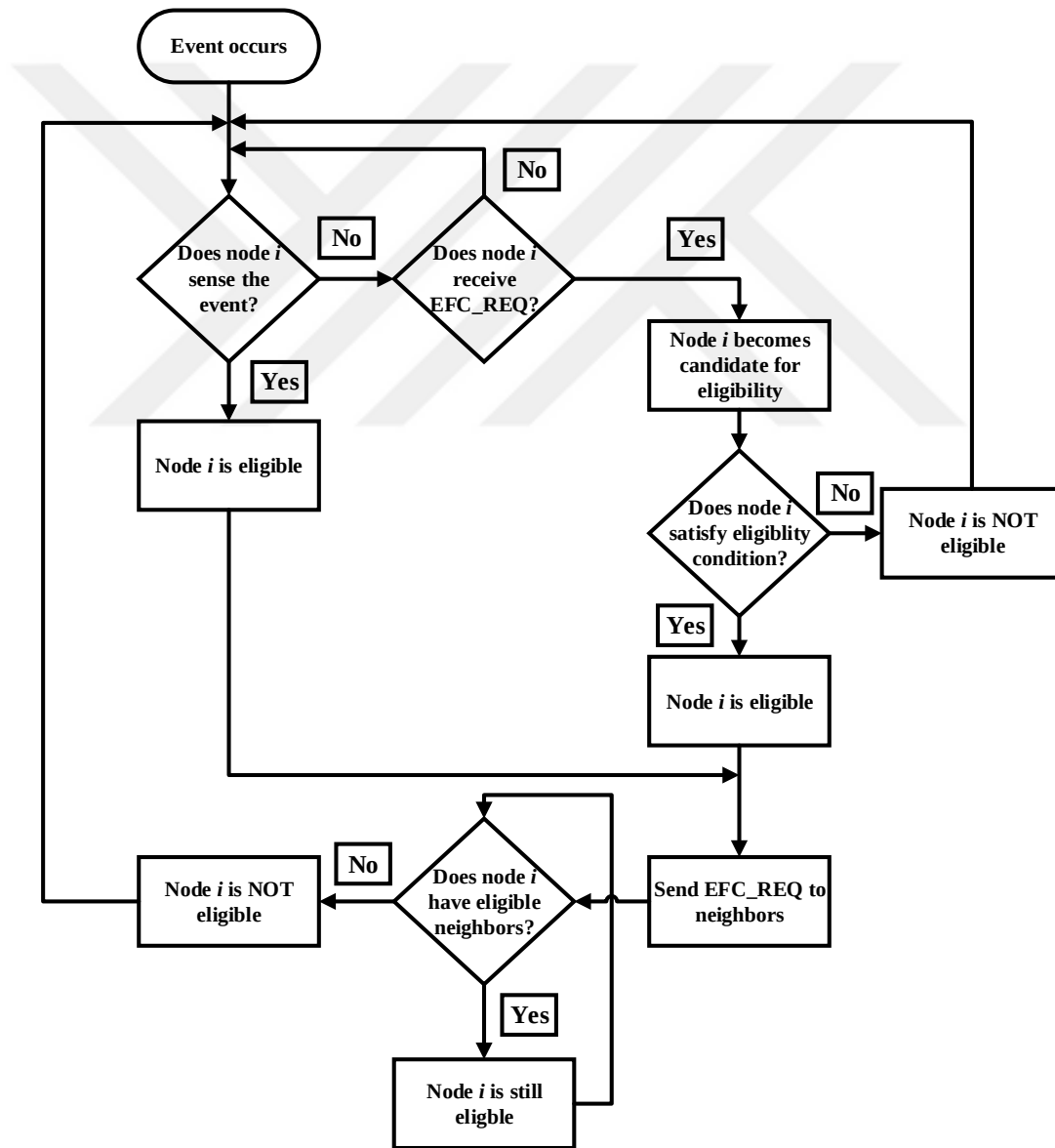


Figure 4.3: Steps for managing eligibility and mobility of the nodes during an event.

The steps of the first phase of the protocol is shown in Fig. 4.3. The mobility

management in this corridor is done in a cooperative manner. If an eligible node moves out of the eligibility corridor which is a result of having no eligible neighbors, it becomes non-eligible and waits for an EFC\_REQ. If a non-eligible node encounters an eligible node and it satisfies the eligibility condition, it becomes eligible.

#### 4.4.2 Cluster-head Selection

The motivation of clustering in sensor networks is to create organizational structures and to manage distributed wireless networks in a structured way. The dynamic radio environment intensifies the need for a clustering scheme to coordinate the communication in a typical CRSN. In this work, we group the eligible nodes in the event-to-sink corridor according to their spectrum availabilities while maintaining intra-cluster and inter-cluster communication. Only the nodes that are appointed as eligible form clusters. The clusters are not maintained in the network if the event detecting nodes do not further sample the event.

Cluster-heads are the local coordinators in the cluster. They perform data aggregation, manage the change of the idle spectrum bands in the clusters and manage the mobility of the nodes. They also receive the event reports from the cluster members that are closer to the event. Afterwards, they perform data aggregation to reduce the event reports and route these reports to the nodes closer to the sink.

Optimal cluster-head selection is an NP-hard problem [56]. Hence, heuristic algorithms are proposed for this problem in literature. In our case, the solution to the cluster-head selection problem also requires spectrum-awareness in the dynamic radio environment. Hence, the cluster-head selection must take into account the vacant spectrum bands of the eligible nodes. In this chapter, we propose an algorithm to determine cluster-heads among the eligible nodes after the first phase. The formed clusters must be stable against the fluctuations of the spectrum availabilities, the energy outage, and the mobility of the nodes. To this end, we take into account several system parameters as in [57]. Every eligible node is assigned a weight according to a combination of different parameters. This weight shows the capability of a nodes to

serve as a cluster-head. In our heuristic selection method, we maximize the weight of the selected cluster-heads. Hence, we select the nodes in the network having maximum capability to serve as cluster-heads. The parameters for selecting cluster-heads can be itemized as follows.

- **Eligible node degree,  $d_i^e$ :** The node with the highest eligible one-hop neighbor must be more likely to be a cluster-head since it has more opportunity to form a cluster and to maintain the formed cluster. Hence, selecting the node with the highest node degree as cluster-head will have higher chance and combination alternatives to form robust cluster with its eligible one-hop neighbors.
- **Number of available channels,  $C_i$ :** Spectrum-aware clustering is performed according to the available channels of cluster-heads and their one-hop neighbors. Hence, the cluster-head must be the one having the highest number of available channels to increase the number of available channels in a cluster. If a node with the highest available number becomes a cluster-head, the cluster becomes more stable since there will be higher chance to have greater number of vacant bands in the formed cluster. If the node with less number of vacant bands is selected as a cluster-head, it will confine the cluster structure to less common channels in the formed cluster and smaller number of cluster member nodes. The selection of cluster-head node with higher vacant channels also increases the probability of inter-cluster communication since the nodes with the highest number of vacant channels in its neighborhood have higher possibility to possess a common channel with the neighboring cluster-heads.
- **Remaining energy,  $E_i$ :** Cluster-heads are more active than ordinary node due to the intra-cluster communication. Therefore, the remaining energy is an important parameter while selecting the cluster-heads.
- **Distance to the sink,  $d_{i,sink}$ :** The data collected by the sensor nodes is aggregated in the cluster-head. The collected data is transferred by the cluster-heads

in the event routing corridor. Hence, the selection of cluster-heads closer to the sink decreases the energy consumption in CRSN.

- **Node speed,  $v_i$ :** It is a good choice to select the nodes whose speeds are low as cluster-heads for stable clusters. In the weight calculation, the node speed is inversely proportional to the weight. The cluster-head is the main entity for a cluster, and if it leaves the cluster region, all the member nodes become non-clustered.

The above parameters are selected to maintain the stability of the formed clusters and to provide the energy-efficiency. These parameters are used separately in literature to select the cluster-heads. For example, the node degree is used for WSN clustering [58], the number of available channels is used CRN clustering [51, 52, 53, 54, 55, 31], the remaining energy and the distance to the sink are used for WSN clustering [49]. However, to the best of our knowledge the combination of these parameters for the cluster-head selection in a dynamic radio environment has not been considered. Hence, we propose a cluster-head election process based on the combination of these parameters. According to these parameters, every eligible node has a weight for the cluster-head election which is defined as

$$P_i = w_1 |d_i^e| + w_2 |C_i| + w_3 |E_i| + w_4 |d_{i,sink}| + w_5 \left| \frac{1}{v_i} \right| \quad (4.1)$$

for an arbitrary eligible node  $i$ . The sum of the weight of the parameters is 1.  $|d_i^e|$  is obtained by the EFC\_REP messages of the neighbor nodes. The other parameters are contained in the node  $i$ . After the first phase, the eligible nodes determine their weights for the cluster-head selection. The units of the parameters are different, however, we are interested in their magnitudes.

The weight of each parameter depends on the system requirements. Although there is not an exact procedure to select the weights of the parameters, the following steps can be carried out to tune the weights of these parameters. Firstly, if one or more parameters are not important to the reader, then the weight of this/these parameters

should be zero. The reader should divide the total weight, which is 1, between the remaining parameters. If the remaining parameters are equally important, the weights of the remaining parameters stay the same. However, if there is one parameter whose importance is greater than the remaining parameters, the weight of this parameter should be increased incrementally by decreasing the weights of the other parameters until the desired system performance is achieved. If there are more than one parameter whose importance is greater than the remaining parameters, the reader should also increase the weights of these important parameters by decreasing the weights of the less important parameters. Hence, the reader/researcher should tune the weight of the parameters to achieve the desired system performance according to the importance of the parameters. The more important parameter should have the greater weight and the less important parameter should have the less weight. For example, if the nodes are not mobile,  $w_5$  must be zero. For an other case where  $w_1 = 1$  and  $w_2 = w_3 = w_4 = w_5 = 0$ , the cluster-head selection depends only on the node degree, and cluster-head selection becomes the highest node degree algorithm in [58]. We are offering a general weighing scheme and optimal values of the parameter weights can be found for different network setups. This optimization is beyond our scope.

In this procedure, the nodes with the highest weight in their neighborhood become cluster-heads. The new cluster-heads and their one-hop neighbors are deprived from the cluster-head election process. The cluster-head election process continues with the nodes that are not deprived from the election procedure. These remaining nodes again control whether they are the nodes with the highest weight among their non-clustered neighbor nodes. This process will go on until all nodes are clustered.

#### *Time Complexity of Cluster-Head Selection*

The cluster-head selection is a completely distributed process. The node which does not have the highest weight among its eligible neighbors waits for its eligible neighbor nodes to become cluster-heads or members of cluster-heads. Thus, this node can become a node having the highest weighted node among its non-clustered eligible

neighbors or can be deprived from the cluster-head selection process by a newly selected neighboring cluster-head. Hence, the time required for cluster-head election procedure depends on the maximum number of hops in the eligibility corridor. It is directly related to the hop diameter of the eligibility corridor which is generally the number of hops between the event and the sink. Thus, the time complexity of the cluster-head selection process depends on the distance between the event and the sink.

#### 4.4.3 Determining Cluster Members

Firstly, each cluster-head investigates whether common channels exist among all its eligible one-hop neighbors. If the number of the calculated common channel is nonzero, then the cluster-head sends C\_REQ to its eligible one-hop neighbors. If there is not even a common channel among the eligible one-hop neighbors, the node calculates the weights of its vacant channels. The weight of a channel is calculated by counting the number of eligible one-hop neighbors having that channel in their vacant channel set. The highest weighted channel becomes the desired cluster channel, and the other common channels are the backup channels against PU appearance. The eligible one-hop neighbors having that channel become the desired cluster members. A tie is resolved in favor of the channel having smaller channel ID number. The cluster-head node sends C\_REQ to these desired cluster members. However, a node may be a neighbor of two or more cluster-heads and it becomes a member of only one cluster-head. Hence, the desired calculated structure may not be achieved since a node will reply to only one of C\_REQs.

The node receiving C\_REQs from multiple neighboring cluster-heads selects the node with the lowest weight. The lowest weight selection is due to the load balancing between cluster-heads. The cluster-head with the lowest weight has less member, and the cluster-heads with higher weight has greater number of members. In order to decrease the burden of the cluster-heads with higher weights, the cluster-head with the lower weight is selected for the cluster membership.

### *Dominating set*

The cluster-head selection is based on the iterative selection of cluster-heads according to the weights of one-hop neighborhood. Hence, the cluster-head selection procedure forms a dominating set among eligible nodes such that every eligible node is either a cluster-head or a neighbor of a cluster-head. Every non-clustered eligible node is covered by cluster-head set. However, an eligible node may not receive any C\_REQ from any of its neighbor cluster-head nodes. In this case, these nodes become cluster-heads. Each eligible node is either a cluster-head or a cluster member. Hence, the set with eligible nodes forms a dominating set.

### *Convergence of mESAC*

Nodes in a formed eligibility corridor are connected due to the assumption of connectivity of the network such that all event messages from the event region reach to the sink ultimately. Hence, the convergence of the eligibility corridor formation, which is the first phase of the algorithm, is guaranteed due to the connectivity.

In the second phase, the cluster-head selection procedure is performed iteratively in a distributed fashion among the formed eligible network,  $G'$ . Hence, the procedure finishes until all the nodes in  $V'$  becomes either a cluster-head or a neighbor of a cluster-head in which the time required for this process depends on the diameter of  $G'$ . Afterwards, the eligible nodes that are not cluster-head respond to the clustering requests from the neighboring cluster-heads having the lowest weight. They become members of the corresponding cluster-heads. If a non-clustered eligible node does not receive any request from its neighboring cluster-heads, it becomes a cluster-head. Thus, each node in  $V'$  becomes either a cluster-head or a member of a cluster-head. This finalizes our algorithm which guarantees the overall convergence.

#### *4.4.4 Topology Change due to Mobility*

A non-eligible node can leave or enter the eligibility corridor during the event transport due to the mobility of nodes. The node leaving the eligibility region may be a cluster-

head or a member node. If it is a member node, cluster structure continues without that node, and the members and the channels of the cluster change accordingly. On the other hand, if the leaving node is a cluster-head, the cluster-head selection procedure is implemented as in Section 4.4.2 and Section 4.4.3.

A node can enter the eligibility corridor. It becomes eligible by EFC\_REQ message from its eligible one-hop neighbors. The incoming node firstly becomes eligible, then it associates itself to the nearest cluster-head if it has the channels of that cluster. Otherwise, it becomes a cluster-head.

#### 4.4.5 Inter-cluster Communication

Inter-cluster communication is performed through the gateway nodes. Due to the fluctuations of the spectrum availability, a common channel may not exist between neighboring cluster-heads. Hence, the inter-cluster communication is performed via gateway nodes and it is coordinated by the cluster-heads. The inter-cluster communication depends on the common channels between the nodes in the neighbor clusters.

The parameter which defines the number of vacant channels while selecting cluster-heads increases the possibility of common channels between the neighboring cluster-heads. If there is a common channel between any pair of neighboring cluster-heads, there is no need to change the operation channel between the cluster-heads and the gateway nodes. This provides energy-efficiency since the channel switching is energy consuming operation.

### 4.5 Efficiency Requirement of Event- to- Sink Approach for Clustering

#### 4.5.1 Average Re-clustering Probability

The spectrum opportunity occurs for a node, if it senses the channel as idle. This event occurs if the node is not around any PU and the channel is successfully sensed as idle, or if it is in the transmission range of the PU and the PU is not active and the node senses the channel as idle, or PU is active and the node falsely senses the channel

idle. To this end, we first find the probability that a node is not in the transmission range of a PU. This probability is obtained as

$$p_w = 1 - \frac{\pi\tau^2}{A} \quad (4.2)$$

where  $\tau$  is the transmission range of a PU and  $A$  is the area of the network.

The imperfections on the channel sensing cause errors. The probabilities of detection and mis-detection can be defined respectively as

$$p_d = Pr[\text{Ch. } i \text{ sensed idle} \mid \text{Ch. } i \text{ is idle}], \quad (4.3)$$

$$p_m = Pr[\text{Ch. } i \text{ sensed idle} \mid \text{Ch. } i \text{ is occupied}]. \quad (4.4)$$

The channel usage of a PU depends on its ON-OFF probabilities. These probabilities can be denoted as  $p_{on}$  and  $p_{off}$ . A CRSN node can have the channel  $i$  in its vacant channel list in 3 cases which can be explained as follows.

- If the node is outside of the transmission range of the PU and the state of the channel  $i$  is detected successfully, the channel  $i$  is in the vacant channel list. This probability can be written as  $p_w p_d$ .
- If the node is inside the transmission range of the PU which is OFF, and the state of the channel  $i$  is detected successfully, the channel  $i$  is in the vacant channel list. This probability can be written as  $(1 - p_w) p_{off,i} p_d$ .
- If the node is inside the transmission range of the PU which is ON, and the state of the channel  $i$  is mis-detected as idle, the channel  $i$  is in the vacant channel list. This probability can be written as  $(1 - p_w) p_{on,i} p_m$ .

The probability that channel  $i$  is in the vacant channel list of a node can be obtained by the union of these 3 independent cases. Hence,  $p_{l,i}$  is

$$p_{l,i} = p_w p_d + (1 - p_w) p_{off,i} p_d + (1 - p_w) p_{on,i} p_m. \quad (4.5)$$

Since ON probabilities of the channels are the same, we can omit  $i$  in the subscripts in Eq. (4.5) and can state the probability that an arbitrary channel in the system is in the list of a node as  $p_l$ . This probability defines the change of the channel availability in our dynamic radio environment under the imperfect channel sensing and the spatial variation of PUs.

$$\begin{aligned} \phi(D) = & \frac{6D^3}{L^8} - \frac{6D^4}{5L^{10}} + \frac{6D^5}{125L^{12}} + \frac{96\sqrt{D^3}}{5L^5} - \frac{1584\sqrt{D^5}}{125L^7} + \frac{36\pi}{25L^2} \\ & + \frac{192D^2\sqrt{D^3}}{175L^9} - \frac{36\pi D}{5L^4} - \frac{48D\sqrt{D^3}}{5L^7} + \frac{9\pi D^2}{2L^6} \end{aligned} \quad (4.6)$$

Under random waypoint mobility model in a wireless network, the distribution of the distance between any pair of nodes,  $D$ , can be found for a square network whose one side length is  $L$ . It is defined for the square of the distance, hence, for  $0 < D \leq L^2$ , the distribution of the distance between any two nodes smaller than  $L^2$  can be written as in Eq. (4.6).

Two nodes become neighbors if they are in the transmission ranges of each other. Hence, the probability that the two nodes are neighbors, which can be denoted by  $p_n$ , can be given as

$$p_n = Pr[D \leq r^2] = \int_0^{r^2} \phi(z) dz. \quad (4.7)$$

The re-clustering condition for a cluster is to have no common channel among its members. Hence, the re-clustering probability of the cluster can be found by considering the overall probability that there is no common channel among the possible cluster members. Firstly, we have a cluster-head for a cluster structure. There can be  $N - 1$  member of a cluster at most since there are  $N$  nodes in the network. Furthermore, any set of channels from the set of channels in the network,  $C$ , can be the common channel set of the cluster. There must be an event occurrence for the cluster formation since our clustering algorithm is event-driven. We denote event occurrence as  $E = 1$ , and the no event case as  $E = 0$ . To this end, the probability of the

re-clustering of a cluster given that an event occurred,  $p_{rc|E=1}$  can be expressed as

$$p_{rc|E=1} = \sum_{k=1}^{N-1} (p_n)^k \sum_{m=1}^M \binom{M}{m} ((1 - p_l)^m (1 - p_l^{(M-m)}))^k \quad (4.8)$$

where  $M$  is the size of the channel set in the system. Hence, the probability of re-clustering can be found as

$$p_{rc} = p_e \sum_{k=1}^{N-1} (p_n)^k \sum_{m=1}^M \binom{M}{m} ((1 - p_l)^m (1 - p_l^{(M-m)}))^k \quad (4.9)$$

where  $p_e = Pr[E = 1]$  is the probability that an event has occurred.

#### 4.5.2 Expected Cluster Coverage Area

Cluster coverage area is the area covered by the cluster-head plus the extra coverage regions contributed by possible cluster members. Applying the procedure in [59], the coverage area of a cluster can be found as follows. In the first step, the coverage area contributed only by the cluster-head is  $\pi r^2$ . Maximum possible total area of a cluster is  $\pi(2r)^2$  since possible one-hop cluster members can be located at a distance  $r$  to the cluster-head so that the maximum radius from the cluster-head becomes  $2r$ . We ignore the edge effects in our computations.

We start with the cluster-head in the coverage area computation of a cluster structure. The cluster-head coverage, which is the minimum cluster coverage area, can be expressed as  $\gamma_1 = \gamma_{min} = \pi r^2$  and the maximum cluster coverage area can be expressed as  $\gamma_{max} = \pi(2r)^2$ . In the next steps, we assume that the cluster-head gains member nodes and we investigate the contribution of the incoming cluster member to the cluster coverage area. For instance, if there are  $k - 1$  nodes in the cluster and one more node joins the cluster, the cluster coverage area of  $k$  nodes becomes as

$$\gamma_k = \gamma_{k-1} + \alpha_k \quad (4.10)$$

where  $\alpha_k$  is the contribution from the  $k^{\text{th}}$  member node. If we take expectation on

both sides of Eq. (4.10), it becomes  $E[\gamma_k] = E[\gamma_{k-1}] + E[\alpha_k]$ .

The fraction of the contribution by the  $k^{\text{th}}$  node with respect to the maximum cluster coverage area can be written as

$$f_k = \frac{\gamma_{\max} - \gamma_{k-1}}{\gamma_{\max}}. \quad (4.11)$$

The contribution of the  $k^{\text{th}}$  node is obtained as

$$\alpha_k = f_k \gamma_1 = \left( \frac{\gamma_{\max} - \gamma_{k-1}}{\gamma_{\max}} \right) \gamma_1. \quad (4.12)$$

The expected cluster coverage area can be written as

$$E[\gamma_k] = E[\gamma_{k-1}] + E\left[\frac{\gamma_{\max} - \gamma_{k-1}}{\gamma_{\max}}\right] \gamma_1 \quad (4.13)$$

where  $\gamma_1$  is a constant.

The procedure for finding the expected cluster coverage area can be iteratively found from the first node, i.e. the cluster-head, to the  $n^{\text{th}}$  node. It can be obtained as

$$E[\gamma_k | k = n] = [1 - (1 - \frac{\gamma_1}{\gamma_{\max}})^n] \gamma_{\max}. \quad (4.14)$$

Some of the nodes in the neighborhood of the cluster-head have the common channels with the cluster-head and they contribute to the expected cluster coverage area. If we denote the probability that there are  $n$  nodes satisfying the clustering criteria as  $Pr[k = n]$ , the expected cluster coverage area can be written as

$$E[\gamma] = \sum_{n=0}^{N-1} E[\gamma_k | k = n] Pr[k = n]. \quad (4.15)$$

Eq. (4.15) can be expanded so as to write the explicit form for  $Pr[k = n]$  as

$$E[\gamma] = \sum_{h=0}^{N-1} \sum_{j=h}^N \sum_{m=1}^M \binom{M}{m} p_n^j (1 - p_n)^{N-j} p_l^{hm} (1 - p_l)^{(j-h)m} E[\gamma_k | k = h]. \quad (4.16)$$

#### 4.5.3 Event Characteristic

The energy-efficiency of our protocol depends on the event characteristics. In the whole network clustering approach, all nodes form and maintain the clusters without any event occurrences. Event-to-sink approach forces the cluster formation with the event occurrences in the region between the event and the sink. Hence, the event occurrence frequency highly affects the energy-efficiency of our approach. We find the average event occurrence frequency,  $f_{ef}$ , for the energy-efficient operation of our approach and the steps to find it can be found in Appendix. The upper limit of event occurrence frequency for different event occurrence frequency is given in the following table. The below table shows that as the event radius increases, the event frequency satisfying the energy-efficiency decreases due to the resulting larger event routing corridor.

|          | $R = 0.1L$ | $R = 0.2L$ | $R = 0.3L$ |
|----------|------------|------------|------------|
| $f_{ef}$ | 15.57      | 6.80       | 4.12       |

## 4.6 Performance Evaluation

We establish a simulation environment in MATLAB to study the performance of our clustering protocol. We perform simulations to test our protocol in terms of the number of data and control packet transmissions, the time steps for clustering, the connectivity, the energy consumed for the clustering, and changes in the distribution of speed of the nodes and coefficient of the speed in node weight calculation. Nodes are distributed randomly in 100 m x 100 m area. The common parameter that we change is the distance between event and sink,  $D_{es}$ . The sink is located at (0, 50) and events are generated on the horizontal line at 50 m level. Simulations are performed for 100 different topologies and the results are averaged to draw a conclusion about

our algorithm. Our algorithm is compared in the simulations with DSAC [31], SOC [53] and Maximum Node Biclique (MNB) Clustering in [11].

The other parameters, which are the CR transmission range,  $r$ , and the event radius,  $R$ , are changed during the simulations. These parameters are used since their changes reflect the performance of our protocol, and the eligibility corridor and spectrum-aware clustering are highly related to these parameters. Furthermore, there are 5 licensed channels in the system. Each PU utilizes a randomly selected channel from these licensed channels.

In our simulations, the coefficients in the weight calculation are selected as  $w_1 = 0.4$ ,  $w_2 = 0.3$ ,  $w_3 = 0.1$ ,  $w_4 = 0.1$ , and  $w_5 = 0.1$ . The sum of the coefficients is 1 and these coefficients can be changed according to the importance of the parameters in the system.

#### 4.6.1 Data and Control Packet Exchange

We investigate the benefits of clustering on the reduction of data packets at the cost of control packets. We explore the performance of mESAC and no clustering (NC) approaches with and without mobility. In NC case, the packets are routed to the neighbor having at least one common channel and located nearest to the sink. The nearest neighbor to the sink is known by the neighbor discovery [41] as in mESAC. The control packet exchange is performed by the receiver and the transmitter to determine the communication channel. Each event detecting node generates one event packet, this is the worst possible case since the number of data packet is the minimum possible. As the number of event packets increases, the number of data packets prevails the number of the control packets and the effect of data packets becomes predominant. Furthermore, PUs are always ON. Hence, the time variation of the spectrum availability does not change but the spatial spectrum availability changes due to the random placement of the primary users. The always ON PU is the worst case possible for the spectrum opportunity for CRSN nodes since there would be no spectrum opportunity in the time domain. In the first study, we observe

the change in the number of packets in terms of  $R$  and  $D_{es}$  without mobility. We study 4 cases and the specifications of these cases can be seen in the following table.

| Case 1        | Case 2        | Case 3        | Case 4        |
|---------------|---------------|---------------|---------------|
| $R = 20$      | $R = 25$      | $R = 20$      | $R = 25$      |
| $D_{es} = 50$ | $D_{es} = 50$ | $D_{es} = 75$ | $D_{es} = 75$ |

As seen in Fig. 4.4, in all cases, the number of transmitted data packets is significantly reduced as compared to the NC case due to the aggregation. The number of control packets increases due to the formation of clustering. On the other hand, there is substantial number of control packet exchange for NC approach to coordinate the communication. It does not benefit from the data aggregation which is one of the main motivation to use clustering. The efficiency of the clustering may be less in Case 3 and Case 4 which mainly depends on the size of the data and control packets. This is the result of the eligibility corridor formation. If the size of the data packet is 2 times the size of the control packet, mESAC becomes inefficient as seen in Fig. 4.4 in Case 3. If the size of the data packet is 4 times greater than the control packet, mESAC becomes more efficient in all cases.

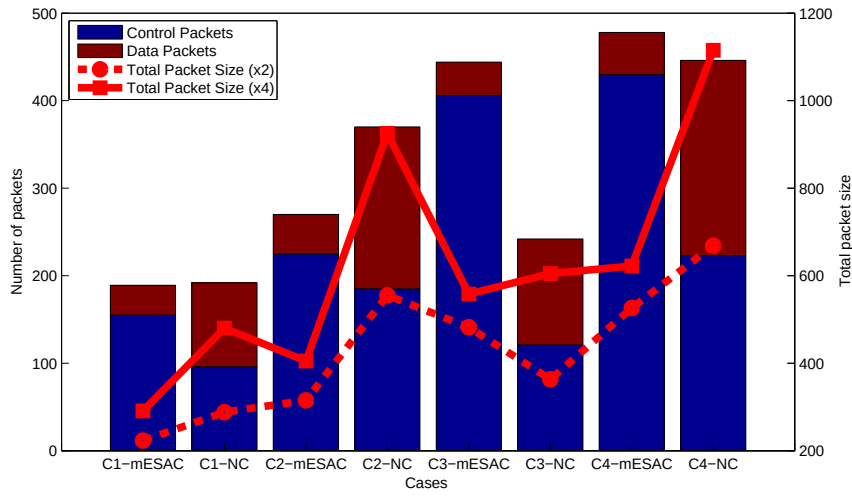


Figure 4.4: Data and control packet exchange for different cases without mobility.

As the event radius increases, there would be more event detecting nodes. It results

in more data and control packet transmissions. Furthermore, the increase in  $D_{es}$  causes more control packet exchange since the event-to-sink corridor is expanded. For NC approach, the increase in  $D_{es}$  causes more data and control packet transmission due to the increase in the number of hops between the event and the sink.

The effect of the mobility is also investigated. In this set of study, the random waypoint mobility model is used and the mean of the nodes speed is changed. CRSN nodes move in random directions in the magnitude of their speed at each time step. We have studied 4 cases where  $R = 20\text{ m}$  which can be tabulated as follows.

| Case 1        | Case 2        | Case 3        | Case 4        |
|---------------|---------------|---------------|---------------|
| $\mu = 0$     | $\mu = 1$     | $\mu = 0$     | $\mu = 1$     |
| $D_{es} = 50$ | $D_{es} = 50$ | $D_{es} = 75$ | $D_{es} = 75$ |

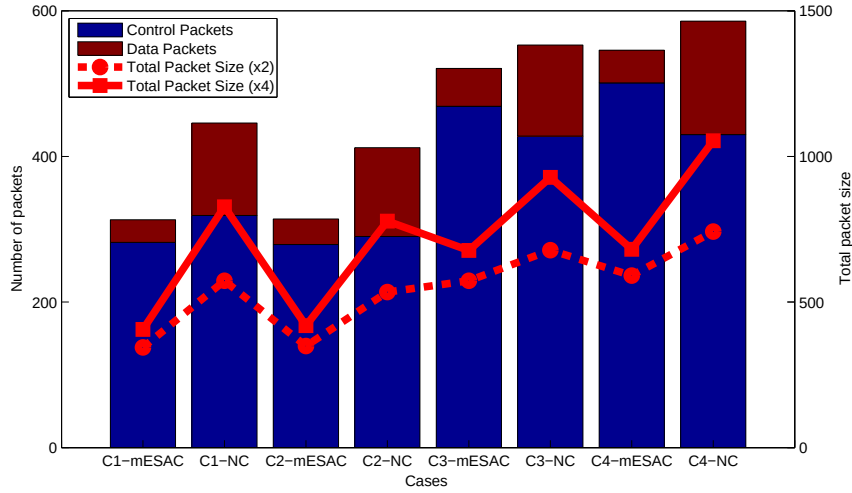


Figure 4.5: Data and control packet exchange for different cases with mobility.

Mobility increases the control packet exchange since the neighborhood of the nodes changes and the routes between the event and the sink changes accordingly. There may be a need of control packet exchanges to establish the routing path from the event to the sink without the clustering. However, the clustering has a resistance to the mobility since it groups the nodes to use other members in case of the changes in the network structure due to the mobility. As seen in Fig. 4.5, as we increase the

speed of the nodes, the number of control packet exchange increases in all cases for the two approaches. In mESAC, the cluster nodes are reserved for the possible relay node selection in the clustering structure. However, in NC approach, the transmitter may lose its contact with the receiver node that is located the nearest to the sink which may cause extra control packet exchange. In this set of study, since the size of the data packet is greater than the size of the control packets, mESAC is more efficient in all the cases as seen Fig. 4.5.

#### 4.6.2 Time steps for clustering

Establishing clusters requires some time steps since they are formed from scratch. In Section 4.4.2, we stated that the time complexity of selecting cluster-heads is related to the diameter of the eligibility corridor. In addition to the selection of cluster-heads, forming the eligibility corridor also requires time.

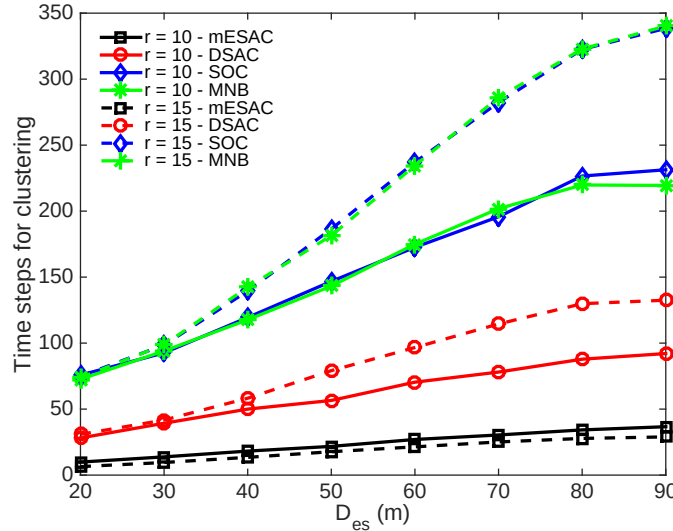


Figure 4.6: Timesteps required for clustering vs.  $D_{es}$  with respect to  $r$ .

As we increase  $r$ , the diameter of the eligibility corridor decreases. It results in a bit less time for clustering in mESAC as seen in Fig. 4.6. Furthermore, the time steps required for clustering increases with the number of hops to reach the sink.

Hence, the increase in the distance between event and sink increases the required time steps. Our algorithm, mESAC, performs the best for event-driven clustering scenarios as seen in Fig. 4.6. DSAC, SOC and MNB need more control packet exchange for clustering, therefore, they need more time steps to finalize the cluster formation.

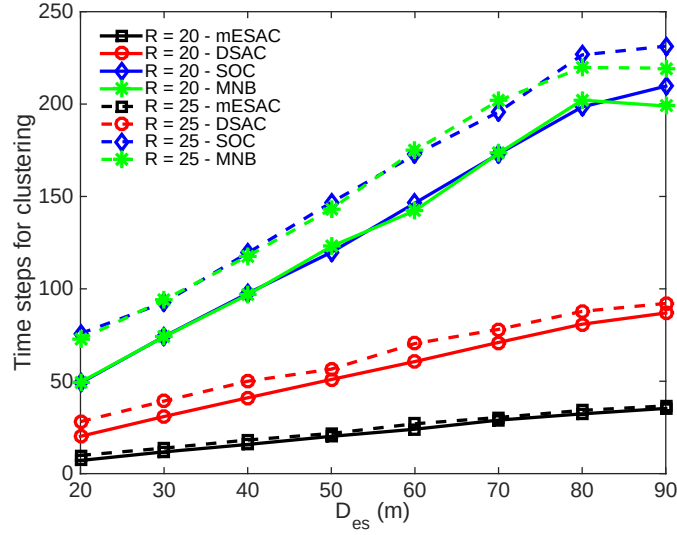


Figure 4.7: Timesteps required for clustering vs.  $D_{es}$  with respect to  $R$ .

The time steps required for clustering slightly increase with an increase in the event radius. This is an expected result since the clustering time depends on the size of the eligibility corridor. This slight difference is due to the expansion of eligibility corridor with the increase in the event radius as seen in Fig. 4.7. This case is the same for the other protocols for an increase in event radius. DSAC performs worse than mESAC and better than SOC and MNB. DSAC needs more message exchange than mESAC since each node agglomerate with its neighbor to form clusters and the formed clusters again combine with neighboring clusters. This increases the message exchange for clustering, and hence the time steps required for clustering.

### 4.6.3 Connectivity

We define the connectivity as the ratio of average number of common channels of a cluster with its neighbor clusters. In mESAC, we select the nodes with the highest number of vacant channel in their neighborhood to increase the possible number of common channels with neighboring cluster-heads.

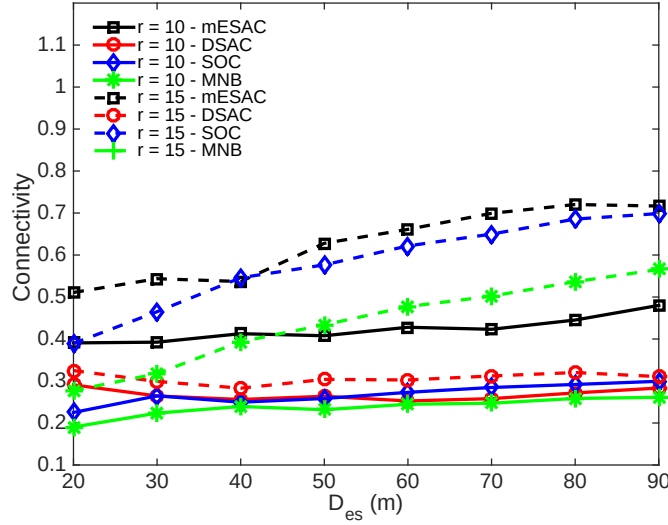


Figure 4.8: Connectivity vs.  $D_{es}$  with respect to  $r$ .

In our algorithm, the cluster-heads are selected in one-hop neighborhood of the eligible nodes. The neighborhood depends on the transmission range of the nodes. If  $r$  increases, it will increase the distance between the neighboring cluster-heads. The occupied channel in a neighborhood is more likely to be vacant for more distant nodes. Thus, it will increase the probability of having higher number of vacant channels between clusters. As seen in Fig. 4.8, the increase in the transmission range increases the connectivity.

The reason for better performance is that the nodes having the highest number of vacant channels in its neighborhood in mESAC are selected as cluster-heads. Having the highest number of vacant channels increases the possibility to be connected with the neighboring cluster-heads. On the other hand, SOC establishes a balance between

the number of cluster members and cluster channels. Hence, it does not consider the inter-cluster connectivity. mESAC establishes more connected clusters as seen in Fig 4.8.

#### 4.6.4 Energy consumption for clustering

Energy consumption is a major design concern for our algorithm since CRSN nodes have limited battery power. In this set of study, we observe the effects of  $D_{es}$  and  $r$  on the energy consumption for clustering. As shown in Fig. 4.9, an increase in the transmission radius increases the energy consumption since more nodes consume energy for cluster formation process.

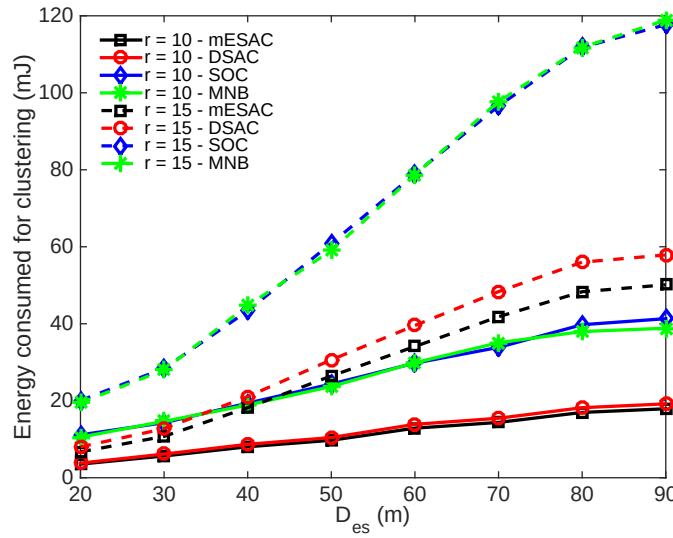


Figure 4.9: Energy consumed for clustering vs.  $D_{es}$  with respect to  $r$ .

SOC has three steps to form and to finalize clusters. Every node informs its neighbors in each step and it causes energy consumption. MNB calculates the weight of each node and forms clusters accordingly as in SOC. Hence, mESAC consumes less energy for clustering than SOC which can be seen in Fig. 4.9 for different  $r$ . DSAC consumes more energy than mESAC due to the iterative agglomeration process.

#### 4.6.5 Re-clustering due to mobility

Mobility of the nodes causes topology changes. It directly affects the cluster stability since the cluster-head may lose its connection with its members due to the changes in the neighborhood and the vacant channel. In this set of experiment, the event is generated at (100,50), and 300 nodes are distributed in the network. The nodes move in the network according to uniform distribution with a density of 1. We observe the effects of the changes in the mean of the uniform distribution. We change the mean of the distribution from  $\mu = 0$  to  $\mu = 1$ . As seen in Fig. 4.10(a), if we increase the mean of the node speed distribution, the average node speed increases and re-clustering is triggered earlier and more cluster-heads are forced to re-cluster in smaller amount of time. Fig. 4.10(a) shows that the slope increases due to increasing  $\mu$ . The ratio of the re-clustered cluster-heads reaches 1 in 40 time steps when  $\mu = 1.0$  m/s.

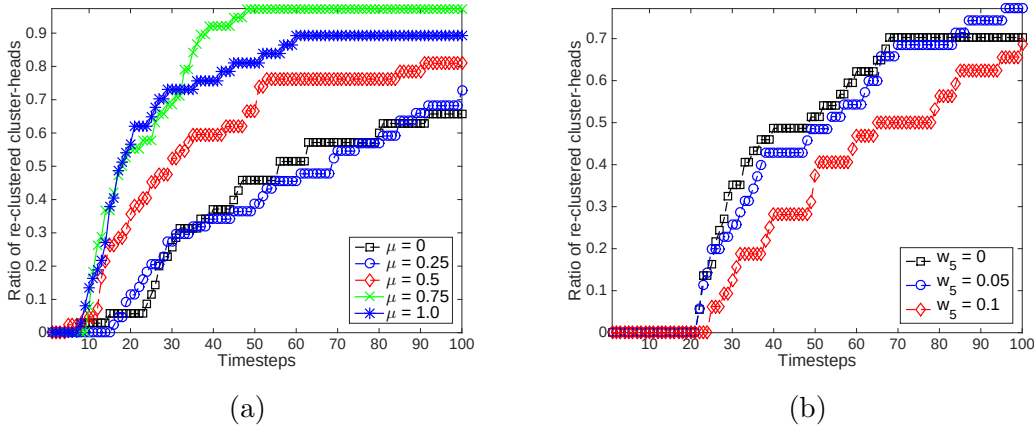


Figure 4.10: Ratio of the re-clustered cluster-heads vs. timesteps for (a) different  $\mu$ , (b) different  $w_5$ .

The coefficient of the speed in the node weight calculation is important for the stability of cluster-heads against the mobility. We change the coefficient of the node speed,  $w_5$ , with the coefficient of the vacant channels,  $w_2$ , accordingly to make the sum of all weight equal to one. As seen in Fig. 4.10(b), if the weight of the speed in the node weight calculation increases, more cluster-heads are forced to re-cluster for

decreasing  $w_5$ . Hence, the increase in the coefficient  $w_5$  makes the cluster-heads more immune to the topology changes.

### Appendix: Energy-Efficient Event Characteristics

The size of the network is  $L^2$ . Average number of cluster in the whole network can be estimated as  $\frac{L^2}{E[\gamma]}$  where  $E[\gamma]$  is the average cluster coverage area. The frequency of re-clustering is  $1/p_{rc}$  and let  $E_{rc}$  be the average energy required for re-clustering. The total energy required for re-clustering in the whole network is

$$E_w = \frac{L^2}{E[\gamma]} \frac{1}{p_{rc}} E_{rc}. \quad (4.17)$$

For the whole network operation, we assume that the event generation rate as 1 since we are maintaining the clusters during the network lifetime.

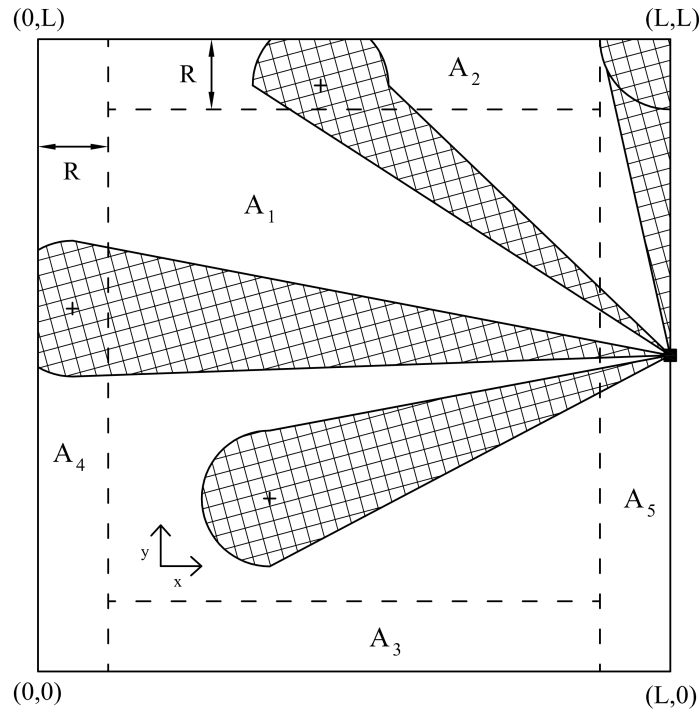


Figure 4.11: The division of the network into non-overlapping regions.

The event can evenly occur in the network for the event-driven scenarios. We can

also approximate the event routing corridor as the half of the circular event region with the triangle region from the event region towards the sink. The event generation frequency,  $f_{ef}$ , is important since the clusters are formed only if events occur. Hence, the average total energy required for re-clustering can be written as

$$E_{e2s} = \int_x \int_y \frac{A(x, y)}{E[\gamma]} E_{rc} f_{ef} \frac{1}{p_{rc}} f_{eo}(x, y) dx dy \quad (4.18)$$

where  $A(x, y)$  is the area of the event routing corridor and  $f_{eo}(x, y)$  is the probability distribution function (pdf) for event occurrence in the spatial domain, and  $(x, y)$  is the event location. The pdf for an event occurrence is uniform, and

$$f_{eo}(x, y) = \frac{1}{L^2} \quad \text{for } 0 \leq x, y \leq L. \quad (4.19)$$

Eq. 4.18 can be simplified as

$$E_{e2s} = \frac{E_{rc} f_{ef}}{E[\gamma] L^2 p_{rc}} \int_x \int_y A(x, y) dy dx. \quad (4.20)$$

We consider the edge effects of the network for finding the integral,  $G = \int_x \int_y A(x, y) dx dy$ . Due to these effects, the network area is divided into 5 non-overlapping regions as seen in Fig 4.11. 4 different event and their corridors are shown in Fig. 4.11. We perform the integral in these 5 areas to calculate the overall integral.

Due to the partitions, the integration can be calculated in 5 steps:

1. First we calculate the integral over the area  $A_1$ . The integral, denoted as  $G_1$ , can be defined as

$$G_1 = \int_{x=R}^{L-R} \int_{y=R}^{L-R} \left( R(L-x) + \frac{\pi R^2}{2} \right) dy dx. \quad (4.21)$$

2. The integration over area  $A_2$ , that is  $G_2$ , can be written as

$$G_2 = \int_{x=R}^{L-R} \int_{y=L-R}^L \left( \frac{\pi R^2}{2} - R^2 \cos^{-1} \left( \frac{L-y}{R} \right) + (L-y) \sqrt{R^2 - (L-y)^2} + R \left( y - \frac{L}{2} \right) \right) dy dx.$$

$$(4.22)$$

3. The integration over area  $A_3$ , that is  $G_3$ , can be written as

$$G_3 = \int_{x=R}^{L-R} \int_{y=0}^R \left( \frac{\pi R^2}{2} - R^2 \cos^{-1}\left(\frac{y}{R}\right) + y\sqrt{R^2 - y^2} + R\left(\frac{L}{2} - y\right) \right) dydx. \quad (4.23)$$

4. The integration over area  $A_4$ , that is  $G_4$ , can be written as

$$G_4 = \int_{x=0}^R \int_{y=0}^L \left( \frac{\pi R^2}{2} - R^2 \cos^{-1}\left(\frac{x}{R}\right) + x\sqrt{R^2 - x^2} + R(L - x) \right) dydx. \quad (4.24)$$

5. The integration over area  $A_5$ , that is  $G_5$ , can be written as

$$G_5 = \int_{x=L-R}^L \int_{y=0}^L \left( \frac{R^2}{2} (\pi - \cos^{-1}(\frac{L-x}{R})) - \frac{(L-x)}{2} \sqrt{R^2 - (L-x)^2} + \frac{R+L-x}{2} |y - \frac{L}{2}| \right) dydx. \quad (4.25)$$

The overall integration is the sum of all the integrals over the areas of the divisions, which is written as

$$G = R(0.5L^3 + 1.7583L^2R - 3.83333LR^2 + 4.6667R^3). \quad (4.26)$$

The energy consumed for our event-to-sink clustering approach must be less than the energy consumed for the whole network clustering for energy-efficiency. Hence,  $E_w > E_{e2s}$ . The condition for the event occurrence frequency becomes

$$f_{ef} < \frac{L^4}{G}. \quad (4.27)$$

The upper limit of event occurrence frequency for different event occurrence frequency is given in the following table. The below table shows that as the event radius increases, the event frequency satisfying the energy-efficiency decreases due to the resulting larger event routing corridor.

|          | $R = 0.1L$ | $R = 0.2L$ | $R = 0.3L$ |
|----------|------------|------------|------------|
| $f_{ef}$ | 15.57      | 6.80       | 4.12       |



## Chapter 5

# OPTIMAL TRANSMISSION RANGE FOR COGNITIVE RADIO AD HOC NETWORKS

### 5.1 Introduction

Proliferation of wireless devices causes a scarcity problem in electromagnetic spectrum although licensed channels are not efficiently utilized. Cognitive radio (CR) technology is proposed to overcome this challenge by its unique functionalities. Spectrum sensing, spectrum decision and spectrum handoff are the key functionalities to utilize the licensed channels opportunistically. This technology is applied to ad hoc and sensor networks to form cognitive radio ad hoc networks (CRAHNs) [9] and cognitive radio sensor networks (CRSNs) [20].

The nodes in these networks are energy-constrained, hence, energy-efficient operation is of utmost importance. The main contribution in the energy consumption of a node is transmission, which is related to the communication range of the node. The dynamic of the network also affects the communication range of the nodes. Higher transmission range results in more energy consumption at each transmission, and it also increases the interference with the primary users (PUs). On the other hand, lower transmission range decreases the distance progress of the packet at each hop, and hence, increases the number of hops to reach the destination.

In most cases, transmission range needs to be set as a system parameter before the nodes are deployed, due to incapability of power control of the nodes. Additionally, limited energy supplies of the nodes require energy-efficient strategies. Adjusting the transmission range before the deployment has been a key issue to extend the network lifetime of the networks. To this end, optimal transmission range investigation has

become a main focus in literature. [1] assumes that there is no power control, and the transmission range is set in the design phase. Hence, the authors in [1] find optimum one-hop transmission distance to minimize the total system energy in a network where there is no primary users' activities. [19] finds the optimal transmission range by using an energy efficiency metric for periodic monitoring applications in Rayleigh fading environment. In [60], hop distance is evaluated according to the Gamma pdf Model of maximum multi-hop distance distribution. Maximum multi-hop distance is defined as the maximum distance that can be achieved through certain number of relay nodes. Furthermore, to propose a range-free localization algorithm, expected hop progress is derived analytically for determining the path distance between any node pair in WSNs under different node density and transmission radius in [61]. However, the existing works do not consider the dynamic radio environment. The main contribution of our chapter is to propose a mathematical optimization method to determine the optimal transmission range by considering energy consumption and dynamic radio environment.

The authors in [62] find the optimal transmission range in wireless ad hoc networks with randomly distributed nodes. Under the assumptions of the existence of a neighbor for forwarding and knowing the location of the nodes, average per-hop packet progress is found and it is used for determining the optimal per-hop transmission range. The aim is to achieve the maximal energy-efficiency. To the best of our knowledge, no attempt has yet been made to find energy optimal transmission range for dynamic spectrum access (DSA) networks. In this chapter, we first characterize the DSA for packet transmission and find the average advance in distance at one hop. After defining an energy-efficiency metric, we include PU dynamics on calculating the per-hop advance of the packet to the destination and find the optimal transmission range according to the hop advance considering the energy-efficiency under reliable and unreliable link conditions.

The remainder of the chapter is organized as follows. In Section 5.2, the system model is introduced. In Section 5.3, the dynamic spectrum access scheme is explained.

We find the expected advance of the source packet towards the destination at one hop in Section 5.4, and using this result, we find energy optimal transmission range of CRAHN nodes under reliable and unreliable link conditions. The numerical results are presented and discussed in Section 5.5.

## 5.2 System Model

### 5.2.1 Network Model

In our network model, there are  $N$  CRAHN nodes which are distributed randomly according to a uniform distribution with a density  $\rho_s$ . These nodes are regarded as secondary users (SUs). The network area is circular, and the network radius is set to be  $\Gamma$ . Nodes in the network form a decentralized network such that there is no entity controlling the communication. SUs coexist with the primary network. PUs are the legacy users of the spectrum band, and they use it without any restriction. SUs use it opportunistically. Some part of the network is shown in Fig. 5.1. The primary and the secondary transmission links are shown differently to distinguish the secondary and the primary transmissions.

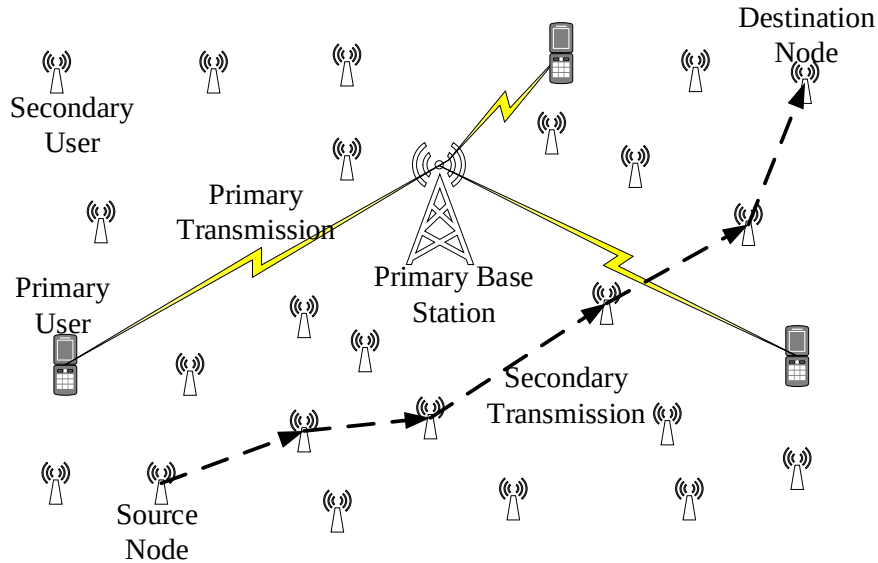


Figure 5.1: An example network.

The interference of SUs to primary network must be minimum. Hence, nodes sense the spectrum in a periodic fashion. According to the spectrum sensing results, they send their data packets to their one hop neighbors. As seen in Fig. 5.2, the time is slotted, and at each slot one frame is transmitted. There are two mini slots in each frame interval. The first mini slot is reserved for the spectrum sensing, and the subsequent mini slot is for the data transmission and the data reception. The time reserved for the spectrum sensing is  $\tau_S$ , and the time reserved for the data transmission is  $\tau_T$ . The time period of one frame is denoted as  $\tau_F$ .

$T_{\text{idle}}$  and  $T_{\text{busy}}$  are the random variables that define the idle and busy time periods of PUs [16, 17]. The idle and busy times of PUs follow exponential distributions whose means are  $\alpha$  and  $\beta$ . Hence, their probability density functions can be written in the following forms:

$$f_{T_{\text{idle}}}(t) = \frac{1}{\alpha} e^{-\frac{t}{\alpha}}, \quad (5.1)$$

$$f_{T_{\text{busy}}}(t) = \frac{1}{\beta} e^{-\frac{t}{\beta}}. \quad (5.2)$$

The OFF ( $P_{\text{OFF}}$ ) and ON ( $P_{\text{ON}}$ ) probabilities of the PU can be stated as  $\frac{\alpha}{\alpha+\beta}$  and  $\frac{\beta}{\alpha+\beta}$ , respectively.

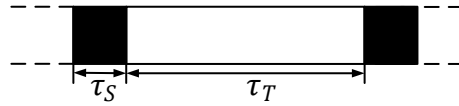


Figure 5.2: The time slot structure.

Energy detection is employed for spectrum sensing due to its practicality. However, imperfections on the spectrum sensing occur, and the probabilities of false alarm and mis-detection are nonzero [16]. Let the hypotheses  $\mathcal{H}_0$  and  $\mathcal{H}_1$  define the absence and the presence of PU activity, respectively. The probability of false alarm is given as

[16]

$$P_{fa} = Pr[\text{Busy}|\mathcal{H}_0] = P_{OFF} \mathcal{Q}\left(\frac{\delta - 2\tau_s B \sigma_n^2}{\sqrt{4\tau_s B \sigma_n^4}}\right), \quad (5.3)$$

where  $B$  is the bandwidth of the channel,  $\delta$  is the detection threshold,  $\sigma_n^2$  is the noise variance, and  $\mathcal{Q}(\cdot)$  is Q-function. The probability of detection is given as [16]

$$P_d = Pr[\text{Busy}|\mathcal{H}_1] = P_{ON} \mathcal{Q}\left(\frac{\delta - 2\tau_s B(\sigma_s^2 + \sigma_n^2)}{\sqrt{4\tau_s B(\sigma_s^2 + \sigma_n^2)^2}}\right), \quad (5.4)$$

where  $\sigma_s^2$  is the PU signal variance. The successful vacant spectrum detection is given as  $P_v = Pr[\text{Idle}|\mathcal{H}_0] = P_{OFF} - P_{fa}$ . The mis-detection probability is given as  $P_{md} = Pr[\text{Idle}|\mathcal{H}_1] = P_{ON} - P_d$ .

### 5.2.2 Energy Consumption Model

The key functionality of CR technology is the spectrum sensing. Energy detection technique is used for the identification of the spectrum opportunity. The energy consumed during spectrum sensing is denoted as  $E_s$ . This energy is consumed during the sensing period at the beginning of each frame. The power required for the spectrum sensing,  $P_s$ , is 700 mW [63].

The packet is transmitted during the transmission period. The energy consumption due to the data transmission can be formulated as [1, 2, 64]

$$E_T = (q_1 r_s^\kappa + q_2) \zeta, \quad (5.5)$$

where  $q_1$  and  $q_2$  are determined according to the system and the channel parameters,  $\kappa$  is the path loss exponent,  $r_s$  is the transmission range of the nodes and  $\zeta$  is the packet size in length.  $q_1$  and  $q_2$  can be defined as follows [1]

$$q_1 = \frac{\gamma_0 F_{rx} N_0 B \left(\frac{4\pi}{\lambda}\right)^\kappa 10^\kappa}{G_a \eta_{amp} R_b}, \quad (5.6)$$

$$q_2 = \frac{P_{elec} + P_{rx}}{R_b}, \quad (5.7)$$

where  $\gamma_0$  is the reference signal-to-noise (SNR) ratio,  $F_{rx}$  is the noise figure of the receiver,  $N_0$  is the thermal noise in a 1 Hz bandwidth,  $B$  is the bandwidth,  $\lambda$  is the wavelength of the signal,  $\eta_{amp}$  is the transmitter amplifier efficiency,  $G_a$  is the antenna gain,  $R_b$  is the bit rate of the channel, spectral efficiency is 1 bit/Hz, and  $P_{elec}$  and  $P_{rx}$  are the power consumed by the device and the power consumed by the receiver. The energy consumed by the receiver during the reception of the packet is  $E_R = P_{rx}\tau_T$ .

At the beginning of each frame, every node consumes energy for the spectrum sensing. Hence, the energy consumed for the spectrum sensing can be written as  $E_S = P_S\tau_S$ . The total energy consumed in a frame between transmitter and receiver becomes

$$E_{onehop} = E_T + E_R + 2E_S. \quad (5.8)$$

This incorporates the transmission and reception energy with the energy consumed for spectrum sensing.

The values of the parameters in the energy consumption model can be found in Table 5.1.

Table 5.1: Parameters and their values [1, 2]

| Parameter    | Value                    |
|--------------|--------------------------|
| $\gamma_0$   | 10                       |
| $F_{rx}$     | 12.589                   |
| $N_0$        | $4.17 \times 10^{-21}$ J |
| $B$          | 250 KHz                  |
| $\lambda$    | 0.125 m                  |
| $\eta_{amp}$ | 0.2                      |
| $G_a$        | 0.01                     |
| $P_{elec}$   | 3.63 mW                  |
| $P_{rx}$     | 11.13 mW                 |
| $R_b$        | 0.25 Mbps                |

The spectrum holes are utilized opportunistically by SUs without interrupting the communication of the licensed users. PU activities cause changes in the use of licensed spectrum, hence, there is a dynamic radio environment. Medium access is controlled in a distributed manner since the secondary network is decentralized. For the sake of simplicity, scheduling between SUs is assumed to be perfect and no collision occurs among SUs and we will extend the study to include SU collisions as well in our future work.

The access to the spectrum is determined according to the spectrum sensing results. However, the spectrum sensing involves some imperfections [16, 17]. These imperfections are the causes of the performance degradation in the secondary network. The nonzero probabilities of false alarm and mis-detection cause 5 different cases in the DSA scheme. These cases are illustrated in Fig. 5.3. The probabilities of these cases are given as follows.

- **Case 1:** The detection case (denoted as C1) is that the presence of an PU signal is determined correctly. Hence, the SU will not be able to benefit from this frame. The probability of the occurrence of this case is given as

$$P_{C1} = P_d = P_{ON} \mathcal{Q}\left(\frac{\delta - 2\tau_s B(\sigma_s^2 + \sigma_n^2)}{\sqrt{4\tau_s B(\sigma_s^2 + \sigma_n^2)^2}}\right). \quad (5.9)$$

- **Case 2:** The mis-detection case (denoted as C2) is the failure in the determination of the presence of the signal. C1 and C2 are the cases that the PU is present in the network. Hence, the sum of the probabilities of these cases sum up to  $P_{ON}$ . The probability of occurrence of this case is given as

$$P_{C2} = P_{ON} - P_{C1} = P_{ON} \mathcal{Q}\left(\frac{2\tau_s B(\sigma_s^2 + \sigma_n^2) - \delta}{\sqrt{4\tau_s B(\sigma_s^2 + \sigma_n^2)^2}}\right) \quad (5.10)$$

The transmission effort becomes a waste of energy of the energy limited nodes.

- **Case 3:** The case of false alarm (denoted as C3) is that the node assumes that

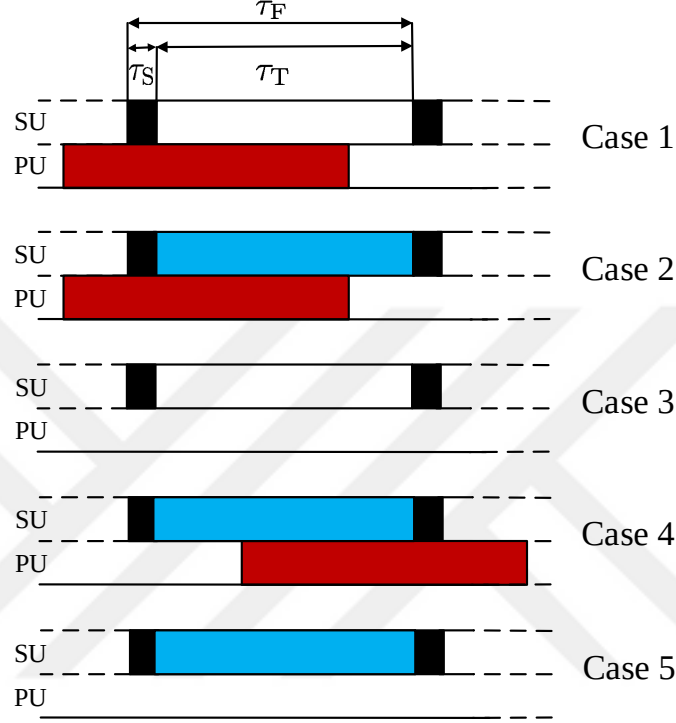


Figure 5.3: The cases that can occur in DSA Scheme.

there are PU activities in the absence of the PU. The probability of C3 is

$$P_{C3} = P_{fa} = P_{OFF} \mathcal{Q}\left(\frac{\delta - 2\tau_S B \sigma_n^2}{\sqrt{4\tau_S B \sigma_n^4}}\right). \quad (5.11)$$

This is a wasted spectrum opportunity.

- **Case 4:** The case of the collision with a PU (denoted as C4) is the event that the SU detects the spectrum opportunity and transmits its message in the frame but the message collides with the PU signal. In this case, the idle interval of the PU must be less than  $\tau_T$ . This probability can be written as

$$Pr[T_{idle} < \tau_T] = \int_0^{\tau_T} \frac{1}{\alpha} e^{-\frac{t}{\alpha}} dt = 1 - e^{-\frac{\tau_T}{\alpha}}. \quad (5.12)$$

In this case, the spectrum opportunity is used but the collision occurs. Hence,

the probability of C4 can be written as

$$P_{C4} = (P_{\text{OFF}} - P_{\text{fa}}) \left( 1 - e^{-\frac{\tau_T}{\alpha}} \right). \quad (5.13)$$

- **Case 5:** The case of successful transmission (denoted as C5) is the event which is the detection of a spectrum opportunity and the transmission the packet in the frame time interval  $\tau_F$ . In this case, the idle time of the PU must not be smaller than the  $\tau_T$ , hence, the probability of this case is given as

$$P_{C5} = (P_{\text{OFF}} - P_{\text{fa}}) e^{-\frac{\tau_T}{\alpha}} = P_v e^{-\frac{\tau_T}{\alpha}}. \quad (5.14)$$

The spectrum opportunity means that the transmitter and the receiver are in C5. However, the spectrum opportunity is not enough for the successful packet transmission. After the link is established when both the receiver and the transmitter are in C5, the successful link probability depends on the reliability of the channel. Hence, we define a probability that captures these effects for the spectrum-aware communications, which is  $P_l$ . It depends on the spectrum opportunity and the channel conditions. We elaborate more on  $P_l$  in Section 5.4.

### 5.3 Cognitive Hop Advance in Dynamic Spectrum Environment

Nodes in CRAHNS are energy-constrained such that a transmitter node cannot reach its destination directly if it is not in the transmission range of the transmitter. Due to the restrictions on the transmission energy, multi-hop routing is adopted in these type of networks. At each hop, there would be an advance towards the desired destination. The difference in distance between the transmitter-destination and the relay node-destination is termed as the *hop advance distance*. The hop advance distance is limited by the transmission range of the nodes. Fig. 5.4 shows a transmitter node, SU  $A$ , whose aim is to transmit its packet towards its destination, SU  $C$ . The packet is conveyed by the nodes between the transmitter and the destination hop by hop. The

next hop is affected by the spectrum availability since the secondary nodes coexist with the PUs. Hence, the hop advance distance is defined as *cognitive hop advance*.

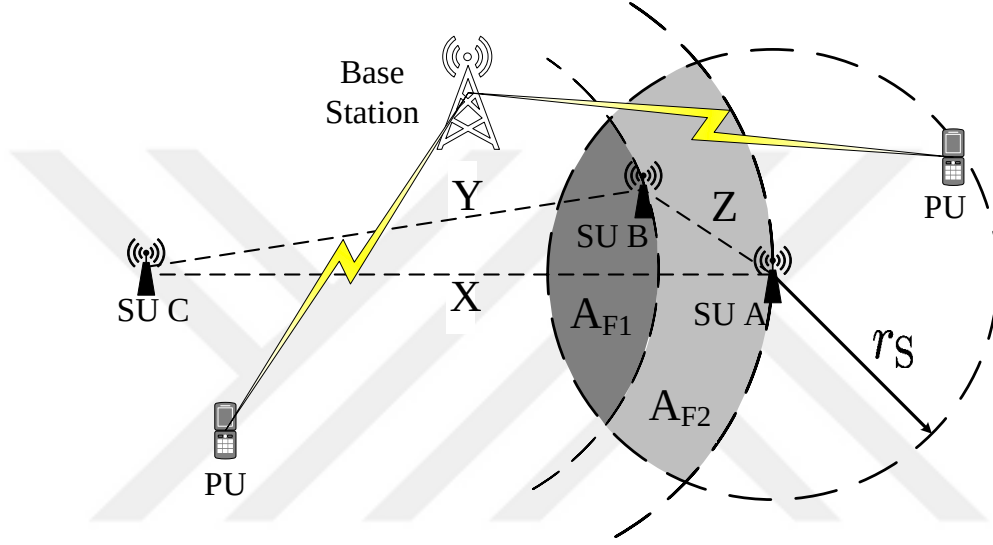


Figure 5.4: Cognitive hop advance in dynamic radio environment.

At each hop, the transmitter or the relay nodes find the most convenient node towards its destination. In this context, the most convenient is the closest node to the destination which has the spectrum opportunity. The relay nodes transmit the packet to the nodes in the forwarding region and the packet is transmitted hop by hop. The forwarding region for the transmitter SU A is the region defined by  $A_F = A_{F1} + A_{F2}$  as seen in Fig. 5.4. At each step, the same process is repeated, hence, each step can be regarded as the first of the remaining process since there is always a directional routing towards the destination [62].

Due to the repetition of the hopping process, we analyze the cognitive hop advance of a random node in the network. Random distribution of the nodes and the dynamic activity of PUs affect the cognitive hop advance. We find the expected cognitive hop advance according to the system parameters. The same methodology in [62] is adopted to calculate the average cognitive hop advance distance.

### 5.3.1 Expected Cognitive Hop Advance

In a dynamic radio environment, there are two constraints on the communication. The first one is the presence of a neighbor within the transmission area. The second one is the spectrum opportunity to transmit. The spectrum opportunity actually means that the transmitter and the receiver are in C5 which is explained in Section 5.3.

Fig. 5.4 shows a transmitter, SU *A*, that wants to transmit its packet towards the destination, SU *C*. At the first hop, SU *A* sends its packet to the SU *B*. The greedy forwarding approach is adopted for the routing algorithm such that the neighbor node which has larger hop advance towards the destination and spectrum opportunity is selected as the relay node. In Fig. 5.4, SU *A* determines its relay as SU *B* at its first hop which is the most convenient node among its neighbors according to greedy forwarding approach.

The distances between the transmitter, the relay and the destination can be characterized by random variables. The random variable corresponding the distance between the SU *A* and the destination node, SU *C*,  $d_{AC}$ , is denoted by  $X$ . The random variable corresponding to the distance between the SU *B* and the destination SU *C*,  $d_{BC}$ , is denoted by  $Y$ . The random variable corresponding to the distance between the SU *A* and the SU *B*,  $d_{AB}$ , is denoted by  $Z$ .

The transmission strategy of a node is to find a relay node that can receive the source packet with mutual spectrum opportunity. Due to the dynamic radio environment, a relay node could not receive the intended packet or the transmitter could not transmit its message. Hence, we define a random variable capturing this effect, it is written as follows

$$F = \begin{cases} 1 & , \text{if } SOP \text{ exists} \\ 0 & , \text{otherwise} \end{cases} \quad (5.15)$$

where SOP is spectrum opportunity. The random variable corresponding to the cog-

nitive hop advance is denoted by  $W$ , and it is defined as

$$W = \begin{cases} X & , \text{if } X \leq r_s \\ X - Y & , \text{if } X > r_s \text{ and } F = 1 \\ 0 & , \text{otherwise.} \end{cases} \quad (5.16)$$

The cognitive hop advance mainly depends on the distance between the transmitter and the destination, and the spectrum opportunity. When  $X \leq r_s$ , SU  $A$  and SU  $C$  are one-hop neighbors, and eventually they have the opportunity to communicate. Hence, the spectrum opportunity is not a parameter which needs to be considered when the source, and the destination are one hop neighbors. However, if the distance between the source, and the destination is greater than  $r_s$ , there should be a node with a spectrum opportunity in the forwarding region towards the destination.

The expected cognitive hop advance is expressed as

$$E[W] = E[W | (X \leq r_s) \cup (X > r_s \cap F = 1)] \quad (5.17)$$

since the the cognitive hop advance is nonzero for the event  $(X \leq r_s) \cup (X > r_s \cap F = 1)$ .

We first evaluate  $Pr[W > w]$  in (5.18) to find the expected cognitive hop advance.

$$\begin{aligned} Pr[W > w] &= Pr[(W > w) | ((X \leq r_s) \cup (X > r_s \cap F = 1))] \\ &= \frac{Pr[(W > w) \cap ((X \leq r_s) \cup (X > r_s \cap F = 1))]}{Pr[(X \leq r_s) \cup (X > r_s \cap F = 1)]} \\ &= \frac{Pr[((W > w) \cap (X \leq r_s)) \cup ((W > w) \cap (X > r_s \cap F = 1))]}{Pr[(X \leq r_s) \cup (X > r_s \cap F = 1)]}. \end{aligned} \quad (5.18)$$

(5.18) can be expanded according to the axioms of probability. There are 4 components in the nominator and the denominator of the second line of (5.18). They can be defined as events as follows:

$$E_1 = ((W > w) \cap (X \leq r_s)), \quad (5.19)$$

$$E_2 = (X \leq r_S), \quad (5.20)$$

$$E_3 = (X > r_S \cap F = 1), \quad (5.21)$$

$$E_4 = ((W > w) \cap (X > r_S \cap F = 1)). \quad (5.22)$$

(5.18) can be rewritten as

$$Pr[W > w] = \frac{Pr[E_1 \cup E_4]}{Pr[E_2 \cup E_3]}. \quad (5.23)$$

$E_1$  and  $E_4$  are two independent events due to non-overlapping intervals for  $X$ . Furthermore,  $E_2$  and  $E_3$  are two independent events due to non-overlapping intervals for  $X$ . Hence, (5.23) becomes as

$$Pr[W > w] = \frac{Pr[E_1] + Pr[E_4]}{Pr[E_2] + Pr[E_3]}. \quad (5.24)$$

Event  $E_1$  states that the distance between transmitter SU  $A$ , and the destination  $C$  is smaller than or equal to the transmission radius,  $r_S$ . This means that  $W = X$ . The cognitive hop advance must be greater than  $w$ , and it must be smaller than  $r_S$ , hence, the probability of event  $E_1$  can be evaluated as

$$Pr[E_1] = Pr[w < X \leq r_S] = \frac{\pi(r_S^2 - w^2)}{\pi\Gamma^2} = \frac{(r_S^2 - w^2)}{\Gamma^2}. \quad (5.25)$$

In this event, the destination is in the transmission range of the transmitter, hence, it directly sends its packet to the destination when there is a spectrum opportunity without a need of relay. We do not include successful link probability since the transmitter eventually sends its packet to the destination.

The event  $E_2$  has no condition on the cognitive hop advance, however,  $X$  must be smaller than  $r_S$ . Hence, the destination is a neighbor of the source node, and it can be defined as

$$Pr[E_2] = Pr[X < r_S] = \frac{\pi r_S^2}{\pi\Gamma^2} = \frac{r_S^2}{\Gamma^2}. \quad (5.26)$$

The event  $E_3$  states that there is at least a node in the forwarding region having the spectrum opportunity to transmit its packet since the destination is not in the transmission range of the transmitter. Hence, the probability of event  $E_3$  can be evaluated as

$$Pr[E_3] = Pr[X > r_S \cap F = 1] \quad (5.27)$$

$$= \int_0^\Gamma Pr[X > r_S \cap F = 1 | X = x] dP_X(x) \quad (5.28)$$

where  $dP_X(x) = \frac{2\pi x dx}{\pi \Gamma^2} = \frac{2x dx}{\Gamma^2}$ . In (5.27), we put condition on  $X$  and integrate over this condition to evaluate the probability of  $E_3$ . The condition is that the distance between the source, and the destination is  $x$  and  $(X > r_S \cap F = 1 | X = x)$  is the event that there is at least one node that has the spectrum opportunity. Hence, this probability can be written as

$$Pr[X > r_S \cap F = 1 | X = x] = (1 - e^{-\rho_S A_F}) P_l. \quad (5.29)$$

The forwarding region is the union of the regions  $A_{F1}$  and  $A_{F2}$ .  $A_{F1}$  is the region further to the destination, and  $A_{F2}$  is the region closer to the destination which can be seen in Fig. 5.4. The forwarding region is defined as

$$A_F = r_S \cos^{-1}\left(\frac{r_S}{2x}\right) + x^2 \cos^{-1}\left(1 - \frac{r_S^2}{2x^2}\right) - \frac{1}{2} r_S \sqrt{(2x + r_S)(2x - r_S)}. \quad (5.30)$$

Hence, the probability of  $E_3$  can be written as

$$Pr[E_3] = \int_{r_S}^\Gamma (1 - e^{-\rho_S A_F}) P_l dP_X(x) \quad (5.31)$$

$$= P_l \left( 1 - \frac{r_S}{\Gamma^2} - \frac{2}{\Gamma^2} \int_{r_S}^\Gamma x e^{-\rho_S A_F} dx \right). \quad (5.32)$$

In (5.31), the lower limit in the integral is  $r_S$  since  $X > r_S$  is defined in (5.28).

The event  $E_4$  imposes another constraint on the cognitive hop advance distance

$W$  in addition to  $E_3$ . This constraint states that the cognitive hop advance must be greater than  $w$ . The probability of  $E_4$  can be written as

$$Pr[E_4] = Pr[W > w \cap X > r_S \cap F = 1] \quad (5.33)$$

$$= Pr[X - Y > w \cap X > r_S \cap F = 1] \quad (5.34)$$

$$= \int_{r_S}^{\Gamma} Pr[Y < x - w \cap F = 1 | X = x] dP_X(x). \quad (5.35)$$

In (5.34), we use  $W = X - Y$  as in (5.16) for the case  $(X > r_S \cap F = 1)$ . In the next step, we put a condition on  $X$  and integrate from  $r_S$  to  $\Gamma$ . We first find  $Pr[Y > y \cap F = 1 | X = x]$  to evaluate the (5.35). Hence,

$$Pr[Y > y \cap F = 1 | X = x] = \begin{cases} Pr[F = 1 | X = x] & , if \ y \leq x - r_S \\ Pr[N_{A_{F1}} = 0 \cup S_{A_{F1}} = 0] \\ \times Pr[N_{A_{F2}} > 0 \cap S_{A_{F2}} = 1] & , if \ x - r_S < y < x \\ 0 & , if \ y \geq x \end{cases} \quad (5.36)$$

where  $N_{A_{F1}}$  represents the number of neighbors in the region  $A_{F1}$ ,  $N_{A_{F2}}$  represents the number of neighbors in the region  $A_{F2}$ ,  $S_{A_{F1}}$  and  $S_{A_{F2}}$  are indicator functions on whether the transmitter can achieve spectrum-aware communication in the region  $A_{F1}$  and  $A_{F2}$ , respectively. In (5.36), if  $y \leq x - r_S$ , there is a cognitive hop advance in the forwarding region, hence the probability becomes  $Pr[F = 1 | X = x]$ . Furthermore, if  $x - r_S < y < x$ , the probability becomes the probability of an event that there is no neighbor node in the region  $A_{F1}$  satisfying the spectrum-aware condition to establish a link, and there is at least one node in the region  $A_{F2}$  satisfying link establishment requirements. First, we find the probability that there is no neighbor node in  $A_{F1}$  satisfying the link establishment requirements. Hence, for this probability there are two events. The first event is that there are not any nodes in  $A_{F1}$ , and the second event is that there are some nodes but they do not satisfy spectrum-aware communication

conditions in  $A_{F1}$ . The probability of the first event evaluated as

$$Pr[N_{A_{F1}} = 0 \cup S_{A_{F1}} = 0] = Pr[N_{A_{F1}} = 0] + Pr[N_{A_{F1}} > 0 \cap S_{A_{F1}} = 0]. \quad (5.37)$$

The first probability in (5.37) can be evaluated as

$$Pr[N_{A_{F1}} = 0] = e^{-\rho_S A_{F1}}. \quad (5.38)$$

For the second probability in (5.37), there may be up to  $N-1$  number of nodes which do not satisfy spectrum-aware communication conditions, and it can be approximated as follows if  $\Upsilon = \rho_S A_{F1}$ ,

$$Pr[N_{A_{F1}} > 0 \cap S_{A_{F1}} = 0] = \sum_{k=1}^{N-1} e^{-\Upsilon} \frac{\Upsilon^k}{k!} (1 - P_l)^k. \quad (5.39)$$

This probability in (5.37) can be written as

$$\begin{aligned} Pr[N_{A_{F1}} = 0 \cup S_{A_{F1}} = 0] &= e^{-\Upsilon} + \sum_{k=1}^{N-1} e^{-\Upsilon} \frac{\Upsilon^k}{k!} (1 - P_l)^k = \sum_{k=0}^{N-1} e^{-\Upsilon} \frac{\Upsilon^k}{k!} (1 - P_l)^k \\ &\approx e^{-\Upsilon} \sum_{k=0}^{\infty} \frac{\Upsilon(1 - P_l))^k}{k!} = e^{-\Upsilon} e^{\Upsilon(1 - P_l)} = e^{-\Upsilon P_l}. \end{aligned} \quad (5.40)$$

In the last line of (5.40), since  $\frac{(\rho_S A_{F1})^k}{k!} (1 - P_l)^k \rightarrow 0$  as  $k \rightarrow \infty$ , we can change the upper bound in the summation of the (5.40) as infinity. This approximation leads to the final result of (5.40).

The second event when evaluating the event  $E_4$  describes the probability that there is at least a node satisfying the spectrum-awareness in  $A_{F2}$ , and it can be written as

$$Pr[N_{A_{F2}} > 0 \cap S_{A_{F2}} = 1] = (1 - e^{-\rho_S A_{F2}}) P_l. \quad (5.41)$$

In (5.36), the probability for  $x - r_S < y < x$  becomes  $e^{-\rho_S A_{F1} P_l} (1 - e^{-\rho_S A_{F2}}) P_l$ . The

probability for  $y \leq x - r_s$  in (5.36) is as follows

$$Pr[F = 1|X = x] = (1 - e^{-\rho_S A_F})P_l. \quad (5.42)$$

In order to evaluate (5.35), we find out

$$Pr[Y \leq y \cap F = 1|X = x] = Pr[F = 1|X = x] - Pr[Y > y \cap F = 1|X = x] \quad (5.43)$$

$$= \begin{cases} 0 & , if \ y \leq x - r_s \\ (1 - e^{-\rho_S A_F})P_l - \\ e^{-\rho_S A_{F1}}P_l(1 - e^{-\rho_S A_{F2}P_l})P_l & , if \ x - r_s < y < x \\ (1 - e^{-\rho_S A_F})P_l & , if \ y \geq x. \end{cases} \quad (5.44)$$

We know that  $0 < w < r_s$ , hence  $x - r_s < y < x$ , and the probability of  $E_4$  can be written as

$$\begin{aligned} Pr[E_4] &= \int_{r_s}^{\Gamma} Pr[Y < x - w \cap F = 1|X = x] dP_X(x) \\ &= \int_{r_s}^{\Gamma} [(1 - e^{-\rho_S A_F}) - e^{-\rho_S A_{F1}}(1 - e^{-\rho_S A_{F2}P_l})]P_l \frac{2x}{\Gamma^2} dx. \end{aligned} \quad (5.45)$$

According to the above derivations, the probability that the cognitive hop advance distance is greater than  $w$  can be evaluated as in (5.46).

$$\begin{aligned} Pr[W > w|((X \leq r_s) \cup (X > r_s \cap F = 1))] &= \frac{Pr[E_1] + Pr[E_4]}{Pr[E_2] + Pr[E_3]} \\ &= \frac{\frac{r_s^2 - w^2}{\Gamma^2} + \int_{r_s}^{\Gamma} [(1 - e^{-\rho_S A_F}) - e^{-\rho_S A_{F1}}P_l(1 - e^{-\rho_S A_{F2}P_l})]P_l \frac{2x}{\Gamma^2} dx}{\frac{r_s^2}{\Gamma^2} + \int_{r_s}^{\Gamma} (1 - e^{-\rho_S A_F})P_l \frac{2x}{\Gamma^2} dx}. \end{aligned} \quad (5.46)$$

It should be noted that  $A_{F1}$  and  $A_{F2}$  depend on  $x$ ,  $r_S$ , and  $w$ . These arguments are dropped in the derivations for the sake of simplification.

The cognitive hop advance distance,  $E[W]$ , can be evaluated as in (5.47).

$$\begin{aligned}
E[W] &= ((X \leq r_S) \cup (X > r_S \cap F = 1)) \\
&= \int_0^\infty Pr[W > w | ((X \leq r_S) \cup (X > r_S \cap F = 1))] dw \\
&= \frac{\int_0^{r_S} \frac{r_S^2 - w^2}{\Gamma^2} dw + \int_0^{r_S} \int_{r_S}^\Gamma [(1 - e^{-\rho_S A_F}) - e^{-\rho_S A_{F1} P_l} (1 - e^{-\rho_S A_{F2}})] P_l \frac{2x}{\Gamma^2} dx dw}{\frac{r_S^2}{\Gamma^2} + \int_{r_S}^\Gamma (1 - e^{-\rho_S A_F}) P_l \frac{2x}{\Gamma^2} dx}
\end{aligned} \tag{5.47}$$

The integral limits for hop advance distance in the second line of (5.47) is from 0 to  $r_S$  since the hop advance is limited to the transmission radius.

The nodes in CRAHNs are inexpensive, hence, they can be deployed in high density in the network area. Due to the high density, some approximations can be made in (5.47). These approximations are  $e^{-\rho_S A_F} P_l \approx 0$ ,  $P_l e^{-\rho_S A_{F1} P_l} \approx 0$ , and  $P_l e^{-\rho_S (A_{F2} + A_{F1} P_l)} \approx 0$ . Hence, (5.47) can be evaluated as

$$E[W] = \frac{\int_0^{r_S} \frac{r_S^2 - w^2}{\Gamma^2} dw + \int_0^{r_S} \int_{r_S}^\Gamma P_l \frac{2x}{\Gamma^2} dx dw}{\frac{r_S^2}{\Gamma^2} + \int_{r_S}^\Gamma P_l \frac{2x}{\Gamma^2} dx} \tag{5.48}$$

$$= \frac{2r_S^3 + 3P_l(\Gamma^2 r_S - r_S^3)}{3r_S^2 + 3P_l(\Gamma^2 - r_S^2)} \tag{5.49}$$

$$= r_S - \frac{r_S^3}{3r_S^2 + 3P_l(\Gamma^2 - r_S^2)} \tag{5.50}$$

As seen in (5.50), the expected cognitive hop advance distance depends on transmission radius,  $r_S$ , network radius,  $\Gamma$ , and successful link probability,  $P_l$ .

#### 5.4 Optimal Transmission Range

The nodes in CRAHNs have limited battery and the main energy consumption is due to the transmission of the packets. However, they also consume energy due to the spectrum sensing which is the result of the cognitive functionality. Optimizing the energy consumption of the resource constrained nodes is the main motivation of our

chapter. Hence, we define a metric that relates the energy consumption per hop and the advance in distance covered towards the destination per hop. According to this metric, we evaluate the energy optimal transmission range in a highly dense secondary network in a dynamic radio environment.

#### 5.4.1 Cognitive Advance-Energy Efficiency

It is important to define a metric to evaluate the efficiency of our transmission effort in a frame as in [62]. Hence, we define a cognitive advance-energy efficiency metric which is the average cognitive hop advance distance per average energy consumption in a frame. This measures the average distance traveled by a packet towards the destination per joule. This metric will be defined for two different link conditions, namely, reliable link and unreliable link.

##### **Reliable link condition**

Under the perfect channel conditions, in one transmission the message is received by the receiver node without error. Hence, the cognitive advance-energy efficiency metric can be written as [62]

$$\Phi(r_S) = \frac{E[W]}{E_{\text{onehop}}} \quad (5.51)$$

$$= \frac{2r_S^3 + P_l(\Gamma^2 r_S - r_S^3)}{((q_1 r_S^\kappa + q_2)\zeta + 2P_S \tau_S)(r_S^2 + 3P_l(\Gamma^2 - r_S^2))}. \quad (5.52)$$

The successful link probability between the transmitter, and the receiver in this case is that they should be in C5. Furthermore, the reliable link means that the the transmission of the transmitter is successfully received by the relay node. Hence, it is written as  $P_l = P_{C5}^2$ .

The (5.52) is a concave function, hence, there is an optimal point which gives the maximum distance-energy efficiency for the transmission range,  $r_S^*$ . In order to find

the energy optimal  $r_S^*$ , we need to solve

$$\frac{d\Phi(r_S)}{dr_S} = 0 \quad (5.53)$$

The solution of the (5.53) can not be written in a closed form. The optimal  $r_S^*$  is studied numerically in Section 5.5.

### ***Unreliable link condition***

In a realistic scenario in wireless networks, the communication links are unreliable. The packets to be sent to the neighbor node can not be received correctly due to bit errors in the packets. Hence, the cognitive advance-energy efficiency metric must consider the unreliability of the link. To this end, after the link is established, the successful communication is only possible if there is no error during the transmission period. We know that that the the transmitter, and the receiver must be in C5 for the link establishment. Under unreliable channel conditions, spectrum aware communication is successful if the transmitter and the receiver are in C5, and the packet is conveyed successfully through the established link.

Under unreliable radio link model [65], the successful transmission probability is the probability that all the bits in the packet are received successfully. It can be written as

$$P_s = (1 - \overline{BER}(\gamma))^\zeta. \quad (5.54)$$

$\overline{BER}$  is the average bit error rate (BER) calculating to evaluate the unreliability of the link.  $\gamma$  is the signal-to-noise ratio in the receiver. Among the 5 cases in a dynamic spectrum environment, the transmitter sends its packet to the relay in 3 cases. These cases are C2, C4, and C5 as seen in Fig. 5.3. In these cases, the transmitter assumes that the channel is idle and the transmitter starts transmission. However, only C5 has the possibility for the successful communication. In C2 and C4, the transmitted packet collides, and the transmission becomes unsuccessful. Hence, the average BER

can be written as

$$\overline{BER}(\gamma) = P_{C5} BER_{C5}(\gamma). \quad (5.55)$$

The BER for  $C5$  can be written as in [19],  $BER_{C5}(\gamma) = 0.5 \operatorname{erfc}(\sqrt{k\gamma})$ , where

$$\operatorname{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_{\sqrt{x}}^{\infty} \exp(-u^2) du, \quad (5.56)$$

the complementary error function. The channel is an AWGN channel, and  $k$  depends on the modulation type used. If the modulation type is BPSK,  $k$  becomes 1.

The average bit error rate becomes

$$\overline{BER}(\gamma) = 0.5 P_{C5} \operatorname{erfc}(\sqrt{k\gamma}). \quad (5.57)$$

Hence, the successful link probability for the unreliable link can be written as

$$P_l = P_{C5}^2 \left( 1 - 0.5 P_{C5} \operatorname{erfc}(\sqrt{k\gamma}) \right)^\zeta. \quad (5.58)$$

According to the successful transmission probability, the packet needs to be transmitted several times for achieving successful communication. Hence, the average energy to transmit a packet to a receiver at a hop distance can be written as

$$\overline{E_{\text{onehop}}} = \frac{E_{\text{onehop}}}{P_l}. \quad (5.59)$$

Hence, the cognitive advance-energy efficiency metric can be written as [62]

$$\Phi(r_S) = \frac{E[W]}{\overline{E_{\text{onehop}}}} = \frac{P_l E[W]}{E_{\text{onehop}}}. \quad (5.60)$$

The cognitive hop advance energy efficiency should be maximized and the optimal transmission range,  $r_S$ , provides the maximal efficiency. The optimal transmission range can be found by solving  $\frac{d\Phi(r_S)}{dr_S} = 0$ . A closed form expression is not found,

however, it is studied numerically since the cognitive advance energy efficiency metric is concave.

### 5.5 Numerical Analysis

In this section, the resulting cognitive hop-advance energy efficiency metric, and the variation of energy optimal transmission ranges are investigated according to the system parameters and the cognitive radio parameters. The parameters for system model are used as given in Section 5.2 unless otherwise stated. In the following studies, we set  $\Gamma = 50$  m,  $\zeta = 200$  bits,  $\kappa = 2$ ,  $\delta = 3$ ,  $\sigma_n = 1$ ,  $\tau_S = 10$   $\mu$ s,  $P_{\text{OFF}} = 0.8$ , and  $B = 10^5$  Hz.

A communication link is established if the receiver and the transmitter are in C5. Furthermore, it also affects the optimal transmission range as seen in (5.52) due to  $P_l$  dependence. Hence, we first investigate the probability of C5,  $P_{C5}$ . As seen in (5.14),  $P_{C5}$  depends on  $P_{\text{OFF}}$ ,  $\delta$ ,  $B$ ,  $\tau_S$ ,  $\tau_T$ , and  $\alpha$ . In Fig. 5.5(a), as  $\tau_T$  increases, the possibility that the node experiences PU activities increases. This has negative impact on  $P_{C5}$  since there would be more collisions with PUs. Furthermore, if the average PU OFF duration increases, PU is less active, and hence,  $P_{C5}$  increases due to more spectrum opportunity. As  $P_{\text{OFF}}$  increases, the possibility that the node experiences PU activity decreases, and  $P_{C5}$  increases which can be seen in Fig. 5.5(b).  $P_{\text{fa}}$  indicates the success to determine spectrum vacancy. As we increase the spectrum sensing time,  $\tau_S$ , we increase the number of samples and have more accurate results about the spectrum. Hence,  $P_{\text{fa}}$  decreases. If  $P_{\text{fa}}$  decreases, the CR node can detect the spectrum opportunity more accurately. This increases the probability of C5 as seen in Fig. 5.5(c).

We evaluate the effect of successful communication probability on the cognitive advance-energy efficiency metric,  $\Phi(r_S)$ , for reliable and unreliable link conditions. We investigate  $P_{C5}$  in the previous analysis. In reliable link condition,  $P_l$  only depends on  $P_{C5}$ . However, in unreliable link condition,  $P_l$  also depends on the unreliable channel characteristics such as BER and SNR, which is seen in (5.58). We directly use different

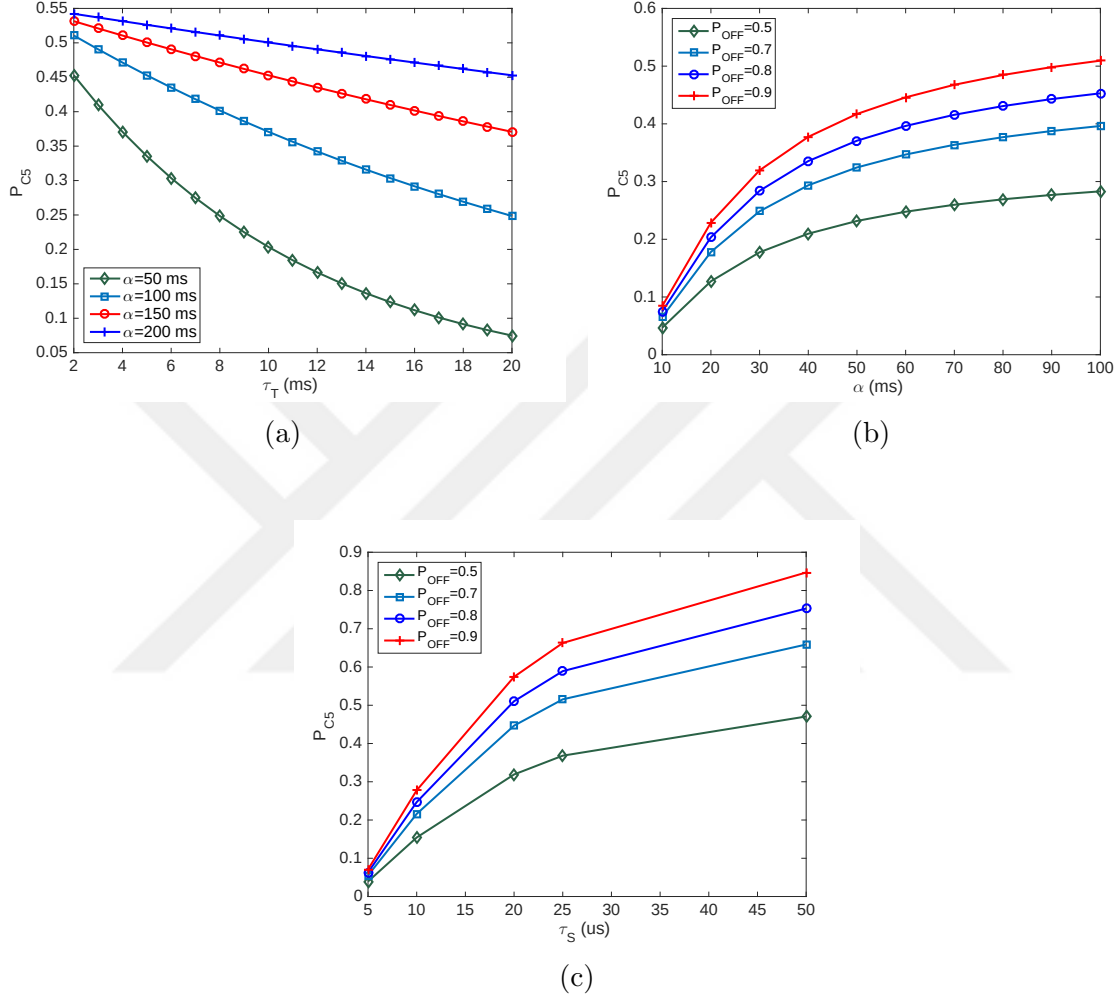


Figure 5.5: (a)  $P_l$  vs.  $\tau_T$  for different  $\alpha$ , (b)  $P_l$  vs.  $\alpha$  for different  $P_{OFF}$ , (c)  $P_l$  vs.  $\tau_S$  for different  $P_{OFF}$ .

values of  $P_l$  for investigating  $\Phi(r_S)$ . The cognitive advance-energy efficiency function is concave with respect to  $r_S$  as seen in Fig. 5.6(a). As the successful link probability increases, the optimal transmission range increases. Less PU activity or decrease in  $P_{fa}$  cause an increase in  $P_l$ . Fig. 5.6(a) show the optimal transmission range for different successful communication probability with the black line. The optimal transmission range for the reliable channel,  $r_S^*$ , is 12.70 m, 13.20 m, 13.64 m, and 13.90 m for  $P_l = 0.1$ ,  $P_l = 0.3$ ,  $P_l = 0.5$ , and  $P_l = 0.7$ , respectively. It should be noted that the

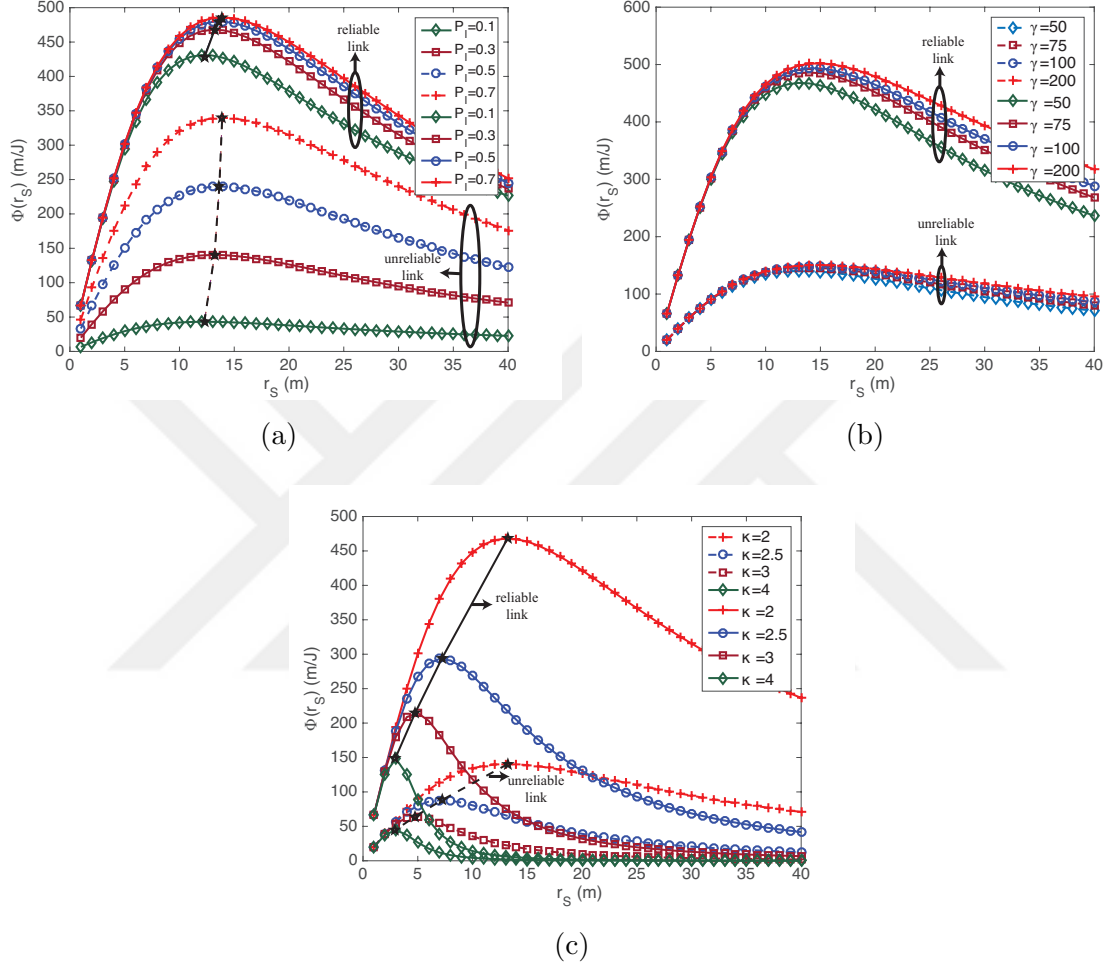


Figure 5.6:  $\Phi(r_s)$  vs.  $r_s$  for (a) different  $P_l$ , (b) different  $\Gamma$  (m), (c) different  $\kappa$ .

increase in the successful link probability may mean a decrease in the activity of PU or better performance of the CRs' spectrum sensing. CR node can reach more distant nodes as  $P_l$  increases, hence, optimal transmission radius increases. Unreliability of the link does not change the characteristics of the cognitive advance-energy efficiency metric since the successful packet transmission on an unreliable link only scales the probability of successful communication between the transmitter and the receiver.

We also change the network radius,  $\Gamma$ , to study its effect on  $\Phi(r_s)$ . We set the successful link probability,  $P_l$ , to be 0.3. As seen from Fig. 5.6(b), as the network radius increases, the optimal transmission range increases due to the effect caused by

(5.50). This actually means that the node can increase its transmission range to find a possible neighbor for the relay. Higher  $\Gamma$  means more available space to reach the neighbors in the network.

The path loss exponent,  $\kappa$ , is also an important factor that affects the optimal transmission range of CRAHN nodes. As seen in Fig. 5.6(c), the cognitive advance-energy efficiency function significantly decreases as the path loss exponent increases. If  $\kappa = 3$ , the optimal transmission range becomes 4.77 m. It would be 7.19 m if  $\kappa = 2.5$ . The rationale behind this fact is the the transmission signal attenuates more as the path loss exponent increases.  $r_s^*$  also becomes 2.94 m for  $\kappa = 4$ . The change in  $\kappa$  highly affects the optimal transmission range of the nodes. In Fig. 5.6 shows that the unreliability of the channel does not affect the optimal transmission range.

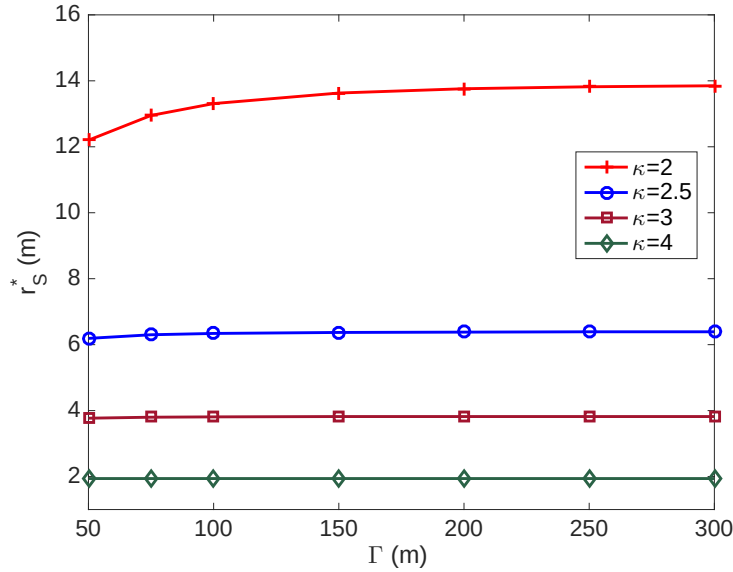


Figure 5.7:  $r_s^*$  vs.  $\Gamma$  for different  $\kappa$  and link is unreliable.

We investigate the optimal transmission range for different conditions. Firstly, we scrutinize the relationship between  $r_s^*$  and  $\Gamma$  for different  $\kappa$ . As seen in Fig. 5.7, if we increase  $\kappa$ , there would be not much deviations for different  $\Gamma$ . This means that the transmission signal attenuates such that the network radius effect becomes negligible. However, if  $\kappa = 2$ , the optimal transmission radius increases as  $\Gamma$  increases.

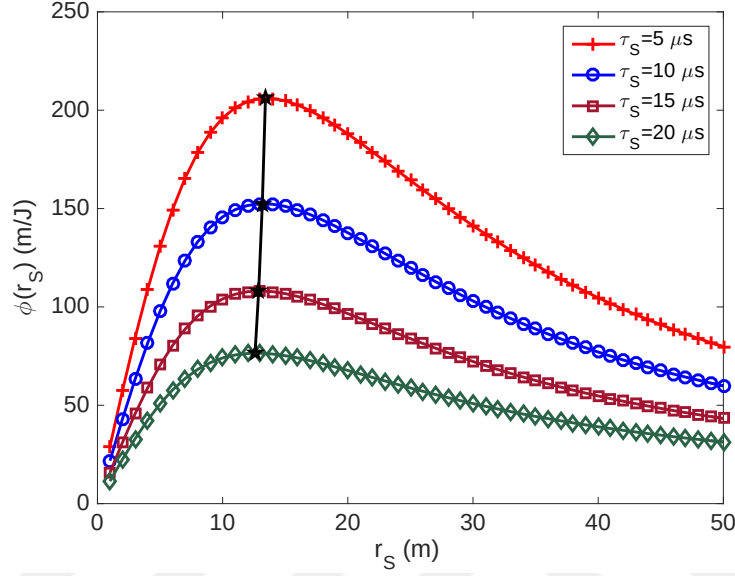


Figure 5.8:  $\Phi(r_S)$  vs.  $r_S$  for different  $\tau_S$  and link is unreliable.

We use only the unreliable link case since the characteristics of the cognitive advance-energy efficiency metric does not change with the unreliability if the link. We investigate the effect of  $\tau_S$  in the calculation of  $\Phi(r_S)$ . Although increase in  $\tau_S$  results in better performance in successful communication probability as we investigated in Fig. 5.5(c), it also increases the energy consumed for sensing. Hence, the overall effect of the  $\tau_S$  causes a decrease in  $\Phi(r_S)$ . Hence, as  $\tau_S$  increases,  $r_S^*$  decreases as seen in Fig. 5.8.  $r_S^*$  is equal to 13.42 m, 13.17 m, 12.88 m, and 12.59 m for  $\tau_S$  being equal to  $5\mu s$ ,  $10\mu s$ ,  $15\mu s$ , and  $20\mu s$ .

We also investigate the effect of the packet transmission time,  $\tau_T$ . The duration for the spectrum sensing affects the energy consumption of the nodes, hence it directly affects our energy-efficiency metric. As seen in Fig. 5.9,  $r_S^*$  decreases if we increase  $\tau_S$ . This trend is due to the  $\tau_S$  in the denominator of  $\Phi(r_S)$ . As  $\tau_S$  increases, the energy consumed for each hop increases, and the optimal transmission range decreases. As  $\tau_T$  increases, the transmission time increases, which decreases the successful transmission probability. This means smaller optimal transmission range for greater  $\tau_T$ .

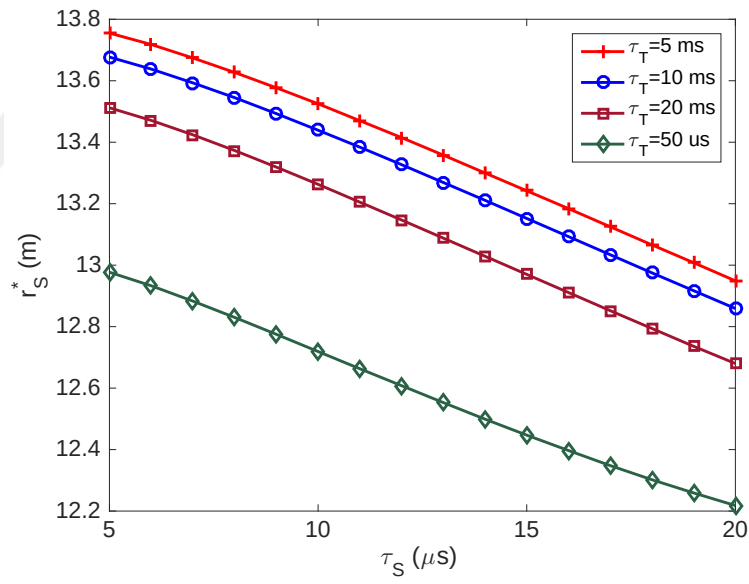


Figure 5.9:  $r_S^*$  vs.  $\tau_S$  for different  $\tau_T$  and link is unreliable.

## Chapter 6

# ON THE NETWORK-CODED MULTICAST COMMUNICATION IN COGNITIVE RADIO AD HOC NETWORKS

### 6.1 Introduction

Excessive use of wireless devices causes a growing demand for the electromagnetic spectrum. However, it is inefficiently utilized due to fixed spectrum allocation. While licensed spectrum bands are underutilized, unlicensed ones are overcrowded. Cognitive radio (CR) technology is proposed to overcome spectrum scarcity problem in the unlicensed channels, and to increase the efficiency in the licensed spectrum use [33]. CR empowers the opportunistic utilization of the spectrum by cognitive functionalities, which are spectrum sensing, decision and hand-off. If wireless ad hoc network nodes are armed with CR capability, the resulting networks become cognitive radio ad hoc networks (CRAHNs) [9].

Primary users (PUs), i.e., licensed users, and CRs coexist in the network. For overlay spectrum sharing, CRs access the licensed channel only if it is sensed to be idle. However, imperfect spectrum sensing and arrival of licensed users during the secondary communication cause collisions with PUs and undesired interference. The unreliability of the wireless links is exacerbated by the dynamic radio environment.

Clustering is one of the most widely used technique to regulate communication by imposing local coordinators, i.e., cluster-heads (CHs), in ad hoc networks. The clustered network becomes hierarchical so that CHs communicate among themselves and with their members in a more structured way [7]. It becomes also crucial in more dynamic networks such as CRAHNs due to change in spectrum availability. Beside

clustering, network coding (NC) is a novel technique, which is proposed to achieve max-flow bound on the information transmission in multicast communications [66, 67]. The information can be combined in the network. Linear codes are constructed in [67] to achieve the max-flow bound, and the encoding and the decoding operations become implementable in practice. Multiple source packets can be encoded to form network coded packets, the intended receivers only need a certain number of network coded packets to decode the information. Hence, NC enables less transmission effort to convey information in the network [66], which increases throughput. On the other hand, these coefficients should be added as a header to keep track of combined codes, which results in packet overhead.

NC is also applied in centralized and ad hoc cognitive radio networks (CRNs). For instance, it achieves higher throughput than the routing by utilizing the layered model of wireless network and linear optimization. An improvement in the throughput of multicast communication in CRNs is achieved by NC with minimum energy-per-bit [68]. Furthermore, the authors in [69] propose a multi-hop multicast protocol, which utilizes NC in the wireless transmission. The authors in [70] consider a primary network utilizing NC to shape the spectrum usage and to increase the predictability of the spectrum availabilities by CRs. On the other hand, it presents a disadvantage since CRN becomes more prone to jamming attacks due to the spectrum shaping effect of NC in the primary network, which is investigated in [71]. Furthermore, a novel jamming-evasive neighbor discovery algorithm which uses network coding for the dissemination of neighbor information is proposed in [72]. On the other hand, Adapcode [73] is proposed for code dissemination by utilizing NC. It changes the number of packets to be combined, i.e., coding window size, according to the link quality without considering spectrum-awareness. There is a growing number of studies which employ NC technique in CRNs. However, the effects of NC on multicast throughput and interference to PU have not yet been investigated in terms of coding window size.

In this chapter, we investigate multicast communication in a clustered setting for

CRAHNS. A CR cluster-head (CR CH) sends its file to some of its members with NC via single hop in a multicast session. We investigate the effects of coding window size in this system setting on multicast throughput and upper bound on average interference time caused by multicast communication. As coding scheme increases, the transmitted packets are sent more reliably due to less packet size. However, multicast session completion time increases due to increasing packet overhead and the need for more packets to be collected at the CH members. Hence, we first formulate the successful packet transmission probability between the CH and its member, and find expected number of transmissions to send the file to all members. According to the coding window size, which is the number of packets to divide the file, we find the multicast throughput and upper bound average interference duration to the PU during this multicast session.

## 6.2 System Model

System model consists of a PU, a CR CH and its members. The CR CH has a file of length  $L$  bits to transmit to a subset of its members, whose cardinality is  $N$ . The PU is owner of the licensed spectrum band, CR CH utilizes it in an opportunistic manner. The use of the spectrum is achieved by the cognitive cycle operations of SUs [33, 9].

We study multicast communication in a cluster setting in CRAHN. To enable NC, the CR CH divides the file into  $K$  packets, each of which is  $M = L/K$  bits. It sends the linear combination of these packets, where the coefficient are drawn from a Galois Field with size of  $2^s$ . Fig. 6.1 illustrates the network model with frame structure to be utilized within the cluster.

The frame for CRs consists of two mini slots. The first mini-slot is for the spectrum sensing, and its duration is denoted by  $T_S$ . The energy detection is used to detect the presence of PUs. The second mini-slot is for the transmission of packet, and its duration is denoted by  $T_P$  depending on the packet size,  $M$ . The communication channel has constant bit rate  $R$  bps. Hence,  $T_P = \frac{M + K \log_2(2^s)}{R}$ , where  $K \log_2(2^s)$  is the

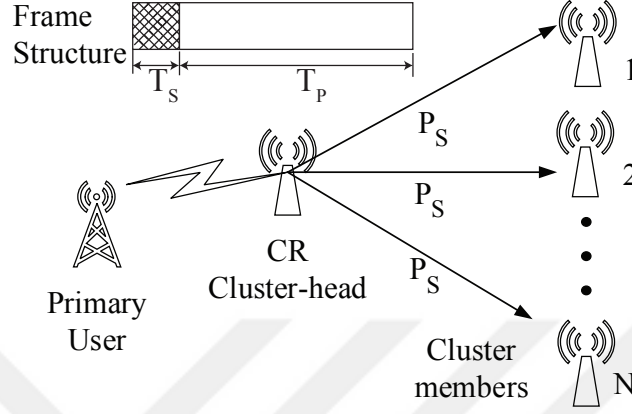


Figure 6.1: Network model.

coding overhead to denote each coefficient for native, i.e., uncoded, packets.

The PU activity can be modeled as a two-state birth-death process [16]. ON and OFF periods of the licensed channel are distributed according to an exponential distribution. The idle period of the channel is represented as a random variable  $T_I$  whose mean is  $\alpha$ , and the busy period of the channel is represented as a random variable  $T_B$  whose mean is  $\beta$ . According to these exponential random variables, the ON and OFF probabilities of the PU are  $P_{ON} = \frac{\beta}{\alpha+\beta}$ , and  $P_{OFF} = \frac{\alpha}{\alpha+\beta}$ , respectively.

### 6.3 Opportunistic Spectrum Access in the Cluster

The successful transmission of the CR CH depends on the channel conditions, PU activity, and the performance of the spectrum detection of the CR transmitter. Furthermore, the unsuccessful transmission may cause interference to the PUs.

The coexistence of CRs with the PU reveals spectrum opportunities, which increases the utilization of the licensed spectrum bands. Hence, CRs periodically sense the spectrum. The activities of the PU and the CR CH cause different cases in accessing the spectrum by the CR CH. These activities cause 6 different scenarios upon the channel access which are given in Fig. 6.2. Each case is explained as follows.

**Case 1:** This case represents the PU detection. The probability of the PU signal

| Cases | Frame | Explanation               |                                       |
|-------|-------|---------------------------|---------------------------------------|
| C1    |       | Detection of PU           | Error Probability<br>$\bar{P}_s$      |
| C2    |       | Misdetection of PU        |                                       |
| C3    |       | False Alarm               |                                       |
| C4    |       | Collision with PUs        |                                       |
| C5    |       | Unsuccessful Transmission |                                       |
| C6    |       | Successful Transmission   | Success Probability<br>$P_s = P_{C6}$ |

Figure 6.2: Spectrum access cases of the CR CH in dynamic radio environment.

detection can be written as [16, 17]

$$P_{C1} = P_d = P_{ON} \mathcal{Q}\left(\frac{\delta - 2T_S B(\sigma_s^2 + \sigma_n^2)}{\sqrt{4T_S B(\sigma_s^4 + \sigma_n^4)}}\right), \quad (6.1)$$

where  $P_d$  is the PU signal detection probability,  $\mathcal{Q}(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-t^2/2} dt$  is Q-function,  $\delta$  is detection threshold,  $B$  is the bandwidth of the licensed spectrum band,  $\sigma_s^2$  is the variance of PU signal, and  $\sigma_n^2$  is the variance of Gaussian noise. In this case, the CR CH does not transmit its packet, hence, the mini-slot reserved for the transmission is shown with white background color in the frame of Case 1 in Fig. 6.2.

**Case 2:** It represents the mis-detection of the PU existence. The PU signal actually exists in Case 1 and Case 2, hence, the probability of Case 2 can be defined as  $P_{C2} = P_{ON} - P_{C1}$  since the ON probability is the probability of the union of the Case 1 and Case 2. The SU attempts to transmit its packet which is shown gray background, however, it collides with the PU.

**Case 3:** It represents the false alarm. The CR CH assumes that PU signal

exists even it does not actually present. The SU does not transmit its packet. The probability of Case 3 can be written as [16]

$$P_{C3} = P_{fa} = P_{OFF} \mathcal{Q}\left(\frac{\delta - 2T_S B \sigma_n^2}{\sqrt{4T_S B \sigma_n^4}}\right), \quad (6.2)$$

where  $P_{fa}$  is the false alarm probability.

**Case 4:** It represents the case that the PU collides with the CR CH. Although the PU does not exist during the sensing interval and the SU perfectly detects the non-presence of PU, PU signal appears during the transmission of CR CH packet. The collision with PU can be defined as the probability that the channel is idle for a time duration less than  $T_P$  which is  $Pr[T_I < T_P] = 1 - \exp(-\frac{T_P}{\alpha})$ . Hence,

$$P_{C4} = (P_{OFF} - P_{C3})(1 - \exp(-\frac{T_P}{\alpha})). \quad (6.3)$$

**Case 5:** It represents unsuccessful transmission of the CR CH packet due to the error in the channel. Packet error probability is denoted by  $P_e = 1 - (1 - BER)^M$ , where  $BER$  is the bit error rate. The cross sign in Case 5 in Fig. 6.2 represents the packet error during the transmission of the packet. Hence,  $P_{C5} = (P_{OFF} - P_{C3} - P_{C4})P_e$ .

**Case 6:** It represents the case that the CR CH packet is successfully transmitted. The probability of successful transmission is written as

$$P_{C6} = (P_{OFF} - P_{C3} - P_{C4} - P_{C5})(1 - P_e). \quad (6.4)$$

According to these cases, the successful transmission only occurs in Case 6, whose probability is  $P_S = P_{C6}$ .

## 6.4 Network-Coded Communication in the Cluster

Opportunistic use of the licensed spectrum band by CR CH in the cluster increases the channel utilization by decreasing the file completion time. Hence, it decreases

the possible interference to the PU. To that end, we investigate the effect of NC on multicast session completion time and average interference duration during multicast session.

#### 6.4.1 Multicast Session Completion Time

In the multicast session, a CH divides a file with  $L$  bits into  $K$  native packets. The CH transmits this file to  $N$  receivers, which are the cluster members. The channel can be regarded as a Bernoulli channel with success probability governed by PU activities,  $BER$ , communication duration  $T_P$  and sensing duration  $T_S$ . The same channel conditions are assumed for all the multicast channels.

We apply linear network coding such that the transmitted packet is the linear combination of the native packets, and the coefficients are randomly drawn from the Galois field,  $2^s$ . As the file is incomplete at the multicast receivers, the CH continues to transmit random linear combinations of the native packets.

The completion time when RLNC is utilized is given as  $C_{RBC}(N, K) = \max_{i \in 1, \dots, N} A_{i,RBC}$ , where  $A_{i,RBC}$  is the random variable capturing number of transmissions for member CR  $i$  having the complete file. Average number of transmissions for the file completion by all the receivers is given as [74]

$$E_{tx} = K + \sum_{i=K}^{\infty} \left( 1 - \left( \sum_{j=K}^i \binom{j-1}{K-1} (1 - P_S)^{j-K} P_S^K \right)^N \right). \quad (6.5)$$

#### 6.4.2 Average Interference Duration in Multicast Session

The imperfections on the spectrum sensing and no extra radio for the sensing lead to the interference to the primary network. The CR CH in the multicast session causes interference if CH communication is in Case 2 and Case 4 as it collides with the PU during its transmission period,  $T_P$ . We follow the method used in [16] to find the expected duration of interference.

The misdetection in Case 2 leads to full or partial interference during the CH packet transmission. PU may be busy during the entire interval of packet trans-

mission. The probability of channel being busy during the entire interval is the probability that the channel busy interval is between  $T_P$  and infinity. It is calculated as  $Pr[T_B > T_P] = \int_{T_P}^{\infty} \frac{1}{\beta} \exp(-\frac{t}{\beta}) dt = \exp(-\frac{T_P}{\beta})$ . Hence, the average interference interval in this case is  $\exp(-\frac{T_P}{\beta})T_P$ . Furthermore, the intermittent PU activity in the transmission duration may cause collision. The probability of this situation is  $1 - \exp(-\frac{T_P}{\beta})$  and the duration of the interval is  $P_{ON}T_P$ . Hence, the interference time duration when PU activity is intermittent during packet transmission is  $(1 - \exp(-\frac{T_P}{\beta}))P_{ON}T_P$ . The overall expected interference time duration in Case 2 is defined as  $T_{C2,int} = \exp(-\frac{T_P}{\beta})T_P + (1 - \exp(-\frac{T_P}{\beta}))P_{ON}T_P$ .

The CR CH in Case 4 encounters PU activity during its transmission. If the idle time is greater than the duration of  $T_P$ , there would be no interference. However, if there is an intermittent PU activity during the transmission of the packet, there would be interference whose mean duration is  $P_{ON}T_P$ . The probability that idle interval of the channel is smaller than  $T_P$  is  $Pr[T_I < T_P] = \int_0^{T_P} \frac{1}{\alpha} \exp(-\frac{t}{\alpha}) dt = 1 - \exp(-\frac{T_P}{\alpha})$ . The overall expected interference time duration in Case 4 is defined as  $T_{C4,int} = (1 - \exp(-\frac{T_P}{\alpha}))P_{ON}T_P$ .

For a multicast session, the CR CH sends its packets to the subset of its members until they are received correctly. In each communication slot, average interference posed by the CR CH is  $T_{int} = \left( P_{C2}T_{C2,int} + P_{C4}T_{C4,int} \right)$ , due to the collision with the PU in Case 2 and Case 4.

The overall expected interference time in CR CH multicast depends on  $E_{tx}$ , which is the number of transmissions to successfully complete the multicast session. Upper bound on the average interference during a multicast session can be defined as

$$T_{mint} = (E_{tx} - K)T_{int}, \quad (6.6)$$

where  $E_{tx} - K$  represents the maximum number of transmissions that may cause interference during the multicast session. It can be used as a performance metric to determine the coding scheme in multicast session.

### 6.4.3 Multicast Throughput

Multicast throughput is total number of bits per second in a session. The total transmission is  $NL$  bits due to  $N$  receivers. Total time spent for the session is given as  $E_{tx}(T_P + T_S)$ . Hence, multicast throughput is given as

$$\theta = \frac{NL}{E_{tx}(T_P + T_S)} \quad (6.7)$$

## 6.5 Numerical Evaluation

In this section, we study the multicast throughput,  $\theta$ , and upper bound on average interference duration,  $T_{mint}$ , with respect to coding window size,  $K$ , in terms of different network parameters. Unless otherwise stated, we set the system parameters as  $B = 10^4$  Hz,  $N = 5$ ,  $s = 4$ ,  $R = 10^4$  bps,  $L = 5 \times 10^4$  bits,  $\alpha = 160 \times 10^{-3}$  sec,  $\beta = 50 \times 10^{-3}$  sec,  $BER = 10^{-5}$ ,  $\delta = 0.3$ ,  $\sigma_n^2 = 1$  and  $\sigma_s^2 = 10$ .

We first investigate the effect of  $L$  on  $\theta$  and  $T_{mint}$  for different  $K$  values. Fig. 6.3(a) shows that  $\theta$  is maximized for some  $K$  values and different  $L$  settings. The corresponding  $P_S$  for these  $K$  values is the maximum achievable values. As  $K$  increases, the packet overhead increases, however, packet length decreases, which means less PU collisions and packet errors. Hence, there is an optimal  $K$  values to achieve maximum  $\theta$ . Optimal  $K$  values,  $K^*$ , are marked with star in figures.  $K^* = 5$  and  $K^* = 58$  for  $L = 1$  Kbits and  $L = 50$  Kbits.  $L$  highly affects  $K$  as it directly changes  $M$  with  $P_S$  and hence  $E_{tx}$ . Fig. 6.3(b) shows upper bound on the average interference duration to the PU in logarithmic scale. As  $L$  increases,  $T_{mint}$  increases due to the higher  $E_{tx}$  and  $T_P$ . At some  $K$  values, minimum  $T_{mint}$  is achieved by minimizing  $E_{tx}$  and maximizing  $P_S$ . When  $L = 1$  Kbits,  $T_{mint} = 11.2$  msec for  $K = 7$ .

Fig. 6.3(c) shows the effect of  $R$  change in  $\theta$ . Higher  $R$  achieves better  $\theta$ . An increase in  $R$  results in less time spent on packet transmission. The increase in  $K$  also deteriorates packet length due to overhead. Maximum  $\theta$  is achieved when  $K = 11$  and  $K = 24$  for  $R = 20$  Kbps and  $R = 1$  Kbps, respectively. As we investigate the interference duration, higher bit rates provides less interference due to

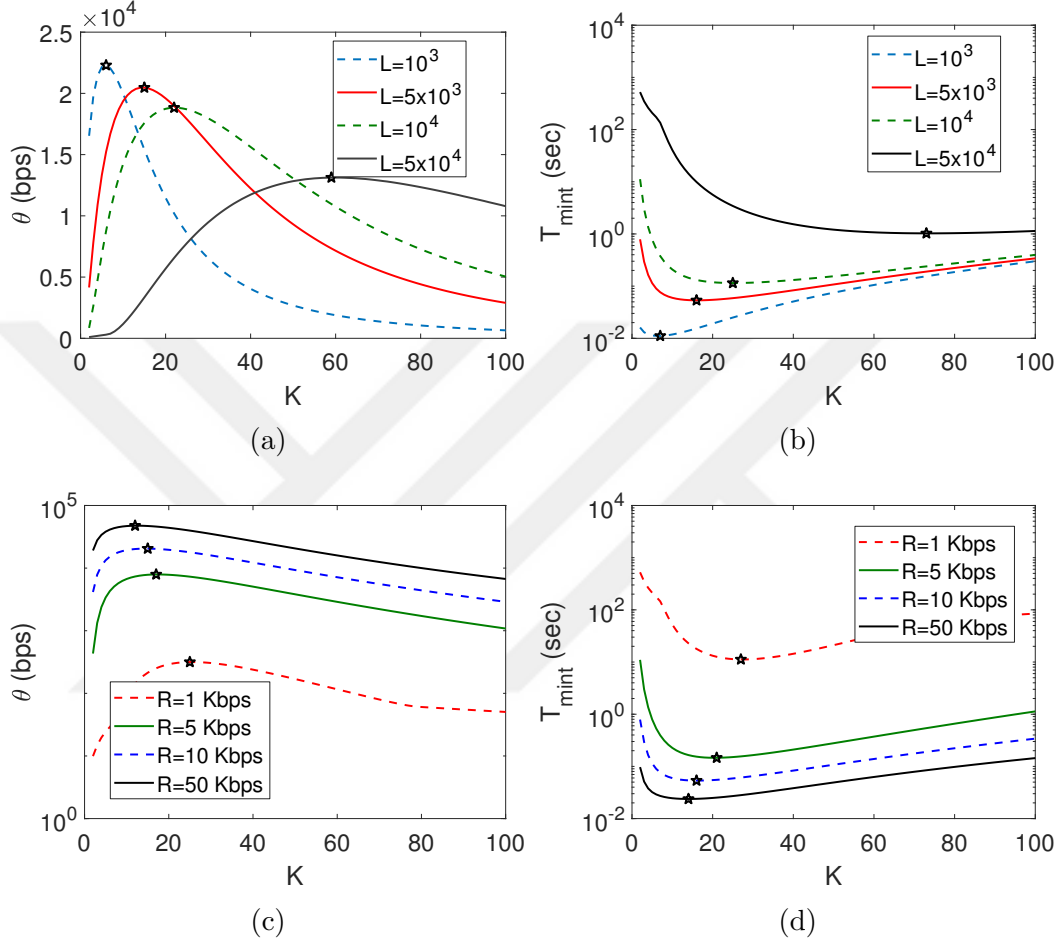


Figure 6.3: Effect of  $L$  on (a)  $\theta$ , (b)  $T_{mint}$ , and effect of  $R$  on (c)  $\theta$ , (d)  $T_{mint}$ .

less transmission time as seen in Fig. 6.3. For  $R = 1$  Kbps,  $T_{mint}$  decreases until 11.2 sec. As seen in Fig. 6.3, sweeping  $K$  results in trade-off between packet overhead and  $E_{tx}(T_P + T_S)$ .

Field size is another metric affecting throughput as larger  $K$  values deteriorates  $\theta$  due to packet overhead as in Fig. 6.4(a). Increase in  $s$  causes decrease in  $K$  achieving maximum  $\theta$ . We also investigate effect of  $N$  on  $K_\theta^*$  and  $K_{int}^*$ .  $N$  dependence on  $E_{tx}$  can be seen in Eq. (6.5). Fig. 6.4b(b) shows that  $N$  has little dependency on  $K^*$  due to limited effect of it in Eqs. (6.5), (6.6), and (6.7).

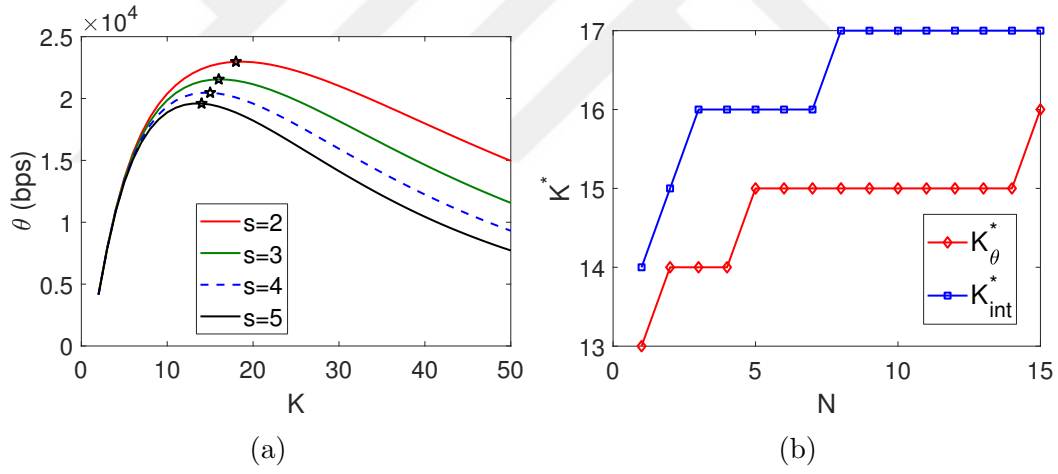


Figure 6.4: (a)  $\theta$  vs.  $K$  for different field size, (b) Optimal  $K$  values for different  $N$  considering  $\theta$  and  $T_{\text{mint}}$ .

## Chapter 7

# MAXIMUM COVERAGE AREA OF COGNITIVE WIRELESS NETWORKED CONTROL SYSTEMS WITH MAXIMUM COST-EFFICIENCY UNDER CONVERGENCE CONSTRAINT

### 7.1 Introduction

Merging communication and control systems has revealed a paradigm called networked control systems (NCSs). Systems can be observed by the sensors and communications system delivers the observations by the system [75, 76]. If the communication system operates in wireless fashion, the system becomes wireless networked control systems (WNCSs), which can be utilized in smart grid [77].

The most important design considerations of WNCSs are maximum coverage area and the convergence of the WNCS estimator. Hence, in this chapter, maximum coverage area of the wireless network is achieved under the convergence constraint of WNCS estimator. In our system, the nodes in the network are with cognitive radio capability. An optimization problem is set to find maximum coverage area under convergence constraint and the spectrum-aware communications. Same methodology as in [78] is followed in the chapter.

The contribution of the chapter is to find maximum coverage area under convergence constraint in dynamic radio environment. The solution is also cost-efficient such that the maximum coverage is achieved with minimum number of deployed wireless nodes. Most related work which are [79, 80, 81], do not consider the convergence issue.

In our network setup, we have wireless sensor nodes with cognitive radio capability

with a multi-hop architecture. Hence, this type of network can be named as CRSN [20]. The measurements by the sensor nodes are conveyed in multi-hop manner by accessing to the licensed spectrum opportunistically. However, these packets may not be received by the WNCS estimator, which degrades the convergence of the estimator. The packet arrival probability to the estimator depends on unreliable wireless channel and dynamic radio environment.

The estimator in the system is designed to be a Kalman Filter [82, 83]. For a normal operation, the Kalman Filter has all the observation data to estimate the system state. However, this is not possible for practical systems since the observations may be intermittent. [82] firstly investigate the Kalman filter with intermittent observations, however, the statistical convergence of the filter is not studied. In [83], the authors investigate the state estimation process, in which the sensor measurements are received or lost completely in a stochastic manner, and they show that if the probability of arrival of an observation is above a threshold, the expectation of the state estimation error covariance is bounded. In [18], the authors consider two sensors, and the measurement of each sensor is independently received or lost by the Kalman filter. Furthermore, in [84], the  $H_\infty$  filtering problem is studied for a class of discrete-time networked nonlinear systems with random delays and packet losses; and in [85], the distributed fuzzy filters are designed so that the filtering error dynamic system to be mean-square stable in spite of time-varying delays and multiple probabilistic packet losses. However, none of these works address the maximum coverage area problem of a WNCS network under the convergence constraint.

We consider the general case of the system presented in [18]. The observation process is divided into  $N$  parts and each part is independently and randomly received or lost by the Kalman filter. Thus, we consider  $N$  separate multi-hop wireless ad-hoc subnetworks for our scenario and each subnetwork includes one sensor node. Based on the derivations presented in [18], we derive the critical arrival probability for the measurement of each sensor such that if the arrival probability of a sensor measurement is larger than the critical value, it is guaranteed that the estimator of

the WNCS is convergent so that the WNCS is stable. In this chapter, we refer the stability of the WNCS as the convergence of the WNCS estimator. Then, we show that there exists a critical hop-diameter of a subnetwork such that if the hop-diameter of the subnetwork is less than the critical hop-diameter, the WNCS is stable where the maximum hop number of the shortest paths between any two node pairs in the network is the hop-diameter. Furthermore, based on the solution of an optimization problem, we find both the optimum hop-diameter and the maximum coverage area of the multi-hop wireless ad-hoc network with maximum cost-efficiency under the constraint of the convergence of the WNCS estimator.

## 7.2 Observation Losses on Kalman Filtering

Kalman filter have the sensor observations from wireless network in the system to estimate the system state. Due to the wireless channel conditions and congestion, these observations may not be received by the Kalman filter. [18] divides the observation process into two parts where two sensors feed the Kalman filter with different wireless channel characteristics. Hence, the estimation process depends on partial observation losses. This chapter generalizes this system into  $N$ . At each part, we have subnetworks, they feed the Kalman filter with partial observation losses.

The system can be regarded as a general multiple-input multiple-output (MIMO) discrete time linear time-invariant system. It is described by the following system equations

$$\begin{aligned} \mathbf{x}_{t+1} &= A\mathbf{x}_t + \mathbf{w}_t, \\ \begin{bmatrix} \mathbf{y}_{1,t} \\ \vdots \\ \mathbf{y}_{N,t} \end{bmatrix} &= \begin{bmatrix} C_1 \\ \vdots \\ C_N \end{bmatrix} \mathbf{x}_t + \begin{bmatrix} \mathbf{v}_{1,t} \\ \vdots \\ \mathbf{v}_{N,t} \end{bmatrix} \end{aligned} \quad (7.1)$$

where  $\mathbf{x}_t \in \mathcal{R}^n$  is the system state vector,  $\mathbf{w}_t \in \mathcal{R}^n$  is the system disturbance vector,  $A \in \mathcal{R}^{n \times n}$  is the system matrix,  $\mathbf{y}_{i,t} \in \mathcal{R}^{m_i}$ , is sensor measurement output vector,

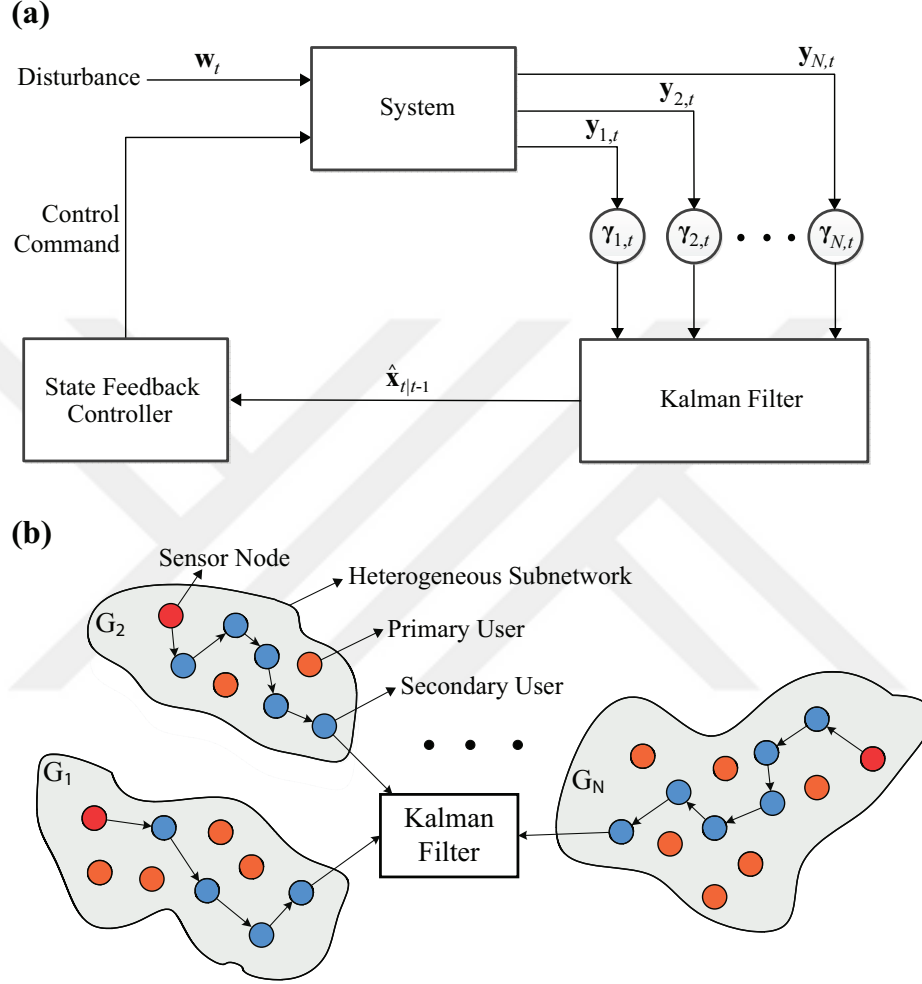


Figure 7.1: (a) The block diagram of the WNCS. (b) The model of the heterogeneous multi-hop wireless ad-hoc subnetworks.

$\mathbf{v}_{i,t} \in \mathcal{R}^{m_i}$  is the measurement noise vector, and  $C_i \in \mathcal{R}^{m_i \times n}$  is the output matrix for  $i = 1, 2, \dots, N$  and the subscript  $t$  indicates the time index. Also note that the bold-face symbols in this chapter represent vectors. We define  $\mathbf{y}_t = [\mathbf{y}_{1,t}, \mathbf{y}_{2,t}, \dots, \mathbf{y}_{N,t}]^T$ ,  $\mathbf{v}_t = [\mathbf{v}_{1,t}, \mathbf{v}_{2,t}, \dots, \mathbf{v}_{N,t}]^T$ , and  $C = [C_1, C_2, \dots, C_N]^T$ . Both  $\mathbf{w}_t$  and  $\mathbf{v}_t$  are assumed to be Gaussian random vectors with zero mean and their covariance matrices are  $Q \geq 0$  and  $R > 0$ , respectively.  $R$  is a  $N \times N$  matrix having elements as  $R_{ij} = E[\mathbf{v}_{i,t} \mathbf{v}_{j,t}']$ . Furthermore, we assume that the system  $(A, C)$  is observable; hence, the Kalman filter converges without sensor measurement losses.

The sensor measurement packets  $\mathbf{y}_{1,t}, \mathbf{y}_{2,t}, \dots, \mathbf{y}_{N,t}$  are encoded independently and

transmitted over different multi-hop wireless ad-hoc subnetworks. We use random variable  $\gamma_{i,t}$  which indicates whether the measurement packet of  $i^{\text{th}}$  sensor,  $\mathbf{y}_{i,t}$ , is correctly received during a given sample period. We assume  $\gamma_{i,t}$  for  $i = 1, 2, \dots, N$  are independent Bernoulli random variables with  $\Pr\{\gamma_{i,t} = 1\} = \lambda_i$  and  $\Pr\{\gamma_{i,t} = 0\} = 1 - \lambda_i$ . That is, if  $\gamma_{i,t} = 1$ , then the measurement packet  $\mathbf{y}_{i,t}$  is correctly received; otherwise, the packet is lost during the wireless data transmission.  $\lambda_i$  depends on the channel gains, the network resource allocation, the network traffic, and the number of hops taken by a packet to reach the Kalman filter. In this chapter, we are only interested in the successful transmission probability of a packet between two nodes and we do not consider the effects of modulation, decoding and encoding processes of the information on the successful transmission probability of a packet.

The block diagram of the WNCS is shown in Fig. 7.1(a). Note that the observation process is stochastic due to the random measurement losses during the packet transmission process. Furthermore, since we assume that  $\gamma_{i,t}$  and  $\gamma_{j,t'}$  for  $i \neq j$  are independent for every  $t$  and  $t'$ , the sensor measurement packets  $\mathbf{y}_{i,t}$  for  $i = 1, 2, \dots, N$  can be independently lost or received. Therefore, the loss of a measurement packet is equivalent to the reception of a measurement having an infinite noise variance. Then, for the measurement noise vectors  $\mathbf{v}_{i,t}$ , we define the following conditional probability distribution function  $f_{\mathbf{v}|\gamma}(\mathbf{v}_{i,t}|\gamma_{i,t}) \sim \mathcal{N}(0, R_{ii})$  if  $\gamma_{i,t} = 1$  and  $f_{\mathbf{v}|\gamma}(\mathbf{v}_{i,t}|\gamma_{i,t}) \sim \mathcal{N}(0, \sigma_i^2 I)$  if  $\gamma_{i,t} = 0$ . Then, we take the limit as  $\sigma_i^2 \rightarrow \infty$  to derive the Kalman equations for random partial losses.

In [83], the authors investigate the state estimation process, in which the sensor measurement packet is received or lost completely, and they show the existence of a critical packet arrival probability  $\lambda^c$  such that  $E[P_{t+1|t}]$  is bounded if  $\lambda > \lambda^c$  and  $E[P_{t+1|t}]$  becomes infinite as  $t \rightarrow \infty$  if  $\lambda < \lambda^c$ . For the general case, based on the derivations and results given in [18], if  $(A, Q)$  is controllable and  $(A, C)$  is observable, for a fixed set of  $(\lambda_1, \lambda_2, \dots, \lambda_{i-1}, \lambda_{i+1}, \dots, \lambda_N)$ , if  $\lambda_i \geq \lambda_i^c$ , the state estimation error covariance is bounded and estimator converges so that the WNCS is stable. If the output matrices  $C_1, C_2, \dots, C_N$  are square and invertible  $A$  has a single unstable

eigenvalue, the upper and lower bounds for  $\lim_{t \rightarrow \infty} E[P_{t+1}|t]$  coincide and the critical packet arrival probability of the measurement packet of the  $i^{\text{th}}$  sensor becomes

$$\lambda_i^c = \max \left\{ 0, 1 - \frac{1}{\alpha^2(1 - \lambda_1) \dots (1 - \lambda_{i-1})(1 - \lambda_{i+1}) \dots (1 - \lambda_N)} \right\} \quad (7.2)$$

where  $\alpha = \max_i |\sigma_i|$  and  $\sigma_i$  is the  $i^{\text{th}}$  eigenvalue of  $A$  [18]. We discuss the appropriate selection of the set of  $(\lambda_1, \lambda_2, \dots, \lambda_N)$  in Section 7.4 for a cost-efficient WNCS with the maximum coverage area under convergence constraint.

### 7.3 Cognitive Radio Networking in WNCSs

Each subnetwork has an ad hoc multi-hop architecture with dynamic spectrum access capability. Due to multi-hop property, large areas can be covered in each subnetworks. Deployment of these type of networks is easy and fast [86]. There is one problem that caused by the wireless channels and multi-hopping. As the hop number to reach the estimator, the packet arrival probability decreases.

In each subnetwork, the wireless ad hoc network with cognitive radio capability is called secondary network. Licensed user network is called the primary network. These networks coexist. The sensor observations are transmitted to the Kalman filter by utilizing the licensed channels in multi-hop manner.

We assume that the PUs (SUs) are distributed according to two dimensional homogeneous Poisson point process having a density  $\rho_p$  ( $\rho_s$ ). We consider that the transmission ranges of all primary (secondary) network nodes are the same and denoted by  $r_p$  ( $r_s$ ). The connectivity of cognitive radio networks is more troublesome than the connectivity of homogeneous networks. That is, the secondary cognitive radio network is connected if each node pair  $SU_i$  and  $SU_j$  in the cognitive radio network satisfies the following conditions: 1) The distance between  $SU_i$  and  $SU_j$ ,  $r$ , satisfies  $r \leq r_s$  condition. 2) Both  $SU_i$  and  $SU_j$  are outside the transmission range  $r_p$  of every active sender in the primary network. 3) There is no active primary network receiver in the transmission range  $r_s$  of  $SU_i$  and  $SU_j$ . In Fig. 7.1(b), the cognitive radio ad-hoc

network model used in this chapter is shown where  $G_i$  denotes the  $i^{\text{th}}$  cognitive radio subnetwork including the  $i^{\text{th}}$  sensor node.

The secondary network is always connected under time-varying spectrum availability if the node density of the network is greater than a critical node density  $\rho_s^*$  [86]. This bound can be defined as

$$\rho_s^* = \frac{5}{r_s^2} \ln \left[ 1 - \sqrt{(1 - (\sqrt{6}/3)^\Lambda) e^{(|R_e| + |R'_e|)\Pi_1 \rho_p}} \right]^{-1} \quad (7.3)$$

where  $\Lambda = (4Ld+2d+1) \times (4Ld+d) + (4Ld+d+1) \times (4Ld+2d) - 1$ ,  $|R_e| = (2 + 2\lceil r_p/d \rceil) \times (1 + 2\lceil r_p/d \rceil) \times d^2$ ,  $|R'_e| = (2 + 2\lceil r_s/d \rceil) \times (1 + 2\lceil r_s/d \rceil) \times d^2$ ,  $L = \lceil \max\{r_p, r_s\}/d \rceil$ ,  $d = r_s/\sqrt{5}$ . We assume that each PU sender is associated with an independent and identically distributed (i.i.d.) alternating renewal process<sup>1</sup>, denoted by  $S_p(t)$ , which alternates between two states: the ON state, during which the licensed channel is used by the PU, i.e., the PU is active; and the OFF state, during which the licensed channel is not used by the PU, i.e., the PU is inactive.  $\Pi_1$  in (7.3) is defined as the probability that the licensed channel is used by a PU, i.e.,  $\Pi_1 = \Pr\{S_p(t) = 1\}$ .

#### 7.4 Maximum Coverage Area Analysis

An increase in the number of nodes in the network results in more coverage. On the other hand, this may result in increase in the number of hops to reach the Kalman Filter, which leads to the decrease in the probability of the packet arrival. The estimator of the WNCS might diverge and WNCS become unstable. Thus, for a stable WNCS, the hop-diameter of the network, denoted by  $d_i$ , becomes a critical parameter.

The successful packet transmission probability between two neighboring nodes is assumed to be constant and the same for each transmission process in the network and it is denoted by  $\beta$ . Therefore, the probability that the  $i^{\text{th}}$  sensor measurement

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<sup>1</sup>An alternating renewal process is a two-state process which alternates between an on-state and an off-state after a random sojourn time, where the on-times and the off-times are independent random variables.

is correctly received by the Kalman filter, i.e.,  $\lambda_i$ , can be expressed as  $\lambda_i = \beta^{M_i}$  for  $i = 1, 2, \dots, N$  where  $M_i$  is the number of hops taken by the packet transmitted by the  $i^{\text{th}}$  sensor until it reaches the Kalman filter.  $M_i$  depends on the routing protocol, network topology, and number of nodes. Here, we assume that the routing protocol is smart enough so that it can find a single shortest route from the sensor to the Kalman filter [87].

Let the critical packet arrival probability of the  $i^{\text{th}}$  sensor measurement be  $\lambda_i^c$ . Based on the definition of the hop-diameter of a network, the maximum number of hop taken by a measurement packet until it reaches the Kalman filter is less than or equal to the hop-diameter of the subnetwork. Then, using  $\lambda_i = \beta^{M_i}$ , the critical-hop diameter of  $i^{\text{th}}$  subnetwork is  $d_i^c = \lfloor \ln(\lambda_i^c) / \ln(\beta) \rfloor$ . That is, if the hop-diameter of the subnetwork  $G_i$  satisfies  $d_i \leq d_i^c$  condition, it is guaranteed that the arrival probability of the packet transmitted by  $i^{\text{th}}$  sensor is larger than the critical arrival probability; hence, the estimator of the WNCS converges. However, if  $d_i > d_i^c$ , the convergence of the estimator is not guaranteed. Since the hop-diameter depends on several factors such as topology, network size, node locations, sensor communication range, and node density, it is difficult to find an upper bound for the maximum number of nodes which ensures a given hop-diameter. Therefore, to guarantee the convergence of the estimator, one can use lower bound for the maximum number of nodes in a subnetwork given as  $m_i(\lambda_i^c) = d_i^c + 1$  where  $m_i(\lambda_i^c)$  denotes the number of nodes which guarantees that the packet arrival probability is greater than the critical value and the proof is straightforward.

If we consider only the convergence criterion, for a given set of  $(\lambda_1, \lambda_2, \dots, \lambda_{i-1}, \lambda_{i+1}, \dots, \lambda_N)$ , as  $\lambda_i^c \rightarrow 0$ ,  $m_i(\lambda_i^c) \rightarrow \infty$ , and hence the total coverage area of the  $i^{\text{th}}$  subnetwork becomes infinite. Indeed, it is irrational and cost-inefficient to place infinitely many nodes in a subnetwork including a sensor node whose critical packet arrival probability is 0. That is, a decrease in  $\lambda_i^c$  decreases the importance of the subnetwork  $G_i$ , and when  $\lambda_i^c = 0$ , the measurements of the  $i^{\text{th}}$  sensor in  $G_i$  become unnecessary for the convergence of the WNCS estimator. Thus, the cost-efficiency of the multi-hop

$$\begin{aligned}
 & \underset{\lambda_1, \dots, \lambda_N}{\text{maximize}} \quad f(\lambda_1, \dots, \lambda_N) = \lambda_1 m_1(\lambda_1) + \lambda_2 m_2(\lambda_2) + \dots + \lambda_N m_N(\lambda_N) \\
 & \text{subject to} \quad \lambda_i \geq \max \left\{ 0, 1 - \frac{1}{\alpha^2(1 - \lambda_1) \dots (1 - \lambda_{i-1})(1 - \lambda_{i+1}) \dots (1 - \lambda_N)} \right\} \\
 & \quad \text{for } i = 1, 2, \dots, N
 \end{aligned} \tag{7.4}$$


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wireless network should also be considered because the selection of a set of packet arrival probabilities of the sensor measurements affects the cost-efficiency.

Since when  $\lambda_i \rightarrow 0$ ,  $m_i(\lambda_i^c) \rightarrow \infty$  and  $\lambda_i m_i(\lambda_i) \rightarrow 0$ , we can use  $\lambda_i m_i(\lambda_i)$  as the efficiency of the  $i^{\text{th}}$  subnetwork. Therefore, to find a cost-efficient multi-hop wireless ad-hoc network, we define a cost-efficiency function as follows

$$f(\lambda_1, \dots, \lambda_N) = \lambda_1 m_1(\lambda_1) + \dots + \lambda_N m_N(\lambda_N) \tag{7.5}$$

where  $m_i(\lambda_i)$  is the number of nodes in the subnetwork  $G_i$  which guarantees that the packet arrival probability is bounded below by  $\lambda_i$  and it is given by  $m_i(\lambda_i) = \lceil \ln(\lambda_i) / \ln(\beta) \rceil + 1$ . Note that the cost-efficiency function is the weighted sum of the number of nodes in the subnetworks. Using (7.2), the set of  $(\lambda_1, \lambda_2, \dots, \lambda_N)$  which both maximizes  $f(\lambda_1, \dots, \lambda_N)$  and ensures the convergence of the WNCS estimator can be found by solving the optimization problem in (7.4) at the top of this page. Note that, the convergence condition of a WNCS estimator is  $\lambda_i \geq \lambda_i^c$  for  $i = 1, 2, \dots, N$  where  $\lambda_i^c$  is given in (7.2) as discussed in Section 7.2.

We numerically evaluated the objective function in (7.4) to obtain a pattern for the solution. Since there is a constraint of the maximization problem, the maximum point changes according to the constraint. That is, if the constraint functions for  $\lambda_i$  for  $i = 1, 2, \dots, N$  are small enough, the maximum point is equal to the global maximum of the objective function and the global maximum point is given by  $e^{-\ln(\beta)-1}$ , which is an analytical result. However, if the constraint functions are larger than a certain value, the maximum is found by considering both the objective and constraint functions. For this second case, we found that the maximum value of the objective function in

(7.4) can be approximately given by  $1 - \alpha^{-2/N}$  according to the numerical evaluations of the objective function. Therefore, the solution of (7.4) can be approximated as

$$\lambda_i^{\text{opt}} \approx \max\{e^{-\ln(\beta)-1}, 1 - \alpha^{-2/N}\} \quad (7.6)$$

for  $i = 1, 2, \dots, N$ , where  $(\lambda_1^{\text{opt}}, \lambda_2^{\text{opt}}, \dots, \lambda_N^{\text{opt}})$  denotes the optimum convergent set having the maximum cost-efficiency. Note that, since we used an approximation for the second case of the optimization problem in (7.4), the solution given in (7.6) is an approximate solution obtained using an ad hoc method. The results show that the solution given in (7.6) accurately satisfies the convergence constraint of the WNCS estimator and maximizes the cost-efficiency.

Using the optimum set of packet arrival probabilities given in (7.6), the optimum hop-diameter of the  $i^{\text{th}}$  subnetwork having the maximum cost-efficiency is given by

$$d_i^{\text{opt}} = \left\lfloor \frac{\ln(\max\{e^{-\ln(\beta)-1}, 1 - \alpha^{-2/N}\})}{\ln(\beta)} \right\rfloor. \quad (7.7)$$

Furthermore, to guarantee the convergence of the WNCS estimator, we use the lower bound for the maximum number of nodes in  $G_i$ , denoted by  $m_i(\lambda_i^{\text{opt}})$ , and it is

$$m_i(\lambda_i^{\text{opt}}) = \left\lfloor \frac{\ln(\max\{e^{-\ln(\beta)-1}, 1 - \alpha^{-2/N}\})}{\ln(\beta)} \right\rfloor + 1 \quad (7.8)$$

for  $i = 1, 2, \dots, N$ . Based on the number of nodes in each subnetwork having maximum cost-efficiency under the convergence constraint, we can derive the maximum coverage of the WNCS. Note also that, (7.6), (7.7), and (7.8) are independent of  $i$  which is an expected result because we consider each subnetwork identical. In our future work, we aim to consider subnetworks having different parameters to make the scenario more realistic.

To find the coverage area of the subnetworks for the number of nodes given in (7.8), we consider the connectivity of the subnetworks. Thus, to have the maximum coverage area for a given number of nodes, we assume that the node density of the het-

erogeneous multi-hop wireless ad-hoc network is the same as the critical node density  $\rho_s^*$  in (7.3). Then, for a stable WNCS, the maximum coverage area of the subnetwork  $G_i$ , which has the maximum cost-efficiency, is given by  $S_i^{ht} = m_i(\lambda_i^{\text{opt}})/\rho_s^*$ . Since the number of nodes found in (7.8) is the same for each subnetwork, the maximum total coverage area of the heterogeneous subnetworks is given by

$$S_T^{ht} = \frac{Nm_i(\lambda_i^{\text{opt}})r_s^2}{5 \ln \left[ 1 - \sqrt{(1 - (\sqrt{6}/3)^\Lambda) e^{(|R_e| + |R'_e|)\Pi_1 \rho_p}} \right]^{-1}}. \quad (7.9)$$

## 7.5 Numerical Analysis

In this section, we present the numerical analyses of both the optimum hop-diameter  $d_i^{\text{opt}}$  and the maximum total coverage area  $S_T^{ht}$  of the heterogeneous subnetworks with respect to several system and network parameters. We assume that the observation model matrices  $C_1, C_2, \dots, C_N$  are square and invertible [83, 18]. Note that, the observation model matrices map the true state space into the observed space and in general, their dimensions are  $m_i \times n$  for  $i = 1, 2, \dots, N$ . If  $C_i$  is a square matrix, the true state space and the observed space have the same dimensions, which is a quite reasonable assumption. The numerical evaluations are conducted using MATLAB.

### 7.5.1 Optimum Hop-Diameter of Subnetworks

We study the relationship between the optimum hop-diameter of subnetworks,  $d_i^{\text{opt}}$ , and the number of sensor nodes,  $N$ , by changing the successful packet transmission probability between two nodes,  $\beta$ . Furthermore,  $d_i^{\text{opt}}$  is investigated with respect to the eigenvalue of  $A$  having the maximum magnitude,  $\alpha$  for different  $N$  values.

$d_i^{\text{opt}}$  with respect to the number of sensor nodes  $N$  for different  $\beta$  values is studied in Fig. 7.2(a). There is a threshold where  $\max\{e^{-\ln(\beta)-1}, 1 - \alpha^{-2/N}\} = e^{-\ln(\beta)-1}$  for  $N > -2 \ln(\alpha) / \ln(1 - e^{-\ln(\beta)-1})$  and  $\max\{e^{-\ln(\beta)-1}, 1 - \alpha^{-2/N}\} = 1 - \alpha^{-2/N}$  for  $N < -2 \ln(\alpha) / \ln(1 - e^{-\ln(\beta)-1})$ . For small  $N$  values, there is an increase in  $d_i^{\text{opt}}$ . After this threshold,  $d_i^{\text{opt}}$  becomes constant. As  $\beta$  increases, more hops to the Kalman filter can

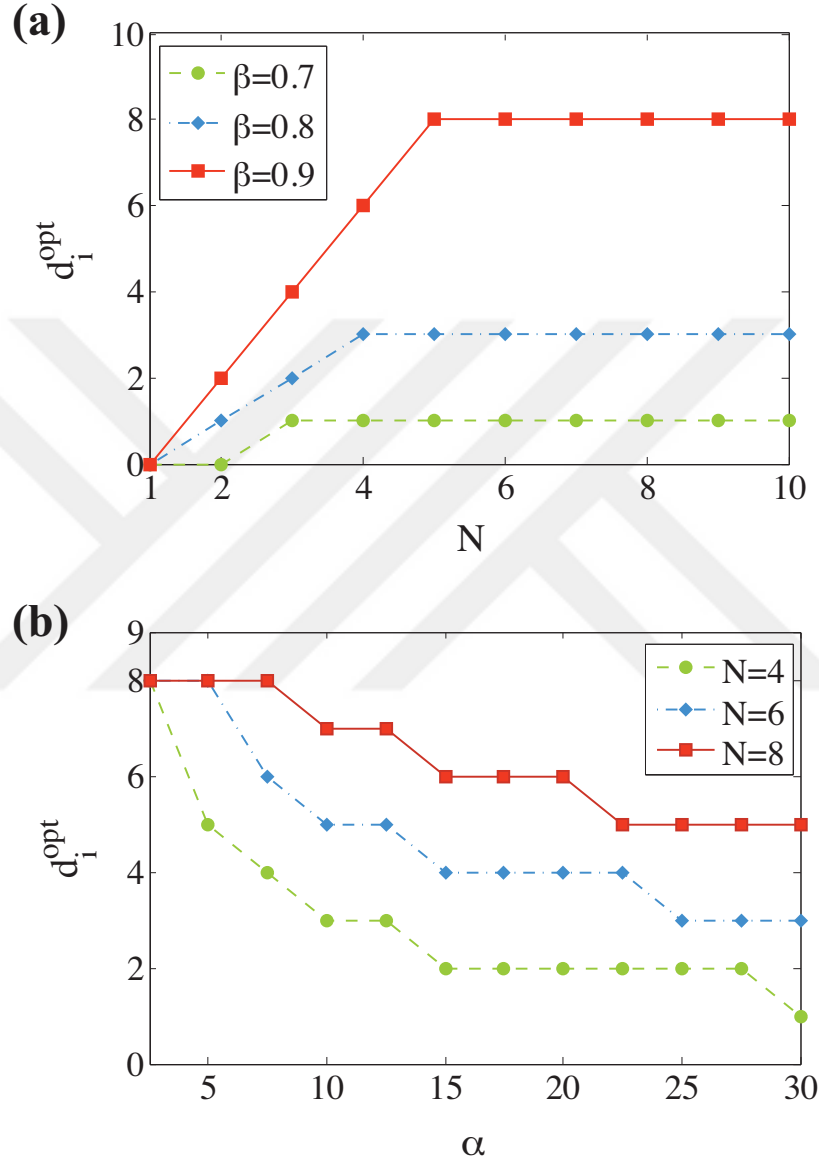


Figure 7.2:  $d_i^{\text{opt}}$  wrt (a)  $N$  for different  $\beta$  values and (b)  $\alpha$  for different  $N$  values.

be tolerated since packet arrival probability would be higher than the critical packet arrival probability. Furthermore, according to the above discussion as  $\alpha$  increases, we observe decrease in  $d_i^{\text{opt}}$ .

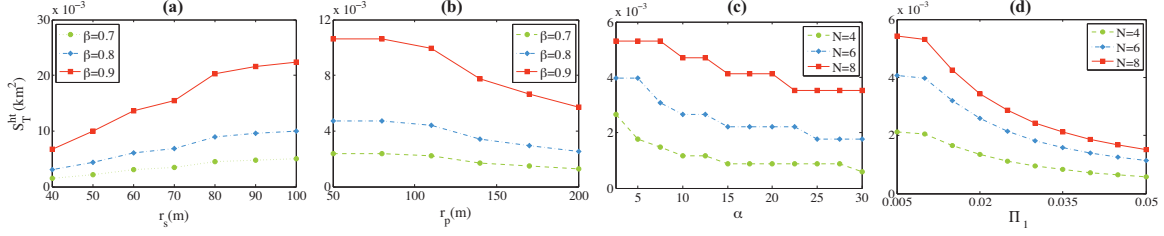


Figure 7.3:  $S_T^{ht}$  with respect to (a)  $r_s$  for different  $\beta$  values, (b)  $r_p$  for different  $\beta$  values, (c)  $\alpha$  for different  $N$  values, and (d)  $\Pi_1$  for different  $N$  values.

### 7.5.2 Maximum Total Coverage Area

We study the effect of  $r_s$ ,  $r_p$ ,  $N$ ,  $\beta$ ,  $\alpha$  on the maximum total coverage area of the subnetworks,  $S_{ht}^T$ , given in (7.9). We assume that every cognitive radio subnetwork is connected. Unless otherwise stated, we set  $\rho_p = 0.01$  nodes/m<sup>2</sup>,  $r_p = 100$ m,  $\Pi_1 = 0.01$ ,  $N = 15$  and  $\alpha = 4.0$ .

Fig. 7.3(a) shows that an increase in  $r_s$  enlarges the total maximum coverage area due to increase in individual coverage. Furthermore, since  $d_i^{\text{opt}}$  increases with  $\beta$ , we have higher  $S_T^{ht}$  for larger  $\beta$  values.

Fig. 7.3(b) shows the effect of  $r_p$  on  $S_T^{ht}$ . In a secondary network, the performance of it highly depends on primary user activities. Most important activity parameter is  $r_p$ . If  $r_p$  increases, the connectivity of the secondary network decreases which degrades the coverage of it.

The effect of  $\alpha$ , i.e., the eigenvalue of the system matrix  $A$  having the maximum magnitude, on the maximum total coverage area  $S_T^{ht}$  is studied in Fig. 7.3(c) for different  $N$  values. We assume that  $\beta = 0.9$ . As we studied in Fig. 7.2(b), an increase in  $\alpha$  causes a decrease in critical hop diameter. Hence, this effect decreases the total coverage area. Modifying the system matrix  $A$  results in a change in  $\alpha$ . For example in [88], the authors consider the problem of minimizing the largest eigenvalue of a matrix. Therefore, this technique can be used to change the largest eigenvalue of the system matrix  $A$ . Furthermore, an increase in the number of subnetworks increases  $S_T^{ht}$ .

Another parameter that affects the secondary network performance is the ON probability of PUs. The increase in ON probability means less connectivity between the secondary nodes, which results in less coverage. This effect can be clearly seen in Fig. 7.3(d). an increase in  $\Pi_1$ , causes a reduction in the maximum total coverage area  $S_T^{ht}$ .



## Chapter 8

# MAXIMIZATION OF ENERGY-EFFICIENCY UNDER CONVERGENCE CONSTRAINT IN WIRELESS NETWORKED CONTROL SYSTEMS

### 8.1 Introduction

Inefficient utilization of spectrum resources has triggered the use of dynamic spectrum access (DSA) techniques in wireless communications. The technology which enables DSA is cognitive radio (CR) [8]. A wireless network consisting of CR capable wireless nodes can opportunistically use the idle spectrum bands. However, a communicating pair of CRs must not cause any interference to active primary users (PUs). Spectrum sensing, spectrum decision and spectrum hand-off are the fundamental operations for opportunistic spectrum usage.

Apart from the inefficient utilization, some spectrum bands are very crowded due to excessive use. Wireless sensor networks (WSNs) suffer from the spectrum shortage. In order to overcome the spectrum scarcity challenge, cognitive radio sensor networks (CRSNs) are proposed [20]. They consist of wireless sensor nodes with CR capability. Most important aspect of CRSNs is that unnecessary energy consumption due to the spectrum scarcity can be decreased by the opportunistic spectrum usage. CRSNs can be used in diverse application areas.

Networked control system (NCS) is a traditional feedback control system closed via a communication network [89]. The communication network is utilized to exchange information between control system components such as sensor, controller, actuator, etc. [75, 76]. If the network has wireless communication capabilities with wireless control system components, the system becomes wireless networked control system

(WNCS). It can be used in diverse application areas such as smart grid, automatic management and navigation systems [77].

The WNCS estimator estimates the system state according to the sensor observations. Hence, the convergence of the WNCS estimator becomes a fundamental issue during the design of a WNCS. For a WNCS, we consider that there are  $N$  wireless subnetwork which are CRSNs such that the sensor measurements are conveyed to the WNCS estimator through idle channels opportunistically.

In our system, the WNCS estimator is a Kalman filter. In the classical approach, the Kalman filter has all the observation information to estimate the state of the system. On the other hand, the dynamic wireless channel conditions cause losses or delays for an observation to reach the Kalman filter. Hence, the observations can be intermittent. [82] studies the state covariance error for the general time-varying Kalman filter in which the observations are intermittent. However, the instability of the Kalman filter is not characterized. On the other hand, [83] models observation packet arrivals through wireless multi-hop sensor network as a random process and characterizes the statistical convergence properties of the Kalman filter. As an extension, [18] divides the state observation process into two parts such that there are two independent sensors providing observation packets to the Kalman filter and investigates the conditions for the convergence. Furthermore, in our prior work [78], we have generalized the division of the observation process in [18] by dividing the process into  $N$  independent subnetworks and characterize the lower bound on maximum total coverage area. Furthermore, we investigate this lower bound in heterogeneous subnetworks which consist of PUs and CR nodes in [90].

In this chapter, we also divide the process into  $N$  parts. This corresponds to a WNCS with  $N$  independent subnetworks, each of which consists of CR capable sensor nodes. Hence, the energy-efficiency is vital due to the resource-constrained nodes. Our aim is to convey the measurement packets by the energy limited sensor nodes to the Kalman filter in a dynamic radio environment under the convergence constraint of the Kalman filter. Hence, we maximize the energy-efficiency of the

overall system. A new energy-efficiency function has been proposed for this purpose and an optimization problem is formulated to fulfill the requirements of the estimator convergence and the resource constraint. The contributions of the chapter are the consideration of spectrum-aware communication in WNCS, the characterization of successful packet delivery probability and the maximization of energy-efficiency and finding lower bound on total network coverage area that guarantees the convergence of the Kalman filter.

The remainder of this chapter is organized as follows. In Section 8.2, convergence condition of Kalman filter with partial observations is presented. Section 8.3 presents our network model. In Section 8.4, the successful packet delivery probability is characterized. Section 8.5 presents our optimization problem and its solution. In Section 8.6, we provide the numerical analysis.

## 8.2 Convergence of Kalman filter with Partial Observations

We divide the system into  $N$  independent parts, hence, the system we consider can be represented as a general multiple-input multiple-output (MIMO) discrete time linear time-invariant system. The system equations can be written as follows

$$\begin{aligned} \mathbf{x}_{t+1} &= A\mathbf{x}_t + \mathbf{w}_t, \\ \begin{bmatrix} \mathbf{y}_{1,t} \\ \vdots \\ \mathbf{y}_{N,t} \end{bmatrix} &= \begin{bmatrix} C_1 \\ \vdots \\ C_N \end{bmatrix} \mathbf{x}_t + \begin{bmatrix} \mathbf{v}_{1,t} \\ \vdots \\ \mathbf{v}_{N,t} \end{bmatrix} \end{aligned} \quad (8.1)$$

where  $\mathbf{x}_t \in \mathcal{R}^n$  is the system state vector,  $\mathbf{y}_{i,t} \in \mathcal{R}^{m_i}$  is the sensor measurement vector,  $\mathbf{w}_t \in \mathcal{R}^n$  is the system disturbance vector,  $\mathbf{v}_{i,t} \in \mathcal{R}^{m_i}$  is the measurement noise vector,  $A \in \mathcal{R}^{n \times n}$  is the system matrix, and  $C_i \in \mathcal{R}^{m_i \times n}$  is the output matrices for  $i = 1, 2, \dots, N$ . The time index is indicated by the subscript  $t$ . Furthermore, the bold letters indicate the vectors. Due to the division of the system observation into  $N$  parts,  $\mathbf{y}_t = [\mathbf{y}_{1,t}; \mathbf{y}_{2,t}; \dots; \mathbf{y}_{N,t}]$ ,  $\mathbf{v}_t = [\mathbf{v}_{1,t}; \mathbf{v}_{2,t}; \dots; \mathbf{v}_{N,t}]$ , and  $C = [C_1; C_2; \dots; C_N]$ .

Both  $\mathbf{w}_t$  and  $\mathbf{v}_t$  are Gaussian random vectors with zero mean and their covariance matrices are  $Q \geq 0$  and  $R > 0$ , respectively.  $R$  is a  $N \times N$  matrix having elements as defined by  $R_{ij} = E[\mathbf{v}_{i,t} \mathbf{v}_{j,t}']$ . If  $(A, C)$  is observable, the Kalman filter converges without any loss in the sensor measurements.

All sensors measurement packets are received in a stochastic manner from different multi-hop cognitive wireless ad-hoc subnetworks by the Kalman filter in our system model as seen in Fig. 8.1. The stochastic reception of the packets is due to the wireless channel conditions. The sensors in these subnetworks encode their measurements as packets  $\mathbf{y}_{1,t}, \mathbf{y}_{2,t}, \dots, \mathbf{y}_{N,t}$ . The arrival of each sensor measurement packet follows independent Bernoulli process,  $\{\gamma_i\}_{t=0}^{t=\infty}$  with  $\Pr\{\gamma_{i,t} = 1\} = \lambda_i$  for  $i = 1, 2, \dots, N$  where  $\gamma_{i,t}$  indicates the correct reception of the  $i^{\text{th}}$  sensor measurement packet during a sample period. In each sample period  $t$ , the Kalman filter receives some of the output measurement packets due to the wireless channel conditions. The probability  $\lambda_i$  depends on the channel characteristics.

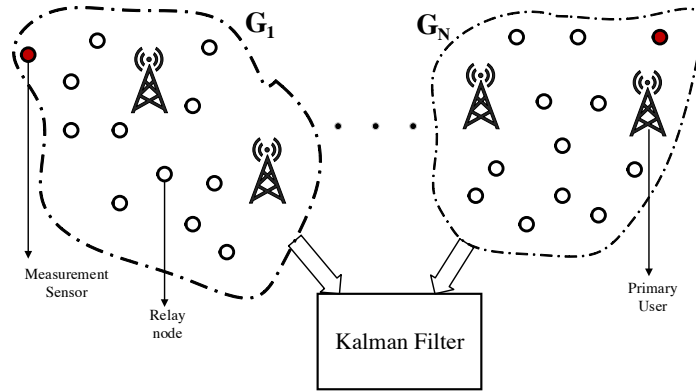


Figure 8.1: A WNCS model consisting of  $N$  subnetworks and a Kalman filter.

It should be noted that for different time indexes  $t$  and  $t'$ ,  $\gamma_{i,t}$  and  $\gamma_{j,t'}$  for  $i \neq j$  are independent. The loss of a packet is modeled as a reception of packet having an infinite noise variance. For the measurement noise vectors  $\mathbf{v}_{i,t}$ , we define the following conditional probability distribution function  $f_{\mathbf{v}|\gamma}(\mathbf{v}_{i,t}|\gamma_{i,t}) \sim \mathcal{N}(0, R_{ii})$  if  $\gamma_{i,t} = 1$  and  $f_{\mathbf{v}|\gamma}(\mathbf{v}_{i,t}|\gamma_{i,t}) \sim \mathcal{N}(0, \sigma_i^2 I)$  if  $\gamma_{i,t} = 0$ . For random partial losses, we take  $\sigma_i^2 \rightarrow \infty$ .

The important result of [83] has revealed that there exists a critical packet arrival probability such that if  $\lambda > \lambda^c$ , the expected state estimation error covariance,  $E[P_{t+1|t}]$  where  $P_{t+1|t} = E[(\mathbf{x}_{t+1} - \hat{\mathbf{x}}_{t+1|t})(\mathbf{x}_{t+1} - \hat{\mathbf{x}}_{t+1|t})' | \mathbf{y}_0^t, \boldsymbol{\gamma}_0^t]$ , is bounded and  $E[P_{t+1|t}]$  becomes infinite as  $t \rightarrow \infty$  if  $\lambda < \lambda^c$ . In our prior work [78], we stated that based on the derivations and results given in [18], if  $(A, Q)$  is controllable and  $(A, C)$  is observable, for a fixed set of  $(\lambda_1, \lambda_2, \dots, \lambda_{i-1}, \lambda_{i+1}, \dots, \lambda_N)$ , if  $\lambda_i \geq \lambda_i^c$ , the state estimation error covariance is bounded and the WNCS is stable. If the output matrices  $C_1, C_2, \dots, C_N$  are square and invertible  $A$  has a single unstable eigenvalue, the upper and lower bounds for  $\lim_{t \rightarrow \infty} E[P_{t+1|t}]$  coincide and the critical packet arrival probability of the measurement packet of the  $i^{\text{th}}$  sensor becomes

$$\lambda_i^c = \max \left\{ 0, 1 - \frac{1}{\alpha^2 \prod_{\substack{j=1 \\ j \neq i}}^N (1 - \lambda_j)} \right\} \quad (8.2)$$

where  $\alpha = \max_i |\sigma_i|$  and  $\sigma_i$  is the  $i^{\text{th}}$  eigenvalue of  $A$  [18]. If all  $\lambda_i$ s are greater than the critical values, the Kalman filter converges.

### 8.3 Multi-Hop Wireless Subnetwork Model

Sensors in each subnetwork transmit their observation packets to the Kalman filter over multiple hops in these subnetworks. Each subnetwork is distributed according to a two dimensional Poisson point process. These subnetworks are separated such that there is no connection between them. We assume that the nodes in the subnetworks have cognitive capability. Hence, nodes can sense the spectrum, change the operating parameters and adapt to the changes in the spectral environment. In fact, these subnetworks are CRSNs [20] such that output measurement packets are transmitted through available channel via multiple hops. Primary users (PUs), which are licensed users and have privilege to use the channel, and secondary users (SUs), which utilize the channel opportunistically, coexist in the subnetworks.  $G_i$  indicates the  $i^{\text{th}}$  subnetwork including the  $i^{\text{th}}$  sensor node for our network system.

PUs are distributed according to a two dimensional Poisson point process with a density  $\rho_p$ . The transmission ranges of PUs,  $r_p$ , are the same. Furthermore, CRSN nodes are also distributed according to a two dimensional Poisson point process with a density  $\rho_s$  and the transmission range of CRSN nodes is  $r_s$ . Fig. 8.1 shows our network model.

Although the spectrum availability changes in time for cognitive radio networks, there is a critical secondary node density  $\rho_s^*$  which provides the connectivity of the network. In [86], the authors show that there exists a critical node density  $\rho_s^*$  such that if the node density of the secondary network is larger than  $\rho_s^*$ , the secondary network percolates at all time, i.e., there exists always an infinite connected component in the secondary network under the time-varying spectrum availability. To guarantee the connectivity of the secondary network, we use the upper bound of the critical node density which is given by [86]

$$\rho_s^* = \frac{5}{r_s^2} \ln \left[ 1 - \sqrt{(1 - (\sqrt{6}/3)^\Lambda) e^{(|R_e| + |R'_e|) \Pi_1 \rho_p}} \right]^{-1} \quad (8.3)$$

where  $\Lambda = (4Ld + 2d + 1) \times (4Ld + d) + (4Ld + d + 1) \times (4Ld + 2d) - 1$ ,  $|R_e| = (2 + 2\lceil r_p/d \rceil) \times (1 + 2\lceil r_p/d \rceil) \times d^2$ ,  $|R'_e| = (2 + 2\lceil r_s/d \rceil) \times (1 + 2\lceil r_s/d \rceil) \times d^2$ ,  $L = \lceil \max\{r_p, r_s\}/d \rceil$ ,  $d = r_s/\sqrt{5}$ .

The state of PU can be represented as a semi-Markov ON-OFF process,  $S_p(t)$ . OFF state is an spectrum opportunity for CRSN nodes since PU does not utilize the channel. On the other hand, ON state refrains CRSN nodes from communicating. Furthermore,  $\Pi_1$  in (8.3) is defined as  $\Pi_1 = \Pr\{S_p(t) = 1\}$ . That is,  $\Pi_1$  is the average ON probability.

To investigate the lower bound on the maximum coverage area of a WNCS, we assume that the network density is  $\rho_s^*$  such that the nodes in subnetworks percolates all the time.

The transmission energy at one hop is  $E_{tx}(N_p, r_s) = E_{elec} \times N_p + \epsilon_{amp} \times N_p \times r_s^2$  where  $E_{elec} = 50 \text{ nJ/bit}$ ,  $\epsilon_{amp} = 100 \text{ pJ/bit/m}^2$ ,  $N_p$  is measurement packet size [43]. The reception energy is defined as  $E_{rx}(N_p) = E_{elec} N_p$ . During the transmission

and reception of the measurement packet at one hop, energy is consumed at both transmitter and receiver side which can be written as

$$E_{hop}^{total} = E_{tx}(N_p, r_s) + E_{rx}(N_p). \quad (8.4)$$

#### 8.4 Successful Packet Delivery Probability

The delivery of a packet between two CR capable nodes depends on link establishment between these two nodes. The first condition of the link establishment is that the two nodes have to be located within the transmission ranges of each other. The second condition is to have a common channel between these two nodes. Furthermore, the common channel must not be sensed as occupied. This wastes the spectrum opportunity and fails the link establishment. Fig. 8.2 shows the two CR nodes which are within the transmission range of each other. The inner circles with solid lines show the maximum transmission ranges of the nodes which are  $r_s$ . There must be no active PU around these nodes to establish a communication link between them. Hence, we determine a guard ring to facilitate spectrum-aware communication. This guard ring is determined by the union of circles whose radius is  $r_p$ . This provides an interference-free environment for the communicating nodes.

We denote the guard ring region covered by  $CR_1$  and  $CR_2$  with  $A_1$  and  $A_2$ , respectively. The areas of these regions are  $A_1 = A_2 = \pi r_p^2$ . We previously stated that there must not be any active PU in the union of these regions to establish a link between  $CR_1$  and  $CR_2$ . Hence, the link establishment probability from  $CR_1$  to  $CR_2$  can be found as

$$p_l(d) = Pr\{No\ PU\ in\ A_1 \cup A_2\}P'_{FA} + Pr\{PU\ in\ A_1 \cup A_2\}\Pi_1^k P'_{FA} \quad (8.5)$$

where  $P'_{FA}$  is no false alarm probability and  $\Pi_1$  is the ON probability of PU and  $k$  is the mean number of PUs in  $A_1 \cup A_2$ ,  $k = \rho_p \times (A_1 \cup A_2)$ , and  $\rho_p$  is the PU node density.

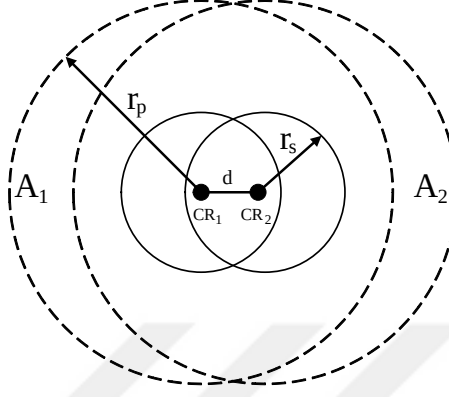


Figure 8.2: Coverage of CR nodes and their guard ring for the link establishment.

The area of the region  $A_1 \cup A_2 = A(d)$  can be found as

$$A_1 \cup A_2 = 2\pi r_p^2 - 2r_p^2 \arccos\left(\frac{d}{2r_p}\right) + \frac{1}{2}d\sqrt{(4r_p^2 - d^2)} \quad (8.6)$$

where  $d$  is the distance between the two nodes.  $p_l(d)$  can be written as

$$\begin{aligned} p_l(d) &= e^{-\rho_p A(d)}(1 - P_{FA}) \\ &+ (1 - e^{-\rho_p A(d)})\Pi_1^k(1 - P_{FA}). \end{aligned} \quad (8.7)$$

We set  $d$  to its maximum value  $r_s$  in our calculations to calculate the worst case for the link establishment probability,  $p_l$ . This probability is lower bounded by the probability when  $d = r_s$ . Then, the constant link establishment probability is

$$\begin{aligned} p_l(r_s) &= e^{-\rho_p A(r_s)}(1 - P_{FA}) \\ &+ (1 - e^{-\rho_p A(r_s)})\Pi_1^k(1 - P_{FA}). \end{aligned} \quad (8.8)$$

As a routing protocol we employ the greedy forwarding approach [87]. In this routing approach, the node sends its packet to its neighbor node that is closest to the destination. We define a random variable  $H$  which indicates that there exists at least

one neighbor node in the forwarding region and it can be expressed as

$$H = \begin{cases} 1, & \text{if } \exists \text{ a node in the forwarding region} \\ 0, & \text{otherwise.} \end{cases} \quad (8.9)$$

In our calculations, we assume the forwarding region as the closer half of the disc to the destination specified by the transmission range of the sender node. There must be at least one node to successfully forward the packet to the destination. The successful packet delivery probability can be written as

$$p_s = p_{s|H=1}Pr\{H = 1\} + p_{s|H=0}Pr\{H = 0\} \quad (8.10)$$

where  $Pr\{H = 1\} = 1 - e^{-\rho_s \pi r_s^2/2}$  and  $Pr\{H = 0\} = e^{-\rho_s \pi r_s^2/2}$ . The successful packet transmission probability when there is no neighbor in the forwarding region,  $p_{s|H=0}$ , is zero since there is no neighbor to forward the packet. The successful packet delivery probability when there is at least one neighbor in the forwarding region,  $p_{s|H=1}$ , is the link establishment probability,  $p_l(r_s)$ . Hence, the successful packet delivery probability becomes as

$$\begin{aligned} p_s &= p_{s|H=1}Pr\{H = 1\} \\ &= p_l(r_s)(1 - e^{-\rho_s \pi r_s^2/2}). \end{aligned} \quad (8.11)$$

### 8.5 Maximum Energy-Efficiency Under Convergence Constraints

Each subnetwork has energy-constrained sensor nodes, hence, the energy to convey the measurement packets to the Kalman filter must be minimized. On the other hand, there is a convergence constraint of the Kalman filter, which states that the probability of measurement packet reception correctly must be above a certain threshold for each subnetwork.

Coverage can be increased if we increase the number of nodes. However, it will increase the number of hops to reach the Kalman filter which decreases the prob-

ability of sensor measurement packet reception by the Kalman filter and increases total energy consumption to convey the measurement packets. Hence, increasing the number of hops may deteriorate the convergence of the Kalman filter and the energy consumption. Hence, we define hop diameter as a parameter which defines the maximum number of hops between any point in the network. Due to the convergence constraint, hop diameter becomes a critical parameter for the stability of the system. We denote the hop diameter of the subnetwork  $G_i$  as  $d_i$ .

We define the critical packet arrival probability for each sensor measurement denoted by  $\lambda_i^c$ . It directly affects the hop diameter of a subnetwork and the critical hop diameter that guarantees the convergence of the Kalman filter is found as  $d_i^c = \lfloor \ln(\lambda_i^c) / \ln(p_s) \rfloor + 1$ . In this case, if  $d_i < d_i^c$  for any subnetwork  $G_i$ , WNCS is stable and the Kalman filter converges since it is guaranteed that the packet arrival probability is greater than the critical value. Otherwise, the system stability and the convergence of the Kalman filter are not guaranteed.

The total energy consumption in a subnetwork  $G_i$  can be expressed as  $E_i^{total} = d_i \times E_{hop}^{total}$ . For a given set of packet arrival probabilities of the subnetworks except for the  $i^{\text{th}}$  subnetwork,  $(\lambda_1, \lambda_2, \dots, \lambda_{i-1}, \lambda_{i+1}, \dots, \lambda_N)$ , the convergence criterion states that as  $\lambda_i^c \rightarrow 0$ , then  $d_i^c \rightarrow \infty$ . While considering the convergence criterion, the critical hop diameter for  $G_i$  becomes infinity and the energy consumed in this subnetwork to convey the measurement packet to the Kalman filter becomes infinity. This energy allocation is not efficient for a subnetwork that consists of energy-constrained nodes. Hence, the energy-efficiency of overall system must be considered.

The energy-efficiency of the overall network can be calculated by considering weights for subnetworks. The subnetworks having smaller critical packet arrival probability should have less weight. When  $\lambda_i^c \rightarrow 0$ ,  $d_i^c \rightarrow \infty$  and  $\lambda_i E_i^{total} \rightarrow 0$ . Hence, we can use  $\lambda_i E_i^{total}$  as energy efficiency of the  $i^{\text{th}}$  subnetwork. We therefore define the total energy-efficiency function of the WNCS as

$$U(\lambda_1, \dots, \lambda_N) = \lambda_1 E_1^{total} + \lambda_2 E_2^{total} + \dots + \lambda_N E_N^{total}. \quad (8.12)$$

$$\begin{aligned}
 & \underset{\lambda_1, \dots, \lambda_N}{\text{maximize}} \quad U(\lambda_1, \dots, \lambda_N) = \lambda_1 E_1^{total} + \lambda_2 E_2^{total} + \dots + \lambda_N E_N^{total} \\
 & \text{subject to} \quad \lambda_i \geq \max \left\{ 0, 1 - \frac{1}{\alpha^2 \prod_{\substack{j=1 \\ j \neq i}}^N (1 - \lambda_j)} \right\} \quad \text{for } i = 1, 2, \dots, N.
 \end{aligned} \tag{8.13}$$

We find the set  $(\lambda_1, \lambda_2, \dots, \lambda_N)$  which maximizes the energy-efficiency in the system to convey the measurement packets to the Kalman filter under the convergence constraint of the Kalman filter which is defined in (8.2). The optimization problem is formulated as in (8.13).

We perform numerical analysis to obtain a solution to the optimization problem. The constraints on the packet arrival probability change the total energy consumption of the system. In our observations, the critical arrival probability should be the same for each subnetwork to maximize the energy-efficiency. Without considering the constraints on  $p_s$  and  $\alpha$ , the maximum energy-efficiency is achieved by  $e^{-\ln(p_s)-1}$  for small values of  $\lambda_i$ . For high values of  $\lambda_i$ , the maximum energy-efficiency can be approximated by  $1 - \alpha^{-2/N}$ . Hence, the optimum solution can be approximated as

$$\lambda_i^{\text{opt}} \approx \max\{e^{-\ln(p_s)-1}, 1 - \alpha^{-2/N}\} \tag{8.14}$$

for  $i = 1, 2, \dots, N$ , which guarantees the convergence of the Kalman filter and achieves the maximum energy-efficiency of the system.

The energy-efficiency maximization imposes a bound on the number of nodes in each subnetworks. If the number of nodes in a subnetwork is equal to the hop diameter, we guarantee the convergence of the Kalman filter since the packet arrival probability is smaller than the critical value. Hence, we can find the lower bound on the maximum number of nodes in the system. This means the lower bound on the maximum coverage with the maximum energy-efficiency under the convergence constraint of the Kalman filter. The lower bound on the maximum number of node

is denoted by  $L_i = d_i^{\text{opt}}$  for  $i = 1, 2, \dots, N$ . In Section 8.3, we stated that for  $\rho_s^*$ , the network percolates at all time. Hence, we can find the coverage area of  $G_i$  as  $S_i = L_i/\rho_s^*$ . The total coverage area of the system can be given by  $S^{\text{total}} = \sum_{i=1}^N S_i = N \times S_i$  due to the same critical packet arrival probability value for each subnetwork.

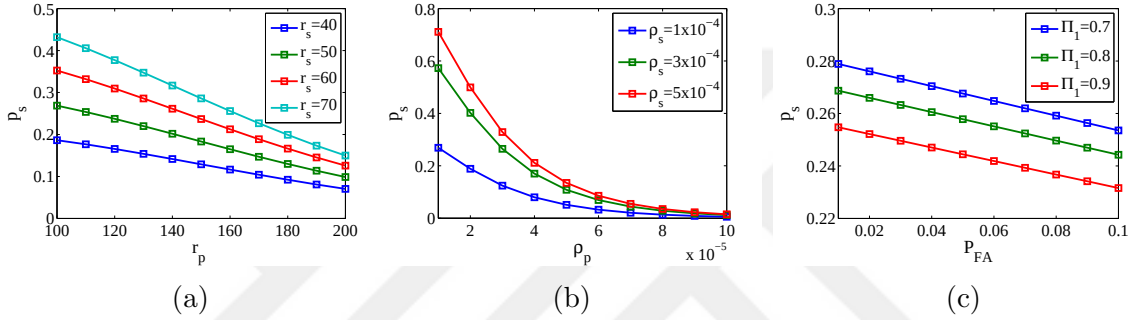


Figure 8.3: Successful packet delivery probability,  $p_s$ , vs. a)  $P_{FA}$  for different  $\Pi_1$ , b)  $\rho_p$  for different  $\rho_s$ , c)  $r_p$  for different  $r_s$ .

## 8.6 Numerical Analysis

We perform numerical analysis of the successful packet delivery probability,  $p_s$ , the total energy consumption,  $E^{\text{total}} = \sum_{i=1}^N E_i^{\text{total}}$ , and the lower bound on the maximum total coverage area,  $S^{\text{total}}$  of the subnetworks with respect to several parameters of the system and multi-hop cognitive wireless subnetworks. The numerical values of system parameters are set as  $\rho_s = 10^{-4}$  nodes/m<sup>2</sup>,  $\rho_p = 10^{-5}$  nodes/m<sup>2</sup>,  $\Pi_1 = 0.8$ ,  $P_{FA} = 0.01$ ,  $r_p = 100$  m, and  $r_s = 50$  m unless otherwise specified. Furthermore, the output matrices  $C_1, C_2, \dots, C_N$  are assumed to be square and invertible so that the upper and lower bounds of the critical arrival probability coincide [18].

### 8.6.1 Successful Packet Delivery Probability

The successful packet delivery,  $p_s$ , depends on  $r_s$ ,  $r_p$ ,  $\rho_s$ ,  $\rho_p$ ,  $\Pi_1$  and  $P_{FA}$  as shown in (8.11). In Fig. 8.3(a), we investigate the effects of  $r_p$  and  $r_s$ . As  $r_s$  increases, the forwarding region expands and  $P\{H = 1\}$  increases. Hence,  $p_s$  increases with an

increase in  $r_s$ . Furthermore, as  $r_p$  increases,  $A_1 \cup A_2$  expands. Hence, it would be less likely to find a neighbor to forward the packet towards the Kalman filter. As  $r_p$  increases  $p_s$  decreases.

As seen in Fig. 8.3(b), higher  $\rho_s$  means higher number of neighbor to choose to forward the measurement packet. An increase in  $\rho_s$  increases  $p_s$ . Also,  $\rho_p$  has negative effect since it increases the number of possible PUs in  $A_1 \cup A_2$  region. Hence, an increase in  $\rho_p$  decreases  $p_s$ .

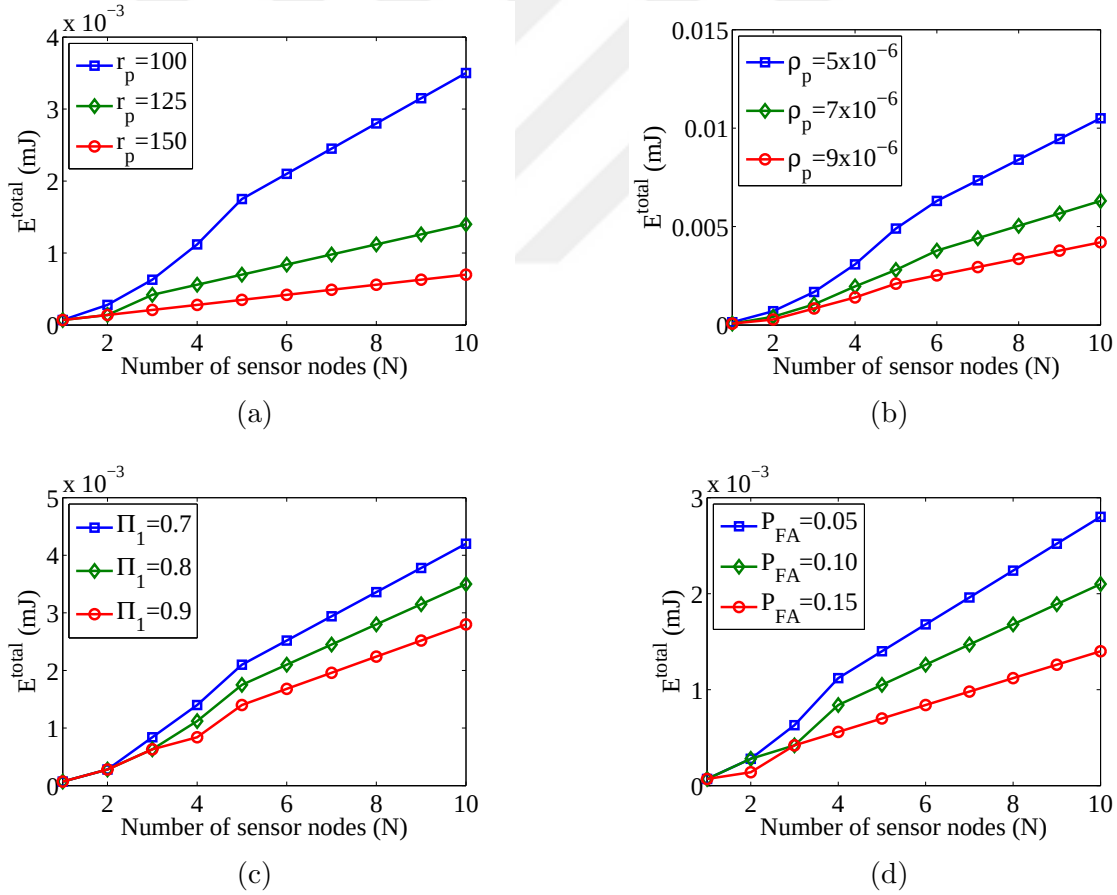


Figure 8.4: Total energy consumption,  $E^{\text{total}}$ , vs.  $N$  for different a)  $r_p$ , b)  $\rho_p$ , c)  $\Pi_1$ , d)  $P_{FA}$ .

As shown in Fig. 8.3(c), the average ON probability of PUs,  $\Pi_1$ , determines the idleness of the channel in  $A_1 \cup A_2$ , and hence an increase in  $\Pi_1$  decreases  $p_s$ . In terms of  $P_{FA}$ , an increase in  $P_{FA}$  increases the chance of spectrum opportunity losses.

Hence, an increase in  $P_{FA}$  decreases  $p_s$  as seen in Fig. 8.3(c).

### 8.6.2 Total energy consumption

We investigate the total energy consumption,  $E^{\text{total}}$ , with respect to the number of subnetworks,  $N$ , for different  $r_p$ ,  $\rho_p$ ,  $\Pi_1$  and  $P_{FA}$ . We select the measurement packet size,  $N_p$ , as 200 bits. The energy consumption at each hop,  $E_{\text{hop}}^{\text{total}}$ , is equal to 0.06 mJ.

In Fig. 8.4(a),  $E^{\text{total}}$  with respect to the number of sensor nodes  $N$  is investigated for different  $r_p$  values.  $E^{\text{total}}$  depends on  $\lambda_i^{\text{opt}} = \max\{e^{-\ln(p_s)-1}, 1 - \alpha^{-2/N}\}$ . For small  $N$  values,  $\lambda_i^{\text{opt}} = 1 - \alpha^{-2/N}$  and we observe non-linear increase in  $E^{\text{total}}$ . For greater values of  $N$ ,  $\lambda_i^{\text{opt}} = e^{-\ln(p_s)-1}$  and we observe a linear increase as shown Fig. 8.4(a) due to  $E^{\text{total}} = N E_i^{\text{total}}$ . Furthermore,  $\rho_p$  affects the packet successful packet delivery probability,  $p_s$ . Hence,  $\rho_p$  changes the value of the transition from the quadratic region to the linear region due to  $\lambda_i^{\text{opt}}$  expression. As we observed in Fig. 8.4(b), an increase in  $\rho_p$  decreases  $p_s$ , and hence it will decrease this boundary as seen in Fig. 8.4(b).

The successful packet delivery probability,  $p_s$ , decreases with increasing  $\Pi_1$ . Hence, it decreases the hop diameter,  $d_i^{\text{opt}} = \left\lfloor \frac{\ln(\lambda_i^{\text{opt}})}{\ln(p_s)} \right\rfloor + 1$ . This results in a decrease in  $E^{\text{total}}$  as seen in Fig. 8.4(c). Furthermore, an increase in  $P_{FA}$  decreases  $p_s$ . Since this effect decreases  $d_i^{\text{opt}}$ ,  $E^{\text{total}}$  decreases as seen in 8.4(d).

### 8.6.3 Maximum Total Coverage Area

In this section of the numerical analysis, we present the effect of  $\alpha$ ,  $P_{FA}$ ,  $\Pi_1$ ,  $\rho_p$  and  $r_p$  on the lower bound of the maximum total coverage area of the subnetworks,  $S^{\text{total}}$ . We stated in Section 8.5 that the lower bound on the maximum number of nodes in subnetwork  $G_i$  is  $d_i^{\text{opt}}$ . In Fig. 8.5(a), the variation in  $S^{\text{total}}$  with respect to  $N$  is investigated for different  $\alpha$  values. The values of  $\alpha$  and  $N$  affect the  $\lambda_i^{\text{opt}}$ , and hence the lower bound on the maximum number of nodes in  $G_i$ . The successful packet delivery probability does not depend on both  $N$  and  $\alpha$ . According to  $\lambda_i^{\text{opt}} =$

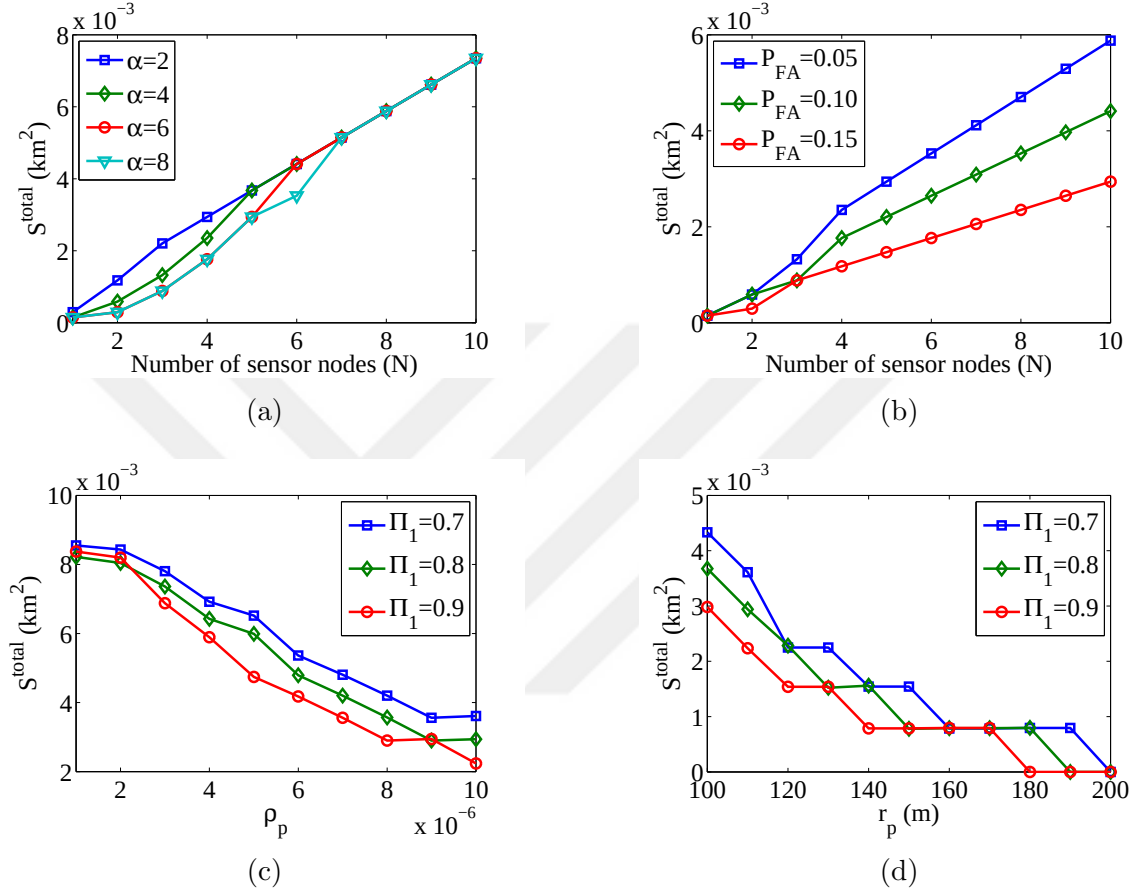


Figure 8.5: Total coverage area,  $S^{\text{total}}$ , vs. a)  $N$  for different  $\alpha$ , b)  $N$  for different  $P_{FA}$ , c)  $\rho_p$  for different  $\Pi_1$ , d)  $r_p$  for different  $\Pi_1$ .

$\max\{e^{-\ln(p_s)-1}, 1 - \alpha^{-2/N}\}$  expression, for smaller values of  $N$ ,  $\lambda_i^{\text{opt}} = 1 - \alpha^{-2/N}$ .  $S^{\text{total}}$  is non-linear below certain  $N$ . In the other case,  $\lambda_i^{\text{opt}} = e^{-\ln(p_s)-1}$ . Since  $S^{\text{total}} = N S_i^{\text{total}}$ , after a certain  $N$  value,  $S^{\text{total}}$  increases with only  $N$ . Furthermore, the probability of false alarm decreases successful packet delivery probability,  $p_s$ . Hence, an increase in  $P_{FA}$  decreases  $d_i^{\text{opt}}$ . This decreases  $S^{\text{total}}$  which can be seen in Fig. 8.5(b).

The PU density,  $\rho_p$ , has a negative impact on  $S^{\text{total}}$  since an increase in  $\rho_p$  decreases  $p_s$  and it results in smaller  $d_i^{\text{opt}}$ . This effect can be seen in Fig. 8.5(c). Hence, an increase in  $\Pi_1$  decreases  $S^{\text{total}}$ . Also,  $\Pi_1$  decreases  $S^{\text{total}}$  due to the decrease in  $p_s$ . The successful packet delivery probability states that an increase in  $r_p$  causes a decrease

in  $p_s$ . Hence, it decreases the total coverage area,  $S^{\text{total}}$ , as can be seen in Fig. 8.5(d).



## Chapter 9

# MULTIMEDIA COMMUNICATION IN COGNITIVE RADIO AD HOC AND SENSOR NETWORKS

### **9.1 Introduction**

Small and low-cost sensor nodes are available thanks to the developments in MEMS technology. These sensor nodes have irreplaceable batteries and they are deployed in specific regions of interest. These sensor nodes form a wireless ad hoc network, namely Wireless Sensor Networks (WSN). The application areas of these networks are environmental or habitat monitoring, military surveillance, medical applications, multimedia applications, and etc. The sensor nodes sense the environment, i.e. heat, pressure, sound, light or motion depending on the application, and form packets related to the event. The sensor nodes collaborate with each other to convey these packets in multi-hop manner to base station or sink [91].

Reliable and timely delivery of data packets is a vital requirement for multimedia communication. Inherent demands of the multimedia communication are limited delay, large bandwidth, jitter, no abrupt changes of transmission rate, and loose reliability [4]. A new networking paradigm has been proposed to realize multimedia communication in WSN, namely Wireless Multimedia Sensor Networks (WMSN). Multimedia communication demands more resources than the mainstream data sensing applications. Event features in sensor networks and the packets generated by source nodes in ad hoc networks contain large byte streams since they are in the form of multimedia, e.g., video, audio, still image. Hence, the main challenges posed by the multimedia communication are high bandwidth demand and strict time-constraint

[92].

Ever increasing demand in the wireless communication has led to the spectrum scarcity problem. Furthermore, the electromagnetic spectrum is not utilized efficiently due to fixed frequency assignment approach. Cognitive radio technology has become the solution to the spectrum scarcity and inefficient utilization problems. Communication between wireless nodes becomes spectrum-aware by cognitive cycle operations which are spectrum sensing, spectrum decision and spectrum hand-off [8]. The inherent features of the cognitive radio have increased the electromagnetic spectrum efficiency and have overcome the spectrum scarcity challenge. The main cognitive radio application areas ad hoc networks and sensor networks [20].

A typical cognitive radio ad hoc network consists of two types of users. These users are secondary users (SUs) and primary users (PUs). PUs are the legacy users of the licensed spectrum. SUs are the cognitive radios and they utilize the licensed bands opportunistically [33]. Cognitive radio capability of wireless nodes provides the adaptation to the environmental changes in the network. A cognitive radio node can find the vacant spectrum bands by spectrum sensing, and utilize them by spectrum decision. If utilized channel becomes occupied by a primary user, the communication continues on another vacant channel by spectrum hand-off function. Hence, CR can change its operating parameters to enable seamless communication.

Wireless sensor networks are characterized by the fixed frequency assignment policy, hence, they suffer from the spectrum scarcity challenge [20]. Event-driven communication nature of WSN causes bursty traffic. The injection of event packets leads to packet collisions and excessive contention delay due to the high traffic and the high node density in the network. Furthermore, sensor nodes inherit limitations in power, communication, processing and memory resources. Hence, cognitive radio sensor network (CRSN) has been proposed by utilizing cognitive radio capability in sensor networks. The cognitive radio capability of sensor nodes increases the efficiency of overall spectrum utilization and decreases the probability of collision and contention by utilizing multiple channels opportunistically. Adaptability to the exist-

ing spectrum meets the unique requirements of WSN such as resource constraint and low processing ability. Furthermore, CRSN benefits from the potential advantages of the salient features of dynamic spectrum access such as adaptability to the environmental changes to decrease collision and to reduce power consumption, and accessing the multiple channels to provide flexibility in spectrum usage.

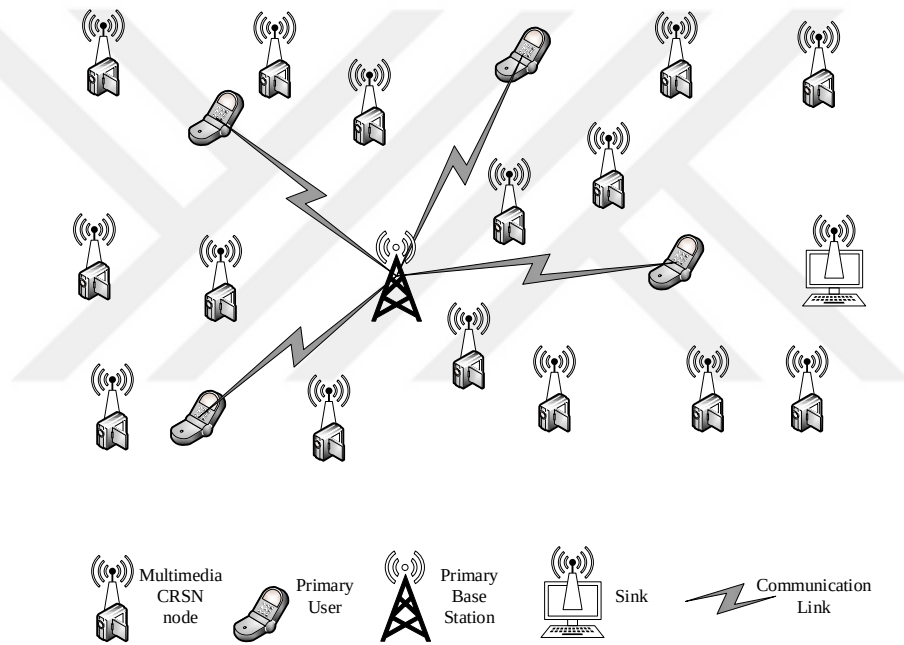


Figure 9.1: A typical CRSN architecture.

Sensor nodes in CRSN sense the environment as well as the spectrum. The event readings of the sensor nodes in the event region are collaboratively conveyed in multi-hop manner through vacant channels. A typical CRSN architecture is shown in Figure 9.1. In this typical architecture, CRSN nodes and PUs coexist and there is a sink having cognitive radio capability. Base stations serve for PUs, and CRSN nodes communicate without interfering with PUs. The cognitive radio capable sink can receive multiple data with its cognitive radio capable transceivers. Furthermore, a typical CRSN topology can be ad hoc, clustered, hierarchical and mobile depending on the application.

A wide range of potential application areas of CRSNs exists in the literature.

These application areas are indoor sensing applications, multi-class heterogeneous sensing applications and real-time surveillance applications [20]. Furthermore, one of the most significant possible application areas is multimedia communication [92].

Multimedia communication has been investigated in wireless sensor and ad hoc network context extensively [92, 93, 4]. However, there is not research on multimedia communication in cognitive radio ad hoc and sensor networks. Communication in dynamic radio environment and multimedia communication has distinctive challenges. Multimedia communication requires seamless communication, bounded delay and a certain level Quality of Service (QoS). However, due to the cognitive radio capability, communication maybe interrupted by the arrival of primary users which results in delay, route changes and variations of QoS. Hence, multimedia communication in a cognitive radio network (CRN) regime intensifies the existing challenges in cognitive radio ad hoc and sensor networks. We survey the approaches proposed for each network layer in WSN, CRN and WMSN, and determine the challenges and potential approaches to overcome them in this chapter.

We survey existing studies and research opportunities of multimedia communication from the perspective of networks layers in cognitive radio ad hoc and sensor networks. We examine the state-of-the art approaches related to WMSN communication and how these methods can be applied for multimedia communication in cognitive radio ad hoc and sensor networks. We clearly indicate the challenges posed by cognitive radio and sensor networks for multimedia communication and investigate how the union of sensor networks and cognitive radio in multimedia communication pose new challenges.

Multimedia streams must be conveyed in timely manner. However, the cognitive radio introduces some delays due to cognitive cycle operations and the coordination activities due to the tuning to the same channel between communicating parties. Hence, these are the specific challenges caused by the cognitive radio capability of wireless nodes. Furthermore, the multimedia application requires limited delay and mandates the transport of packets in timely manner. In the light of the above men-

tioned challenges and limitations, we investigate the existing protocols and open issues. In application layer, the multimedia encoding techniques are investigated and the open issues have been presented for cognitive radio sensor and ad hoc networks. The existing transport layer approaches for multimedia communication in WSN, CRN and CRSN have been examined and the potential approaches for cognitive radio and ad hoc networks have been presented according to reliability of the transport and congestion control. In network layer, routing issues have been investigated by examining the previous works on WSN, CRN and CRSN. In the MAC layer, potential approaches for medium access control protocols have been presented for cognitive radio ad hoc and sensor networks. We outline the open research issues in each layer to realize multimedia communication in cognitive radio ad hoc and sensor networks.

## **9.2 Factors Influencing Multimedia Communication in Cognitive Radio Ad Hoc and Sensor Networks**

Cognitive radio ad hoc and sensor networks impose limitations on designing protocols such as limited energy and memory capability, decentralized architecture, node failures, dynamic radio environment etc. Energy and memory limitations are inherited from WSN paradigm, opportunistic spectrum access is inherited from the cognitive radio capability. These challenges are amplified by the union of sensor network paradigm and cognitive radio. On the other hand, multimedia communication has unique requirements which are high bandwidth demand, application-specific QoS requirements and delay bound [92]. These requirements of multimedia communication must be revisited from the perspective of dynamic radio environment. Satisfying these requirements is the main motivation of multimedia communication. These requirements are also the factor influencing the quality of multimedia communication. The factors influencing the multimedia communication cognitive radio ad hoc and sensor networks are explained as follows.

**High bandwidth demand :** Multimedia traffic contains large packets and they must be transported to the destination within certain delay. Hence, high bandwidth

is a vital requirement for real-time multimedia communication. On the other hand, dynamic radio environment due to primary user activities poses a significant challenge to this factor. The channel conditions change by arrival of primary users and spectrum hand-off.

**QoS requirements and limited delay :** Either processing time or communication latency in WMSN causes the delay [92]. Furthermore, channel access delay should be taken into account for the delay in cognitive radio ad hoc and sensor networks. The delay and the high throughput are the main QoS requirement in multimedia communication. Also, jitter degrades the performance of continuous media such as audio and video. It can be avoided replay buffering at receiver side.

**Dynamic radio environment :** Cognitive capability of nodes offers flexibility in utilizing communication channels. However, they pose significant challenges. For example, the coordination of the communication is a difficult task since the communication between cognitive nodes requires tuning to the same channel for communication.

**Power consumption :** Nodes have irreplaceable batteries, hence the energy-efficiency is a vital requirement. Collision, unnecessary packet transmission, extensive overhead due to the communication coordination and high duty cycle operation are the most important factors.

### **9.3 Application Layer in Multimedia Communication for Cognitive Radio Ad Hoc and Sensor Networks**

Application layer is perhaps the most important platform in multimedia communications, since it governs the communication quality of the end user. In a WSN or CRSN, application layer needs to compress the field data efficiently and obtain a proper representation to it, such that data is transported via wireless links in multi-hop manner.

Application layer is responsible from

1. Managing traffic based on application requirements

2. Performing source coding via a suitable approach based on the resource constraints of the sensor nodes.

Both of these challenging tasks have been investigated in the context of WSNs before. However, intermittent communications in Cognitive Radio concept and its additional operational requirements necessitate revisiting them and assess their applicability to CRSNs.

### 9.3.1 Challenges and Requirements

The challenges faced by the application layer in WMSN and multimedia communication in CRSNs are mostly driven by the high bandwidth multimedia nature of the data to be communicated. We invite users interested in general challenges on application layer of traditional WSN to read [91], an excellent survey of WSNs and their challenges. [93], [92] and [4] are excellent sources for general overviews on the challenges and requirements of application layer for WMSN. Based on the tasks of managing traffic with respect to the application requirements and source coding, challenges of application layer in WMSNs and CRSNs will be investigated along different dimensions, as shown in Figure 9.2.

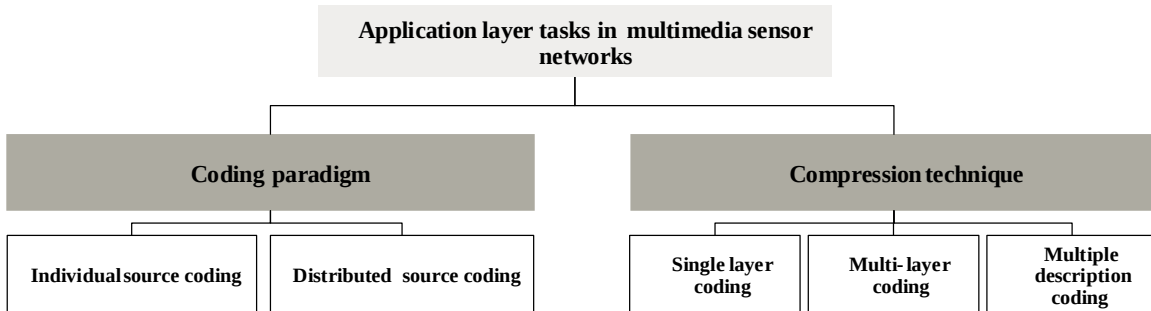


Figure 9.2: Application layer tasks in multimedia sensor networks [4]

1. Quality of Service (QoS) is an important metric to be considered in sensor networks, even more in multimedia sensor networks. In that sense, based on

application requirements, sensor nodes may need to differentiate different types of traffic. Therefore, existing measures in this respect and their applicability to CRSNs is worthy of consideration.

2. Multimedia applications demand high bandwidth, which is scarce in Industrial, Scientific and Medical bands populated by WSNs. Although CRSNs can offer a remedy to the bandwidth problem, efficient source coding techniques are needed to carry out source to sink multimedia relaying in an energy efficient manner. Depending on the network and application, Distributed Source Coding or Individual Source coding may be used in WMSNs [4]. Besides, chosen compression technique brings differences in resilience to errors, energy efficiency and adaptability to network conditions among other properties. Since communication is intermittent in CRSN with constant adaptation of communication parameters and additional tasks regarding cognitive cycle brings additional challenges in communications and energy expenditure, compression techniques need to be revisited for multimedia communications in CRSN.

### 9.3.2 Existing Application Layer Solutions

#### *Wireless Multimedia Sensor Networks*

In traffic management, application layer responsibility in a WMSN depends on whether the application is delay tolerant, and is concerned about a multimedia stream or a specific data. In real-time applications, tolerance for delay is very low, which in turns requires CR nodes in case of CRSN to carry out the cognitive cycle in a quicker manner, with the shortest possible spectrum sensing duration and acceptable false alarm and false detection levels. In real-time applications, whether greedy forwarding rather than nearest neighbor forwarding is better suited for less delay should be assessed and actions should be taken, which in turn requires cross-layer coordination. In a delay tolerant setting, CRSN nodes can periodically turn on and off their transceivers, field sensing units or both. No study has been made up to this date, which considers a

sleeping schedule for the transceivers and field sensing units of CRSN nodes at the same time, which would be governed by the traffic management task of the application layer.

In terms of the coding paradigm, Individual Source Coding refers to the case where each node codes its own field readings independently [4]. Simplicity is an advantage of individual source coding since it does not require communications and/or coordination between nodes for coding purposes. Such individual coding has been shown to be suboptimal, especially in case of spatio-temporal correlation of the sensed field is significant [50]. Accordingly, in a WMSN, it is possible to choose representative number of nodes  $M$  for an event, and adjust their reporting frequency  $f$  such that significant power savings can be achieved while conforming to a maximum distortion at the sink, i.e.,  $D(f, M) < D_{max}$ .

H.264, the technique in video compression, possesses excellent rate-distortion performance with its advanced compression techniques [94]. Newly proposed H.265 [95] will even surpass it in terms of compression efficiency. Nevertheless, such predictive coding schemes bring processing complexity and require excessive energy consumption for compression. In addition, predictive coding schemes require complex encoders and enable simpler decoders. Usage of these complex encoders are not feasible for resource-constrained sensor nodes. To solve these problems, Distributed Source Coding has been proposed as the paradigm to balance the communication needs and processing cost with a good rate-distortion performance.

Slepian and Wolf first proved that for lossless compression of two correlated signals, separate simple encoding and joint decoding is as efficient as joint decoding [96]. Considering  $X$  and  $Y$  as two correlated random variables, from Shannon's source coding theorem, a rate  $R \geq H(X, Y)$  is sufficient. This may be obtained by a rate  $R_Y \geq H(Y)$  and  $R_X \geq H(X|Y)$ , which in turn produces a total rate of  $R_X + R_Y \geq H(X|Y) + H(Y) = H(X, Y)$ . Slepian and Wolf stated that  $R \geq H(X, Y)$  is sufficient for the separate encoding of correlated  $X$  and  $Y$ , which translates to  $R_X \geq H(X|Y)$  being achievable without knowing the explicit  $Y$  at the encoder but knowing the

joint statistics of  $X$  and  $YY$  only. Wyner-Ziv coding was proposed as an extension to Slepian and Wolf, where correlated discrete signals are coded in a lossy manner this time, with respect to a fidelity criterion. Wyner-Ziv is challenged though, with the fact that obtaining explicit joint probability density functions to compress the the sources (nodes) in distributed manner is difficult [97]. Exploitation of spatial correlation among sources is the key to overcome this challenge. This is natural, given the fact that video sources are usually anisotropic. From CRSN perspective, leveraging the spatial correlation via DSC is encore more challenging, since DSC would require synchronization between two nodes to be jointly decoded at the sink. Due to temporal variation of licensed user traffic, even neighbors nodes might not be able to communicate for proper synchronization, especially in delay intolerant applications.

Distributed source coding via Wyner-Ziv paradigm (simple encoder at nodes, complex decoder at sink) is a very attractive technique to exploit the temporal correlation of each source's readings within itself. DSC is indeed one of the hot topic in research, with various works to find a balance between computation and communication efficiency in sensor networks [98]-[99]-[100]-[101]. On exploitation of temporal correlation of each node, routing schemes may need to be revisited in the case of CRSN especially, where routes to the sink may lose connectivity even permanently, depending on the primary user behaviour.

On the compression technique side, single layer and multi layer coding techniques have been nicely summarized in [4]. Accordingly, in single layer coding, a reference layer and only consecutive differences between frames are transmitted until the next reference frame. This type of coding does not provide error resilience. Nevertheless, in underlay cognitive networks, besides bad channel conditions for secondary users, a frame is to be retransmitted (potentially through another channel) anyway once it is interrupted via licensed user traffic. However, for cognitive radio networks using underlay spectrum sharing, transmission can still continue until tolerable threshold limit on licensed users has been crossed by the secondary users. In that sense, it is more suitable to employ multi layer coding, which allows for joint source and channel

coding, hence error resilience, in underlay cognitive radio sensor networks.

### *Cognitive Radio and Sensor Networks*

Works regarding multimedia communications in CRNs and CRSNs is much scarce compared to WSN, given they are relatively new paradigms.

[102] is a related work in the context of cognitive radio networks, where QoS is optimized via varying the intra refreshing rate together with the access strategy and spectrum sensing of CR nodes. The idea with intra refreshing rate is that, an intra coded macroblock does not depend on the previous blocks, which might have been corrupted by errors in previous transmission, hence limiting error propagation and lowering of QoS. Nevertheless, since the work is about CRNs, the assumed multimedia model is based on advanced compression techniques of H.264 and alike, which are not suitable for low complexity nodes of CRSNs.

Authors in [103] also study multimedia communications in CRN. A streaming optimization problem is set and is solved based on the bandwidth budget available to cognitive radio nodes. Results reveal that GoP based optimization is less computationally expensive, but is also has slightly less QoS compared to frame based optimization. Again, the work is based on Scalable Video Coded H.264, and is not directly applicable to resources constrained CRSN.

[104] is an interesting work in CRSN regarding the optimal allocation of power to two sensing tasks, namely the field sensing and spectrum sensing. Although results are insightful, the network model needs to be extended to a multi-hop network, which is usually the case in CRSNs.

### *9.3.3 Open Research Issues for Application Layer*

Several open issues in CRSN regarding the application layer can be listed as follows:

- For traffic management, an application layer protocol that decides upon sleep and wake up schedules of transceivers and field sensor of CRSN nodes is needed for enhanced network lifetime

- An energy efficient, cross layer scheme for source and channel coding in CRSN is needed to ensure reliable monitoring
- Routing schemes need to be revisited in CRSN aspect, to make sure that Wyner-Ziv coding that is targeted to leverage node based temporal correlation makes each packet arrive to the sink, given that connectivity in CRSN is intermittent among many nodes

#### **9.4 Transport Layer in Multimedia Communication for Cognitive Radio Ad Hoc and Sensor Networks**

Transport layer provides end-to-end reliability for the data transfer and the congestion and flow control in traditional computer networking. Transport layer protocols regulate data flows, control congestion, decrease packet loss, and guarantee a certain level of end-to-end reliability in WSN [105]. However, due to the inherent features of WSN such as network topology, traffic characteristics and application-dependent nature, traditional transport layer protocols such as TCP and UDP do not suit WSN.

Transport layer solutions are vital for the realization of multimedia communication in cognitive radio ad hoc and sensor networks. Reliable data delivery of the event features and the amount of the traffic injection upon event detection are the main issues of transport layer. The existing challenges for cognitive radio and sensor networks need to be reconsidered for the realization of the multimedia communication in cognitive radio ad hoc and sensor networks. Apart from WSN paradigm, cognitive radio ad hoc and sensor networks impose new challenges for transport layer functionalities. In order to achieve efficient transport layer solutions, the unique characteristics of cognitive radio ad hoc and sensor networks paradigm and the distinctive requirements of multimedia communications must be analyzed in detail to develop transport layer solutions.

#### 9.4.1 Challenges and Requirements

Main duties of the transport layer are the reliability and the congestion control. Multimedia communication in wireless networks is delay sensitive data communication. Hence, timely delivery of the data packets is more important for the performance than the reliability. Delay bound and strict QoS demands impose significant challenges on communication. The multimedia packets have higher size than the conventional data packets. Hence, the potential delays cause buffer overflows and the loss of data packets.

In sensor networks, event readings are injected to the network and this injection creates high and bursty traffic. This situation requires certain level of congestion control and end-to-end reliability to preserve the limited resources of the nodes. The end-to-end reliability is achieved by the arrival of sufficient number of event packets to the sink. Congestion control is the enabling the event traffic towards the sink to not exceed the capacity of ad hoc or sensor networks. These functionalities of the transport layer are used to provide energy efficiency and to prevent the waste of communication resources [20].

Cognitive radio has unique features to be carefully considered in order to propose efficient solutions. Due to inherent features of cognitive radio, there exist unique challenges which are itemized as follows.

- **Spectrum sensing** : Spectrum sensing is a vital cognitive cycle operations that provides information about the availability of spectrum. During spectrum sensing, the transmission function is paused since they can not be performed simultaneously. Operating channels can be changed after the channel sensing. The channel characteristics may change or even the channel becomes occupied by the primary users. Furthermore, the channel sensing period may be changed due to the spectrum efficiency and interference avoidance [16]. The scheduling of sensing duration must be organized to decrease the collision probability. Different sensing periods of nodes results in variation of packet latency, i.e., jitter. Transport layer functionality rate control must consider these heterogeneity

in spectrum sensing duration which causes the degradation of transport layer performance.

- **Interference by the primary user :** The mainstream of spectrum sensing technique is the energy detection. This technique may lead mis-detection, and hence the transmission continues despite the existence of legacy user on that communication band. Furthermore, the transmitted packet by a CR source node may be received erroneously. The precious resources of wireless nodes are wasted. Successful packet transmission probability decreases by the activities of the primary users.
- **Spectrum hand-off :** During the communication between event and sink in CRSN, and between source and destination in CRAHN, the changes in the licensed user activity are observed. These changes may deteriorate the performance of secondary network. Upon detection of licensed user in the communication channel, spectrum hand-off is performed. The communication is stopped until finding a new vacant channel. Also, the delay characteristics and the loss rate change on the communication link which affects the communication performance.
- **Dynamic spectrum access :** If a cognitive radio does not find any vacant band, then it has to wait for a spectrum opportunity. The waiting time for an opportunity causes extra time delay for packet transmission. In sensor networks, the data packet may become obsolete due to the delay.
- **Spectrum mobility :** The cognitive radio capability of cognitive radio ad hoc and sensor nodes provides the change of operating parameters in case of spectrum hand-off. The channel and delay characteristics, and also noise level change due to the variations in the operating channel parameters.
- **Spectrum coordination :** Dynamic spectrum environment requires spectrum

coordination. The exchange of control packets for the channel selection and the sensing duration are the main functionalities of spectrum coordination. The spectrum coordination is utmost necessary to perform cognitive cycle operations such as spectrum decision and spectrum hand-off.

The challenges posed by cognitive radio ad hoc and sensor network paradigm are amplified by the unique requirements of multimedia communication. Dynamic spectrum access scheme provides gain by opportunistic channel access, however, licensed user activities may deteriorate the multimedia communication. Furthermore, the energy efficiency is an important challenge for resource constrained wireless nodes. Hence, the DSA and licensed user activities should be carefully examined to avoid unnecessary power consumption due to the collision, the interference and the loss by buffer overflow.

#### *9.4.2 Existing Transport Layer Solutions*

##### *Wireless Sensor Networks*

The main duties of the transport protocols are the mitigation of the congestion and packet losses, also fair allocation of limited bandwidth between the wireless nodes. Hence, according the energy efficiency, reliability and fairness metrics, a number of WSN transport protocols are proposed.

Different techniques can be combined to control and mitigate the congestion in WSN. In [106], three techniques which are hop-by-hop flow control, source rate limiting scheme and prioritized MAC layer that give priority to the backlogged nodes are combined to mitigate and control the congestion. The congestion is detected when the fraction of space of the output queue is less than a threshold [106]. To mitigate the congestion, hop-by-hop rate adjustment is performed. On the other hand, the authors in [107] detect the congestion in WSN by also observing the state of the channel for a certain period of time. If the utilization of the channel is greater than a certain threshold, the congestion bit of outgoing packet is set to 1. Congestion mit-

Table 9.1: Existing WSN congestion control protocols in WSN

| Protocols | Congestion detection           | Congestion Mitigation        |
|-----------|--------------------------------|------------------------------|
| [106]     | observing output queues        | hop-by-hop rate adjustment   |
| [107]     | observing state of channel     | hop-by-hop rate backpressure |
| [108]     | service time of packet         | hop-by-hop rate adjustment   |
| [109]     | inter-arrival and service time | hop-by-hop rate adjustment   |

igation is performed by hop-by-hop backpressure to locally change congestion policy or end-to-end source rate regulation.

Congestion can be detected in several ways in WSN. For example, in [108], the authors look packet service time for congestion detection. On the other hand, [109] uses inter-arrival times of the packets in addition to the service time of the packet to detect congestion. Furthermore, the congestion is mitigated by hop-by-hop rate adjustment in [108, 109]. Table 9.1 outlines the congestion detection and mitigation techniques used in literature.

Multimedia communication in cognitive radio ad hoc and sensor networks require efficient congestion detection and mitigation mechanism since the congestion highly affects the real-time communication. Large packet size, the dynamic radio environment and limited capability of sensor nodes necessitate novel schemes by considering the challenges posed by cognitive wireless sensor network paradigm.

Apart from congestion detection and mitigation techniques, the reliability is another important functionality of the transport layer in WSN. RMST [110] provides end-to-end reliability for all the packets in WSN and does not take into account the correlated nature of the event packets. The packet reliability is provided by the requesting data by *NACK* from the source or the cache nodes. MMSPEED [111] provides reliability at different QoS levels in addition to the timeliness. It utilizes multi-path to increase the delivery probability of packets and to propose dynamic compensation scheme such that the inaccurate decisions made by a node in the path can be compensated in the route the sink. PSFQ [112] injects or pumps messages slowly to the network. Furthermore, the intermediate nodes cache data for local loss

recovery. If there is a gap in the received file fragments, NACK is sent in the reverse path to recover the lost packets. However, the packet loss due to the congestion is not addressed in PSFQ.

Transport layer requires end-to-end reliability in wireless ad hoc networks. However, the sensor observations are correlated in sensor networks [50]. Hence, the end-to-end reliability is not a strict requirement. The sufficient number of sensor observations must be collected by the sink to extract the event features with a certain estimation distortion. This reliability model is *event reliability* [113]. TCP protocols, which require re-transmission of lost packet, are not efficient for WSN paradigm since the re-transmission consumes the scarce resources of sensor nodes.

End-to-end reliability is provided at the sink or the source nodes. In [113], application dependent reliability level is satisfied at the sink according to the reporting rate of source nodes in the event region. If the received packets from the sensor reports satisfy the reliability level, the reporting rate is decreased. Otherwise, the reporting rate is increased to achieve the desired level of event reliability. According to this adaptive feature of ESRT, the event is extracted thanks to the correlated nature of sensor observations.

RCRT [114] is a reliable transport protocol for applications which are not tolerant to packet losses. It utilizes end-to-end loss recovery. Furthermore, congestion detection and rate adaptation are done at the sink. It implements NACK based end-to-end loss recovery scheme to guarantee the reliability. It also utilizes the cumulative ACK to remove the packets at the source node that are received by the sink.

Wireless sensor and actor networks (WSAN) are heterogeneous networks that sensor nodes and actors coexist. Sensor observe the environment and the actors perform actions according to the sensor observations.  $(RT)^2$  [115], proposes real-time reliable transport for sensor-actor and actor-actor communication. It considers event reliability as in ESRT [113].

The reliable delivery of all data packet for multimedia communication in cognitive radio ad hoc and sensor networks is not necessary due to the correlated nature of

Table 9.2: Reliability of transport protocols in WSN

| Protocols        | Multimedia communication issues                                                                                                    |
|------------------|------------------------------------------------------------------------------------------------------------------------------------|
| RMST<br>[110]    | - end-to-end reliability for all packets<br>- no consideration of correlation between packets<br>- NACK based re-transmission      |
| MMSPEED<br>[111] | + reliability at different QoS level and timeliness<br>+ multi-path support<br>+ dynamic compensation against inaccurate decisions |
| PFSQ<br>[112]    | + cache data for loss recovery<br>- NACK based re-transmission<br>- no congestion loss consideration                               |
| ESRT<br>[113]    | + event reliability<br>+ reporting rate adjustment                                                                                 |
| RCRT<br>[114]    | + real time support<br>- end-to-end loss recovery by NACK                                                                          |
| $RT^2$<br>[115]  | + event reliability<br>+ real-time reliable transport                                                                              |

the sensor observations. Hence, the protocols must consider event reliability and offer certain level of QoS. Table 9.2 outlines reliable transport protocols in WSN and their advantages and disadvantages for multimedia communications. Advantages and disadvantages are indicated by + and -, respectively.

#### *Cognitive Radio Ad Hoc and Sensor Networks*

The unique constraints encountered at the transport layer in WSN are amplified by the cognitive radio capability in CRAHN. Cognitive cycle operations affect the transport layer protocol design. For example, the transport layer functionality is disrupted by the spectrum sensing, and if the timeout occurs, the source rate is decreased without the congestion. The delay between two nodes increases by the spectrum switching due to PU arrival on the communication channel. In [116], the optimal balance is achieved between the spectrum sensing duration and the throughput of

the CR network. It is known that if the sensing duration increases, the end-to-end throughput decreases [117]. Spectrum switching due to PU activities causes changes in the channel characteristics. This change results in the variation of the bandwidth and hence TCP congestion window is adaptively modified [116]. Consequently, the classical TCP is adapted to the dynamic radio environment. A prior work, TP-CRAHN [118], is proposed for establishing a spectrum-aware window-based transport layer protocol.

Cross layer design is also used to improve the performance of the transport layer in CRN. In [119], the cognitive cycle operations, physical layer coding and modulation scheme, and data-link layer frame size are concurrently optimized to maximize the TCP throughput in CRN. Furthermore, effects of the varying link capacity and the PU detection errors on TCP throughput are studied in dynamic spectrum access network with centralized base station [117]. However, it does not consider the ad hoc nature of the communication.

In CRAHN, the existing works mainly regard the adaptation of TCP to the dynamic radio environment by considering cognitive cycle operations. Transport layer is also investigated in CRSN. In [120], it is pointed out that existing WSN transport layer solutions are not suitable for CRSN since they do not consider the additional delay caused by spectrum sensing and spectrum mobility. It indicates the open research issues for CRSN transport layer. It is concluded that in order to propose novel transport layer solutions, packet losses and delays due to the cognitive cycle must be considered with energy constraints of the CRSN nodes.

#### *Wireless Multimedia Sensor Networks*

Multimedia communication in WSN requires the transportation of great volume of data with high transmission rate and bounded delay. The high volume of data produced by multimedia applications results in buffer overflow and congestion. Queue based Congestion Control Protocol with Priority Support (QCCP-PS) [121] is proposed for fair and reliable transport in WMSN. Queue length is used as a congestion

degree and rate assignment to a traffic source is done according to its priority index and congestion degree. Priority index is used to discriminate the priority of the traffic sources in WMSN. However, this approach does not consider spectrum-aware communication and hence it can not be directly applied to the cognitive radio ad hoc and sensor networks.

#### 9.4.3 Open Research Issues for Transport Layer

In preceding subsections, we investigated the challenges for the multimedia communication in cognitive radio ad hoc and sensor networks. Furthermore, we surveyed the important existing transport layer solutions in WSN, CRAHN, CRSN and WMSN.

The transport layer protocols for WSN can not be applied to the cognitive radio and ad hoc networks due to no support for DSA functionalities. CRAHN and CRSN solutions do not satisfy the unique requirements of the multimedia communication such as bounded delay, jitter and smooth variation of the throughput. WMSN transport layer solutions satisfy the multimedia communication requirements, however, they do not consider the spectrum-awareness. Hence, the open research issues can be itemized as follows.

- In the light of above discussions, it is necessary to develop novel transport layer algorithms to satisfy the requirements of multimedia communication and DSA functionalities. The proposed transport protocol should be adaptive to the licensed user activities and the cognitive cycle operations to deliver the multimedia data in energy-efficient and timely manner.
- Varying network capacity is detrimental for multimedia communication. Spectrum-handoff results in the change of operating channel parameters and the link capacity changes accordingly. Hence, licensed user behavior can be estimated to prevent frequent spectrum-handoff and deterioration of the multimedia communication.

- Novel congestion detection mechanism must be developed by considering the extra delay caused by cognitive cycle operations such as spectrum sensing and the spectrum-handoff.
- Novel rate control mechanism must be designed to decrease the buffer overflows and re-transmissions. Rate control in cognitive radio ad hoc and sensor networks should consider the varying licensed user activity, spectrum sensing duration and spectrum-handoff delay.
- In addition to reliable transport protocols for multimedia communication, they should support real-time communication to satisfy the multimedia application deadlines.
- Due to the energy-constraints, limited capability of sensor nodes and the dynamic spectrum environment and DSA capability, cross-layer communication protocols must be investigated to support energy-efficient and reliable multimedia communication in CRSN.

### **9.5 Network Layer in Multimedia Communication for Cognitive Radio Ad Hoc and Sensor Networks**

Network layer provides connection between transport layer and MAC layer. It is mainly provides routes from source to destination which satisfy certain QoS requirements such as energy-efficiency and delay. In wireless ad hoc networks, multi-hop communication is utilized to save energy and to have high quality communication links. Hence, the efficient network layer solutions are imperative for establishing energy-efficient routes and providing information to the transport layer.

#### *9.5.1 Limitations and Challenges*

Multimedia communication in cognitive radio sensor and ad hoc networks has some limitations due its inherent nature. Furthermore, spectrum-awareness of wireless

nodes poses extra challenges in the network layer.

Multimedia communication has stringent delay requirements and requires high bandwidth. Furthermore, there are limitations on multimedia communication in wireless sensor networks as stated in [92] which are summarized as follows. Multimedia communication has query-driven or event-driven data delivery model. The continuous data delivery drains out the energy of wireless nodes. Source aggregation and in-network processing are not efficient methods in multimedia communication due to the anisotropic nature of video signals. Furthermore, local communication should be limited for the processing of the multimedia data. Multimedia communication should satisfy a certain level of QoS. This limitation could be achieved by the multipath communication.

The limitations of the multimedia communication are amplified by the unique features of cognitive radio. For example, data delivery models must be revisited for the spectrum sensing and spectrum hand-off mechanisms. Also, dynamic radio environment poses challenges for multi-path communication since the multi-path routes between event and the sink may be disrupted by the activities of primary users. Predetermined routes may break due to dynamic channel condition.

### 9.5.2 Existing Network Layer Solutions

#### *Wireless Sensor Networks*

Wireless sensor nodes have energy and processing constraints, hence the energy-efficiency is the main consideration of routing protocols in WSN. The route is established and maintained at the network layer to maximize the lifetime of WSN. Furthermore, excessive number of sensor nodes is deployed in sensor networks, classical IP addressing would be an overhead for energy-constrained WSN regime. Hence, attribute-addressing is used such that the node having the required information communicates to the sink over multiple hops by the routing protocols.

Routing protocols in WSN are classified into three categories which are flat, hierarchical and location-based [122]. In flat network routing, all the nodes in the network

have the same role and collaboratively send the observation data to the sink. In hierarchical network routing, clustering is proposed and the cluster-heads behave as source aggregation nodes and decrease message content to provide energy-efficiency. In geographical network routing, each node in the network know its position by triangulation and localization techniques. The source packets are routed towards the sink with the location information.

SPIN [123] is a flat network routing protocol such that every node sends advertisement (ADV) message to announce its data packet and the node needing this packet sends request (REQ) message to the node and the node with the data sends it with DATA message. This protocol is not suitable for multimedia communication in cognitive radio ad hoc and sensor networks since it does not guarantee the delivery of data packets which degrades the performance of the multimedia communication. Furthermore, Directed Diffusion [124] is a query-based data-centric routing protocol such that the sink sends interest signal to request the information from the source nodes. Source nodes set up gradients towards the sink and the sink reinforces some paths according to QoS requirements. Source nodes send the information from reinforced paths. This process requires end-to-end control data transfer, hence the routing discovery process may increase delay bound. On the other hand, the multi-path support satisfies the multi-path limitation of multimedia communication. A variant of Directed Diffusion, Rumor Routing [125], which decreases energy-consumption by avoiding flooding the queries, does not provide multi-path support, therefore, it is not suitable for multimedia communication.

Hierarchical routing for multimedia communication has some drawbacks due to the communication and processing burden of multimedia data at the cluster-head and poor channel quality between cluster-heads which the result of high communication range between the cluster-heads. In Low-Energy Adaptive Clustering Hierarchy (LEACH) [43], the sensed data by the cluster members is gathered at the cluster-head, and aggregation technique is applied. It proposes a routing architecture such that the aggregated data at each cluster-head is conveyed collaboratively by cluster-heads. It

offers scalability, lifetime improvement, and energy-efficiency. Due to the aggregation limitation of multimedia data and the poor quality of the communication link between the cluster-heads, multimedia communication is not suitable for this architecture.

On-the-fly event-driven clustering is proposed in [49], named as Event-to-Sink Directed Clustering (ESDC). Upon the detection of an event, a routing corridor is established between event and sink. The data packets are routed by the cluster-heads. Multimedia packets are large packets and their processing, i. e., aggregation, requires large memory size which is not suitable for limited capability of sensor nodes. Hence, this approach has disadvantage for the multimedia communication.

The clustering based routing is very promising in WSN, however, the unique characteristics of multimedia application can not use the benefits of hierarchical routing in case of homogeneous network. On the other hand, if cluster-heads are more powerful nodes which are capable of processing multimedia data, the hierarchical routing becomes efficient way for network layer solutions in multimedia applications.

If the direction of the base station is known, the event packets propagate towards to directly to the sink. The node firstly broadcast its packet to the one-hop neighbors and the node with the least cost to the base station continues the data flow. In this approach, Minimum Cost Forwarding Algorithm (MCFA) [126], each node knows the cost to reach base station through the messages sent by the base station. This protocol is convenient for multimedia communication since the multimedia data is forwarded to the base stations upon the detection of the event without any delay to setup routes.

In location based networks, the routing is performed according to the location information. For example, in Geographical and Energy Aware Routing (GEAR) [127], location-aware and energy-aware nodes utilize heuristic approach for selecting neighbor to route the packets towards the sink. In [128], the energy minimization is achieved through location information and relay region determination accordingly. Minimum energy paths are established beforehand, hence, the topology changes and reconfiguration of WSN may lead to inefficiency of the routing protocol. However, lo-

cation based networks setup routes in smaller delay and reduced energy consumption. Hence, it is more appropriate for multimedia communication.

According to the protocol operation, the routing protocols can also be divided into five categories, which are negotiation-based, multi-path, query-based, QoS based and coherent based protocols [122]. In negotiation-based protocol, negotiation is performed between nodes to prevent the duplication and redundancy before data communication. In multi-path communication, the same data has been sent through different paths to increase the reliability and the bandwidth. Query-based protocols start the data transmission and setup routes upon queries sent by the sink. QoS based routing protocols establish routes to satisfy certain parameters such as delay, throughput, jitter, etc. In coherent based routing protocols, the raw data at the nodes are processed. According to this characterization, multi-path and QoS routing protocols are suitable for multimedia communication since it requires reliability, high throughput, low delay bound and jitter.

QoS based protocols setup and maintain the routes according certain metrics such as link delay, bandwidth, energy-efficiency, residual energy, or weighted combination of some of them. In [129], an energy-aware QoS routing protocol is proposed. It considers the end-to-end delay to establish QoS routes for real-time data delivery. According to a cost function which is evaluated by transmission energy, error rate, residual energy, the least-cost path is selected with delay constraint. Real-time Power-aware Routing (RPAR) [130] addresses the challenge of energy-efficient communication with a certain QoS requirement, i.e., delay. It is achieved by adapting the transmission power of the nodes and the routing decisions based on packet deadlines dynamically. It supports real-time communication in WSN. This type of protocols is very promising for multimedia communication in cognitive radio ad hoc and sensor networks since they satisfy certain QoS requirement, i.e. delay, with energy-efficiency constraint. However, these protocols do not support cognitive radio functionality. Hence, they need to be modified to adapt the spectral changes.

Table 9.3 outlines the routing protocols in WSN and its advantages and disadvan-

Table 9.3: Routing protocols in WSN

| Protocols                   | Multimedia communication issues                                                                   |
|-----------------------------|---------------------------------------------------------------------------------------------------|
| SPIN<br>[123]               | - flat network routing<br>- no guarantee of data delivery                                         |
| Directed Diffusion<br>[124] | + query-based data centric routing<br>+ multi-path support<br>- delay due end-to-end control data |
| Rumor Routing<br>[125]      | + a variant of Directed Diffusion<br>[124]<br>+ no flooding of queries<br>- no multi-path support |
| LEACH<br>[43]               | + scalability and lifetime improvement<br>- poor link quality between cluster-heads               |
| ESDC<br>[49]                | + on-the-fly event-driven clustering<br>+ routing corridor between event and sink                 |
| GEAR<br>[127]               | + route selection according to energy<br>and location                                             |
| [128]                       | + relay region determination<br>through location information                                      |
| MCFA<br>[126]               | + routing towards the sink<br>+ no delay to setup routes to the sink                              |
| [129]                       | + energy aware QoS based routing<br>+ QoS routes for real time data delivery                      |
| RPAR<br>[130]               | + energy efficient routing with low delay<br>+ routing decisions according to packet deadline     |

tages for realizing multimedia communication in cognitive radio ad hoc and sensor networks. Advantages and disadvantages are indicated by + and -, respectively.

### *Cognitive Radio Ad Hoc and Sensor Networks*

Dynamic spectral environment and cognitive cycle operations of wireless nodes make routing a very challenging task in CRN. The flexibility in the spectrum access brings about complexity in the protocol design. The main challenges of the routing multi-hop CRN are spectrum-awareness, setup of quality routes and route maintenance/ reparation [131]. Furthermore, routing protocols in CRN depend on either full spectrum knowledge or local spectrum knowledge.

Using full spectrum knowledge in CRN, optimal routes can be setup. In practical networks, the full knowledge may not be achievable, however, optimal routes can be used as a benchmark for the routing protocols. In the routing process, interference avoidance to primary users is a must, hence routing protocols establish routes to not interfere with licensed users. In [132], the spectrum information is known apriori and mixed integer linear programming (MILP) is used to provide fair routing for different traffic demands by considering spectrum sharing and flow routing with interference considerations.

Spectrum-aware opportunistic routing (SAOR) [133] is proposed to employing multipath transmissions and QoS guaranteed throughput with decreased delay. It employs spectrum map from local sensing observation and opportunistic routing. Furthermore, opportunistic cognitive routing is proposed in [134]. Cognitive radios select the relay node based on the location information and channel usage statistics. A new metric, cognitive transport throughput (CTT), is defined to assess the potential relay gain.

Link scheduling is important for CR networks to decrease the interference. The routing problem in multi-hop CRN is studied with link scheduling [135]. Scheduling and routing are performed under unpredictable primary users. They try to perform OSA, scheduling and multi-path multi-hop routing in CRN by minimizing the network resource usage. The spectrum vacancy of a licensed band is modeled as a random variable to estimate the channel vacancy condition. [135] is an important study to realize multimedia communication in cognitive radio ad hoc and sensor networks.

Spectrum aware on-demand routing protocol is a reactive protocol which balances the channel switching and spectrum sharing through routing and frequency band selection [136]. Routes are selected according to their effectiveness in terms of spectrum switching delay and backoff delay. The authors in [137] also propose an on-demand routing and channel assignment protocol which does not utilize common control channel. The protocol also decrease backoff delay and the overhead due to channel switching and tries to avoid deafness problem due to channel switching. Re-

Table 9.4: Routing protocols in CRN

| Protocols | Multimedia communication issues                                                                                       |
|-----------|-----------------------------------------------------------------------------------------------------------------------|
| [132]     | + can be considered benchmark<br>+ fair routing for different traffic demands<br>- spectrum information known apriori |
| [133]     | + multi-path opportunistic routing<br>+ QoS guaranteed throughput with decreased delay<br>+ local spectrum sensing    |
| [134]     | + relay node selection based on location information<br>and channel usage statistics                                  |
| [135]     | + joint routing and scheduling                                                                                        |
| [136]     | + balance between spectrum sharing and channel switching<br>+ consider spectrum switching and backoff delay           |
| [137]     | + route selection according to energy and location                                                                    |
| [138]     | + smooth delivery of multimedia data<br>+ clustered QoS routing                                                       |

active protocols are more advantageous than the proactive protocols since dynamic nature of environment make obsolete the routes established beforehand. Hence, on demand, i.e. reactive, routing protocols are more applicable to cognitive radio ad hoc and sensor networks.

Enabling multimedia communication of WMSN over CRSN poses challenges due to the distributed nature of CRSN, and dynamics of network and spectrum usage. Hence, the routing protocols should provide rate adaptation with opportunistic bandwidth, and delay and jitter control [138]. Spectrum-aware clustering protocol for energy efficient routing (SCEEM) [138] is proposed such that clustering manages dynamic spectrum access and QoS routing for multimedia communication in CRSN. The contributions of SCEEM are smooth multimedia data delivery by the isolation of time and frequency variability of the spectrum and energy efficiency with QoS aware routing.

Table 9.4 outlines the routing protocols in CRN and CRSN, and their advantages for multimedia communication in cognitive radio ad hoc and sensor networks.

The routing protocols in CRN consider delay, throughput and licensed user ac-

tivities, however, they do not deal with energy-efficiency challenge. The delay and throughput considerations are compatible with the requirements of multimedia communication. On the other hand, these protocols need appropriate modifications such as energy efficiency to be utilized in cognitive radio ad hoc and sensor networks.

### *Wireless Multimedia Sensor Networks*

New routing solutions have been proposed to satisfy the unique requirements of multimedia communication in WMSNs. Readers may infer the comprehensive survey about routing protocols in WMSN presented by authors in [139]. In this section, we present some of the recent proposals for routing in WMSN.

Table 9.5: Routing protocols in WMSN

| <b>Protocols</b> | <b>Multimedia communication issues</b>                                                           |
|------------------|--------------------------------------------------------------------------------------------------|
| [140]            | + reinforce multi-paths with high quality links with low latency                                 |
| [141]            | + multi-channel multi-path routing<br>+ real-time data delivery                                  |
| [142]            | + disjoint route establishment<br>+ additional paths in case of congestion and lack of bandwidth |

The authors in [140] extend directed diffusion to reinforce multiple paths with high quality of links and low latency. It also offers better throughput with lower delay than directed diffusion. Furthermore, [141] proposes multi-channel, multi-path routing protocol in which routes are determined by adjusting the required bandwidth dynamically and the differentiation of delay which is proportional to the path length for real-time data. [142] provides necessary bandwidth for the multimedia applications by establishing disjoint routes and avoiding inter-session and intra-session interference. One path is built for each session, if there is congestion or lack of bandwidth, additional paths are established. The interfering nodes are forced to be passive to decrease the interference and unnecessary energy consumption.

The routing protocol is also proposed for multimedia streaming which requires delay bound and high bandwidth demand [143]. The protocol is online multipath routing protocol for WMSN. Route decisions are made at each hop by using location information. Two schemes, which are smart greedy forwarding scheme that selects the most appropriate node and walk back scheme to bypass network holes, are used to achieve energy-efficiency and load-balancing.

Table 9.5 outlines the state-of-the-art routing protocols and their advantages for realizing the multimedia communication in cognitive radio ad hoc and sensor networks. In general, the proposed routing solutions in literature employs location-based and multi-path routing. They support traffics demanding high bandwidth and low delay. However, the proposed solutions do not consider the dynamic radio environment which is a missing issue for multimedia communication in cognitive radio ad hoc and sensor networks.

### 9.5.3 Open Research Issues for Network Layer

Numerous efforts focus on network layer solutions in WSN, CRN and WMSN. These efforts mainly concentrate on routing protocols. Multimedia communication requirements are satisfied by the WMSN routing solutions. However, they must also overcome the challenges of cognitive radio and sensor networks. Open research issues in network layer can be itemized as follows.

- Back off delay and channel switching delay must be take into account to provide delay bounded path establishments. Additional delay comes due to the licensed user activities in cognitive radio ad hoc and sensor networks.
- Dynamic radio environment causes changes in the spectrum opportunities, hence reactive protocols are more appropriate for multimedia communication in cognitive radio ad hoc and sensor networks. Hence, this type of protocols must be designed.

- Due to the dynamic spectral environment the established path can become obsolete. Hence, the multi-path protocols are appropriate for multimedia communication and there is no such study in cognitive radio ad hoc and sensor networks.

## **9.6 MAC Layer in Multimedia Communication for Cognitive Radio Ad Hoc and Sensor Networks**

MAC layer is mainly responsible for channel access mechanism, scheduling, buffer management and error control mechanisms in wireless networks. Channel access mechanism affects the delay and reliability of the packet, scheduling is used to schedule the packet transmission in the medium to decrease the collision probability. The bursty nature of multimedia communication requires efficient buffer management policies to decrease buffer overflows. Furthermore, there are two error control mechanism which are Automatic Repeat Request (ARQ) and Forward Error Correction (FEC) schemes. Due to the real-time data delivery requirement of multimedia communication, ARQ scheme may not be used since it requires the re-transmission of the packet.

Energy-aware MAC layer solutions are necessary to satisfy the unique requirements of sensor networks paradigm as well as the requirements of multimedia communication. Novel techniques are required for the adaptation to dynamic spectral environment in cognitive radio ad hoc and sensor networks. Accesses to the medium, error control and packet transmission reliability are highly influenced by the requirements of multimedia communication, sensor network, and cognitive radio. In this section, we survey the MAC layer solutions in literature, how they can be extended for multimedia communication in cognitive radio ad hoc and sensor networks.

### *9.6.1 Challenges and Requirements*

The major requirements of MAC protocols in sensor networks are real-time or QoS requirements, decentralized operation, power-awareness, flexibility to different kinds

of application [144]. The requirements of multimedia communication in MAC layer are the packet transmission with minimum error, delay and collision. Contention in the medium access may result in collision and hence delay and energy consumption. Latency, delay and jitter are the vital QoS parameters for multimedia communication.

The most important challenge for the multimedia communication in cognitive radio ad hoc and sensor networks is the intermittent communication due to cognitive cycle functions. These fundamental operations result in delay and channel quality degradation, and hence decrease in communication quality for the multimedia communication. In cognitive radio communication, there is nonzero probability of colliding with the packets of primary users as well as with the packets of secondary users. Furthermore, there are much more parameters that needs to be taken into account to realize the multimedia communication in cognitive radio ad hoc and sensor networks.

### 9.6.2 Existing MAC Layer Solutions

Despite surveys on MAC layer in WSN [145], and CRN [146, 147], they do not explain how to enable efficient multimedia communication in dynamic radio environment. In this section, in addition to explaining the state of the art solutions on MAC layer, we emphasize required changes to realize the multimedia communication in cognitive radio ad hoc and sensor networks.

### Wireless Sensor Networks

Many MAC layer protocols are proposed with different objectives for WSNs. However, they do not satisfy the requirements of multimedia communication and the challenges posed by cognitive radio and sensor networks. In sensor networks, the primary concerns are energy-efficiency and scalability, however throughput and latency attributes are secondary concerns [145]. They all must be primary concerns for multimedia communication.

MAC protocols can be divided into two categories which are contention-free and contention protocols. Contention-free protocols are TDMA-based, FDMA-based and

CDMA-based which make division on time, frequency and code, respectively. On the other hand, contention protocols do not reserve resources, they are allocated to the network users on demand. CSMA protocol and its variants are used for medium access control in sensor networks as contention protocols.

The main attributes of MAC protocols are energy-efficiency, scalability and adaptivity, channel utilization, latency, throughput and fairness [148]. In contention-free protocols, scheduling is organized in time, frequency and code domain to eliminate the interference and collision. TDMA protocols [149] support low duty cycle operation which decrease idle listening, however, TDMA protocols have scalability issues and do not support distributed functionality. Furthermore, TDMA protocols require global synchronization which is a burden for sensor networks. The clustering approach has been proposed for scalability issue and scheduling. LEACH [43] proposes TDMA scheduling for its cluster and cluster members. Furthermore, [150] uses different sub-channels by frequency division and code division and hence utilize FDMA and CDMA. Reservation of the network resources decreases collision, delay and jitter and increases throughput and provide real-time guarantees which are fundamental requirements of multimedia communication [4]. However, as disadvantages they are complex and require centralized control and extra complexity on sensor nodes.

The contention-based protocols use carrier sensing and collision avoidance mechanisms [144]. The challenge of contention based protocols is the collision due to the insufficiency in coordination. For example, two disparate nodes may send packets to the same receiver and there may be collision at the receiver node. This is called *hidden node terminal problem*. MACA [151] eliminates this problem by extra control signals which are RTS and CTS. It uses three way handshaking to coordinate the communication. The control signals may collide, however, collision probability is low due to the small control packet size. There are variants of this approach such as MACAW [152] and MACA/PR [153].

IEEE 802.11 [154] is a standardized protocol for wireless LAN. It combines the features of CSMA/CA, MACA and MACAW. IEEE 802.11 Distributed Coordination

Function (DCF) is designed for ad hoc networks. It utilizes CSMA/CA and RTS/CTS handshaking mechanism. If the medium is idle for a predefined interval, node is allowed to transmit. If channel is sensed to be busy, a random back-off interval has been chosen uniformly from the contention window interval. Furthermore, ACK and virtual carrier sensing by Network Allocation Vector (NAV) are used. The main disadvantage of this protocol is the listening to the channel during the back-off period which is energy consuming.

Hybrid schemes combine the contention based period with the contention-free period. Nodes in a neighborhood firstly contend for the reservation of the medium. After the reservation period, reserved communication resources are used by the nodes. CSMA approaches do not need clock synchronization and global knowledge about the network. However, contention-free protocols are not tolerant to the failures of the sensor nodes and clock synchronization and central controller are necessary. Dynamic topology changes in sensor networks may be costly due to the global rearrangement of schedules. Low contention in sensor networks causes lower channel utilization and higher delay than CSMA since the node should wait for its TDMA schedule to communicate, on the other hand, the node communicates when the channel is sensed to be idle in CSMA [155]. Hence, Rhee *et al.* proposes Z-MAC, a hybrid MAC protocol to combine the strengths of CSMA and TDMA while decreasing the inefficiencies of them. Main advantage of Z-MAC is the adaptability of network contention level. Under low contention it becomes TDMA, under high contention it becomes TDMA.

Table 9.6: MAC protocols in WSN

| Protocols | Type            | Technique       | Disadvantages       |
|-----------|-----------------|-----------------|---------------------|
| [149]     | contention-free | TDMA            | global sync         |
| [43]      | contention-free | TDMA            | clustered structure |
| [150]     | contention-free | CDMA-FDMA       | scalability         |
| [144]     | contention      | Carrier sensing | coordination        |
| [151]     | contention      | Carrier sensing | collision           |
| [154]     | contention      | CSMA/CA         | idle listening      |
| [155]     | hybrid          | CSMA-TDMA       | -                   |

From the perspective of multimedia communications, the collision-free protocols can provide real-time guarantees and tolerable delay bounds and desirable throughput by organizing the communication schedule. On the other hand, these types of protocols are not scalable and they do not adapt to the dynamic environment of sensor networks. Contention-based protocols can not provide real time guarantees due to the collisions. Hybrid protocols can be used for multimedia communication since the disadvantages of the contention-based and contention-free protocols by combining them. Hybrid mechanisms are more resilient to the scalability, energy-consumption and collisions.

Table 9.6 outlines the MAC protocols, their types, techniques used and disadvantage for multimedia communication in cognitive radio ad hoc and sensor networks.

### *Cognitive Radio Networks*

One of the most fundamental challenges for designing MAC protocols in cognitive radio networks is spectrum management. The medium access is highly affected by the spectrum sensing results and the communication between nodes is interrupted by spectrum hand-off and spectrum sensing. The resource allocation is performed to eliminate collision between cognitive radios and to avoid harmful interference to the primary users.

MAC protocols can be split into two categories, which are Direct Access Based (DAB) and Dynamic Spectrum Allocation (DSA) [147]. In DAB protocols every node optimizes its own goals and the resource allocation is performed by sender receiver handshake. DSA protocols try to achieve global network optimization.

The coordination among the nodes is a difficult challenge in CRN. Two nodes within the communication region of each other communicate if they have common channel. The agreement on communication channel can be performed on in-band channel or out-of-band channel. In-band channel negotiation utilizes the data channels, on the other hand, out-of-band channel negotiation utilizes different channel for the negotiation and the sharing of the spectrum sensing results. Generally, out-

of-band approach is used in MAC protocols. Out-of-band approach can be divided into two which are common control channel (CCC) and Split Phase (SP). The former approach uses a common control channel for signaling [156] and the latter approach allows the transceiver on each node to switch between control phase and data phase in a time frame [157]. The former needs two transceivers and handles synchronization problems, the latter is cost-efficient but reduces the network utilization due to the separate control phase. The common control channel approach is much more convenient than the SP approach since it overcomes the problem of synchronization and the system inefficiency. However, placement of two transceivers on one sensor node is not practical. Multimedia QoS requirements can be satisfied in a more robust way by CCC approach. However, it should be noted that the guarantee of common control channel among the network is not feasible due to the dynamic nature of spectral environment in CRN. On the other hand, Frequency Hopping Sequence (FHS) approach utilizes in-band and sensing interruptions do not affect the system performance by hopping the frequency to enable the communication [158]. It may satisfy throughput and QoS requirements of multimedia communication.

Contention in cognitive radio networks can be avoided by centralized or distributed algorithms. As classified in [146], there are three kinds of CR MAC protocols: random access, time-slotted and hybrid. In random access MAC protocols, CRs utilizes CSMA/CA like architectures for accessing the medium for control and data packets. Centralized carrier sensing CSMA based mechanism is proposed for CRN coexisting with a primary system. It utilizes in-band signaling and CR nodes have single transceivers. In time-slotted MAC protocol, time is synchronized and slots for data and control channel are reserved. In C-MAC [159], time is divided into superframes which contain slots for beacon period and data transmission period. It uses multiple transceivers to enable high throughput and resilience to the dynamic spectrum environment. Rendezvous channel is used for the coordination of the nodes. Backup channel is determined from out-of-band in case of PU appearance on rendezvous channel. In hybrid protocols, medium access is achieved by utilizing random access

and time-slotted schemes. For example, in OS-MAC [160] there are pre-determined intervals for the communication coordination. Common control channel is used to exchange the control packets and each node is a member of a cluster.

From multimedia communication perspective, MAC protocols face with very challenging difficulties. The existing MAC layer approaches do not support real time communication, seamless communication due to primary user and high throughput requirements, jitter and delay bound. An important MAC protocol is proposed to support multimedia communication in CRN [161]. It is a distributed QoS-aware MAC protocol for multi-channel CRN. Based on the channel usage statistics the channels to be sensed and the data channels are determined to satisfy the certain QoS requirements. For various traffic types spectrum sensing duration is changed to enhance the QoS provisioning. The authors in [161] offers a priority based spectrum access scheme for heterogeneous traffic to further improve QoS. MAC protocols for multimedia applications must consider QoS requirements such as traffic, primary user activities, real-time communication and delay bound. Furthermore, cognitive cycle operations must be considered for medium access such that spectrum sensing results and spectrum decision are fundamental operations that affect the performance of the communication.

### *9.6.3 Open Research Issues for MAC layer*

There are extensive approaches for MAC layer in WSN which satisfies the requirements of multimedia communication. On the other hand, the protocols proposed for CRN mainly consider to decrease the interference to the primary users and to increase channel utilization. They mainly do not consider multimedia communication. Hence, there is a need to design a MAC protocol to realize multimedia communication in cognitive radio multimedia ad hoc and sensor networks.

The proposed MAC protocol must minimize the delay caused by spectrum hand-off as well as contention. Furthermore, it must offer high throughput against changing operating channel and its condition. Hence, designing a MAC protocol satisfying the

requirements of multimedia communication is a challenging task.



## Chapter 10

# NETWORK CODING FOR COGNITIVE INTERNET OF THINGS

### 10.1 Introduction

The interaction of humans with the digital world becomes more powerful and sophisticated with the advancements in the technology. The wireless communications technology plays a vital role for these advancements. In this respect, the Internet of Things (IoT) is one of the most innovative paradigm for next generation wireless networks [162, 163].

The IoT enables the interconnection of every electronic device in the world through the Internet [163]. Although the idea of the IoT is clear, the exact definition of this phenomenon is not determined thoroughly. It can be viewed as a union of next-generation devices that sense the surrounding and harvest information from the physical world [164].

The interconnection of the devices with each other and communication among them will cause a large volume of traffic and congestion in the electromagnetic spectrum. As these devices in the IoT mainly use already crowded ISM bands, the problem of spectrum scarcity is intensified by the introduction of the IoT. Furthermore, the licensed spectrum bands are underutilized according to [165]. To overcome the problems of spectrum scarcity in unlicensed spectrum bands and the under-utilization of licensed spectrum bands, cognitive radio (CR) technology has been proposed [166]. The wireless devices with CR capability can use the spectrum opportunistically. Unlicensed users, i.e. CR nodes, coexist with licensed users, i.e., primary users (PUs). Cognitive cycle operations, which are spectrum sensing, spectrum decision and spec-

trum hand-off, enable CRs to use the licensed channels in an opportunistic manner. These operations provide scanning of the spectrum for an opportunity to transmit and ceasing the transmission if PU activities exist during communication. Hence, cognitive capability of devices increases the efficiency of the spectrum utilization and overcomes the spectrum scarcity problem by opportunistically utilizing idle licensed spectrum bands. To this end, devices with CR capability are utilized due to their benefits in wireless networks [8], sensor networks [20], and wireless ad hoc networks [9].

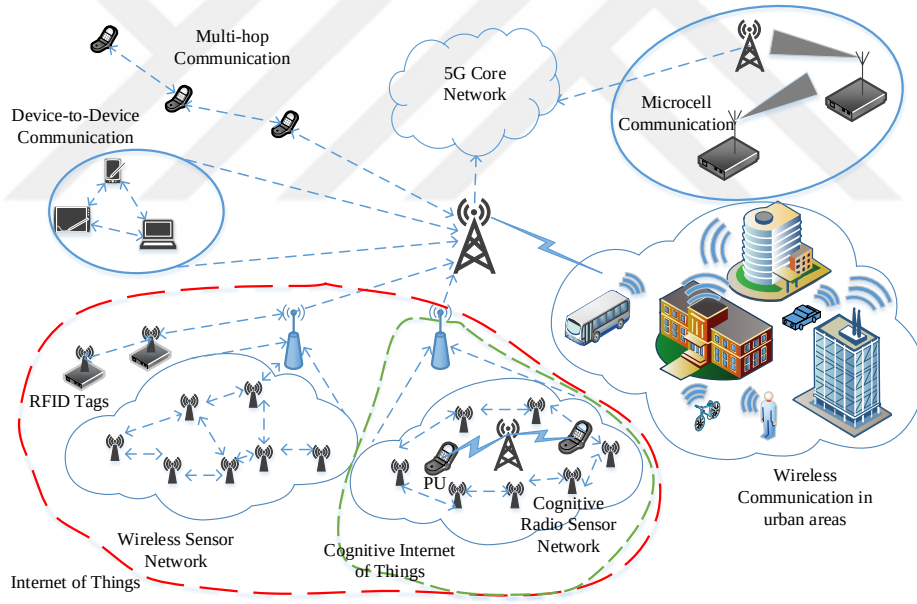


Figure 10.1: Elements of 5G networks.

The connectivity between the IoT devices is not enough to fully realize IoT since these objects should also interact with their environments by learning, thinking and understanding. Hence, the authors in [167] proposed a new paradigm called cognitive Internet of Things (CIoT). In this type of IoT, the objects can perform cognitive tasks such as perception and knowledge discovery. It is an enhanced version of IoT with a potential to make connection between the physical world and the social world by seamless network operation, intelligent IoT services, and smart automatic decision making. In this chapter, we will investigate the cognition in spectrum usage of IoT

devices. We will consider the CIoT objects with CR capability so that they can utilize unused licensed spectrum bands. We want to enhance IoT paradigm with the capability in terms of spectrum usage.

5G is defined to be an inclusive network such that all different network interfaces are combined together to offer seamless communication with high throughput, low latency and better quality of service [168]. The IoT is considered to be a part of 5G wireless networks due to its ability to offer an infrastructure handling the enormous amount of traffic [169]. The IoT consists of different types of networks based on different applications such as wireless sensor networks (WSNs). WSNs provide inter-connection of sensor nodes among themselves through ISM bands [5]. The nodes in sensor networks sense an attribute of the physical surroundings in which they are deployed. They form a distributed wireless network. Furthermore, they can collaborate to convey the extracted information to the outside world with the help of IoT technology. The sensor nodes may have CR capability which leads to a new networking paradigm, cognitive radio sensor networks (CRSNs). It provides opportunistic access to the licensed spectrum bands, which will provide higher throughput and QoS. This feature of CRSNs makes them to be the main components of the CIoT. In this chapter, we consider CRSNs in the context of the IoT. Fig. 10.1 shows the architecture of 5G including different types of networks such microcell networks with communication by directional antennas, WSNs, RFID tags, and CRSNs, etc. The IoT is mainly the union of RFID tags, WSNs and CRSNs. In this chapter, we define CIoT as the CR capable IoT.

The IoT devices produce excessive amount of information due to their large number of deployments, and their packet transmissions result in congestion in the network. Network coding (NC), a technique utilized in [66, 170, 67], may play an important role to manage the information since it has changed the perception of conveying the information. Instead of store-and-forward approach, the information packets can be combined and transmitted with NC. The generated packets are combined linearly where coefficients are drawn from a Galois field. If destination node receives suffi-

cient number of network coded packets, it can decode all the source packets. It also increases immunity to failures by this mixing operations. Furthermore, it offers some benefits such as increase in throughput, decrease in interference, and enhancements in reliability and data persistence [171]. Hence, effects of the dynamic radio environment due to the CR capability of IoT such as communication failures due to PU activity and errors in spectrum sensing can be mitigated by utilizing more efficient communication with NC. Furthermore, there are two kinds of network coding according to the number of coded sources. The first one is intra-flow in which nodes encode only its own packet. The second one is inter-flow in which nodes encodes the packets coming from different source nodes [172]. Hence, NC may be considered as an efficient method to handle the information in the IoT from different sources as well as from the same sources.

In this chapter, we investigate the communication with NC in the CIoT. Adaptation to the dynamic spectrum environment with CR capability and the application of NC pose challenges in the CIoT domain. Hence, we investigate the technical challenges of NC in CIoT. We investigate the sensor networks with CR capability since they are the main elements of the CIoT. To this end, we focus on two issues. The first domain is the Internet connection of CRSNs. The second one is the application of NC inside the CRSNs. The fundamental requirement of the CIoT is to connect every device in dynamic radio environment to the Internet such that the information can be restored, manipulated and interpreted anywhere and anytime. Hence, the integration of CRSNs to the Internet makes possible to reach almost every physical knowledge in the world, to generate the information about the physical environment, and to store and process such an enormous amount of information in a dynamic radio environment. To this end, we first state the challenges to enable the CIoT. Afterwards, we investigate approaches of the integration between CRSNs and the Internet to realize the CIoT when using NC. Afterwards, we investigate the NC applications inside CRSNs to benefit from the advantages of it in the CIoT domain. We also state the challenges and open issues of the application of NC for the CIoT. Finally, we

conclude the chapter.

## 10.2 Technical Challenges for Enabling NC in the CIoT

Sensor networks are the main elements of the IoT. Billions of sensor nodes will be connected to the Internet when the IoT is realized. Sensor networks can be considered as digital skin which provides a virtual layer to capture the physical world and to realize the IoT vision [5]. However, there is a spectrum shortage that poses a challenge in wireless communications. This problem is intensified with the large number of devices deployed in the IoT. CR can overcome this challenge by opportunistically using the licensed spectrum bands. Hence, sensor nodes in CRSNs provide dynamic access to the spectrum. Furthermore, NC is a method that supports encoding operations by intermediate nodes in the network. Due to these facts, the IoT vision, CR capability, the sensor networking, and NC pose challenges as follows.

### 10.2.1 Challenges posed by the IoT

**Service differentiation:** IoT merges different technologies such as ZigBee, IEEE 802.15.4, 6LoWPAN etc. The functioning of different systems in the network poses a challenge. The sensor nodes may be application specific systems, however, different type of sensor nodes must cooperate to achieve a common goal such as e-health system. Different sensor nodes deployed in human body must be compatible with one gateway, which may be the mobile phone of the person.

**Limited computational capability of CRSN nodes:** The limited capability of sensor nodes imposes challenges to realize complex tasks. NC could be complex operation if the number of sources increases. The sensor nodes are also energy-limited. However, NC can be used to decrease the number of transmissions to convey information packets due to its resiliency to channel losses. Hence, NC can be used to overcome the energy challenge of CRSN nodes.

### 10.2.2 Challenges posed by the CR

**Dynamic radio environment:** Wireless channel is an unreliable due to path loss, shadowing and multi-path fading. They cause the communication errors and the failures in the transmissions of the packets. In addition to failures due to wireless channel conditions, the dynamic radio environment poses challenges to access the communication channel. The communication link may fail due to the activities of PUs, which are the holders of the licensed spectrum bands. These failures due to the activities of PUs affect the NC for CRSNs.

**Synchronization for spectrum sensing:** Cognition of sensor networks comes from the spectrum sensing capability. As the spectrum sensing does not distinguish the difference between the CR signal and PU signal, the neighbor CR nodes around the sensing CR node must be silence to prevent the possible spectrum opportunity.

**Spectrum sensing:** Spectrum sensing is the one of the most important cognitive cycle operation of CRSN nodes since the nodes access the channel according to the results of the spectrum sensing. It might lead to the missing spectrum opportunity by sensing the existence of PU in case of no PU presence. Furthermore, the CRSN nodes may sense the spectrum band as idle during the presence of PU.

### 10.2.3 Challenges posed by the NC

**Spectrum-aware broadcasting:** The CIoT nodes will make their transmission on idle licensed bands. Hence, if the nodes in its transmission range do not operate on that channel, it cannot hear that transmission. Hence, the receiver may not also receive the packet. Opportunistic listening, where the neighbor nodes overhear the packet due to the broadcasting, may be degraded due to spectrum-aware environment. In COPE [173], the neighbors overhear packets and opportunistic coding, determining which packets to be combined to maximize the benefit of NC, is performed to support the network coded transmission for throughput increase. However, dynamic radio environment may deteriorate the gain of broadcasting.

**Batch Completion:** For successful NC operation, the destination node must

have  $N$  number of linearly independent packets. However, due to PU activities or imperfections in cognitive cycle operations such as spectrum sensing, sufficient number of packets do not arrive at the destination node. This makes the received network coded packets useless. Hence, this poses a reinforced challenge in network coding due to CR capability of nodes.

### 10.3 Integration of CRSNs with the Internet using NC

NC enables the nodes in the networks to encode multiple packets linearly. Linear coefficients are used to produce a network coded packets, and these coefficients are stored in the header of the network coded packet [171]. CRSNs and the Internet have different packet structures, in which the integration may become problematic for proper functioning of the CIoT. Hence, the integration of CRSNs with the Internet is important for the CIoT using NC.

CRSNs are distributed networks as there is no central entity that regulates the communication. Furthermore, the nodes send their observations to the sink over multiple hops if the scale of the network is large. The CRSN nodes can also reach to the sink in one-hop according to the application of sensor networks and their network scale. Another critical feature of CRSN is to use the electromagnetic spectrum opportunistically.

The main problem of the sensor networks in the CIoT is how to interconnect the nodes to the Internet. Novel architectures must be presented to allow the CIoT sensors to be fundamental elements in 5G. These architectures may help realizing the CIoT. To this end, we overview architectures in [5, 6] to enable the connection of CRSNs with the Internet. We study network architectures for the Internet connection to investigate the application of NC in CRSNs in the context of the IoT. The integration of CRSNs with the Internet will provide flexibility to diverse applications, rapid connectivity on the deployment area, and compatibility with different architectures in the Internet [164].

There are two integration approaches which are stack-based [5] and topology-based

[6]. The similarities of the network stacks between the sensor network and the Internet are the key to the stack-based integration approaches. These approaches are front-end solution, gateway solution, and TCP/IP solution. The front-end solution advocates the independence between the Internet and the sensor networks. As the Internet uses TCP/IP, the sensor network uses its own specific protocol. The gateway solution uses tunneling for the exchange of information to enable integration. The TCP/IP solution advocates the integration by utilizing the same networking protocols in both sides. The topology-based approaches depend on the deployment of the Internet-connected nodes in the sensor networks.

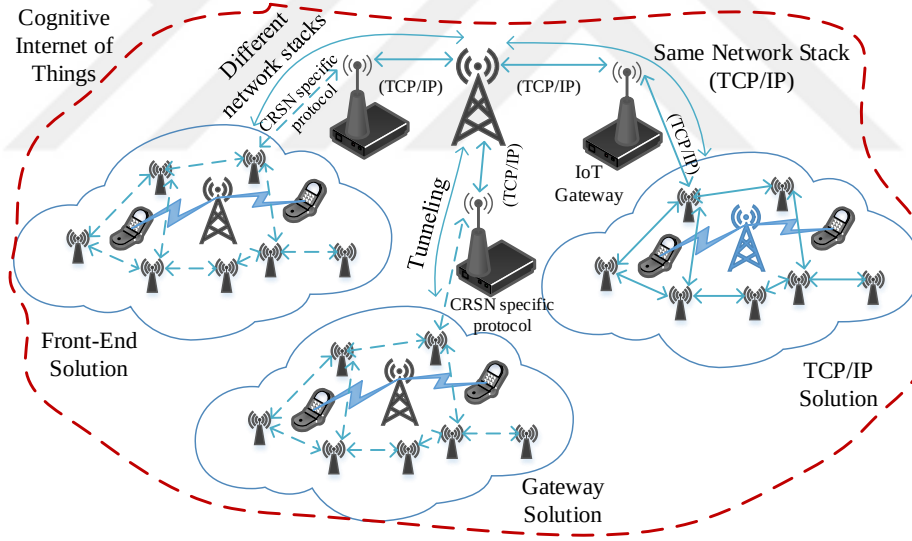


Figure 10.2: Stack-based integration [5].

### 10.3.1 Stack-based Integration

The stack-based integration solutions for CRSN has an important difference since the communication is spectrum-aware due to the CR capability. The three stack-based approaches are illustrated in Fig. 10.2. The base stations which provide the connectivity to the Internet must operate in an opportunistic manner, and they also behave as CRs. However, they do not have limited power, which makes them capable of complex operations. In front-end solution, the base station has two interfaces: one

for CRSN, and one for the Internet connectivity. The information coming from the CRSN nodes opportunistically is stored in the base station and the base station sends it to the cloud or to an Internet user in a remote area using TCP/IP. In this architecture, CRSN nodes are connected to the IP networks through base stations at the edge of CRSNs. This architecture is the classical approaches existing in literature.

The gateway solution offers the addressing of CRSN so that a user on the Internet can directly communicate with a CRSN node in the network. It is implemented by IP tunneling, and it requires that all information goes through the base station. It may degrade the benefits of the NC due to extra bits for encapsulation of the IP packet.

The TCP/IP solution integrates the sensor networks to the Internet fully such that a user on the Internet can directly reach any CRSN node. IPv6 approach for WSNs is very promising to connect every sensor node to the Internet [174]. The use of IPv6 would realize the TCP/IP solution for CRSNs in IoT/5G. It provides interoperability between CRSN and different network systems in 5G which will emulate always-on link and hence connectionless communication [174].

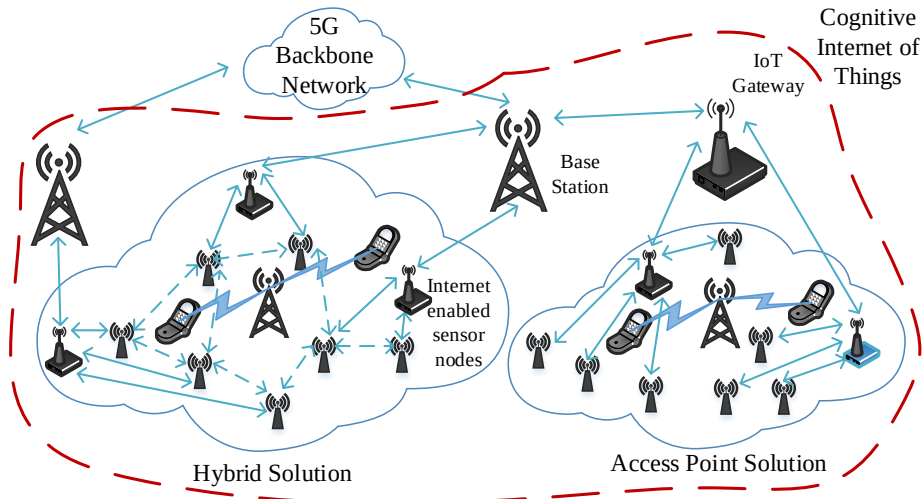


Figure 10.3: Topology-based integration [6].

### 10.3.2 Topology-based Integration

The topology-based integration solutions discuss the location and deployment of the nodes or base stations which are directly connected to the Internet [6]. The hybrid solution advocates multiple nodes which have access to the Internet. These nodes are the neighbors of base stations. In access point solution, sensor nodes have direct access to the access points. These Internet-enabled nodes and the CRSN nodes form trees for the integration. The topology-based integration approaches are seen in Fig. 10.3.

The main aim of the IoT is to connect every device to the Internet. The CRSNs are the main components of devices that can extract information from the environment, hence they are the main pillar of the CIoT. The harvested information by the CRSN nodes is important for the actions to be taken and the information processing. The integration of CRSN with the mobile networks or the Internet realizes the IoT, and manages the communications in CRSNs. Table 10.1 shows the summary of integration approaches for the application of NC.

Table 10.1: Summary of Integration approaches for NC

| Integration Approaches for Network coding |                     |                                                                                                                                                                                                                                                                                                                                            |
|-------------------------------------------|---------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Stack-based integration                   | <i>Front-End</i>    | <ul style="list-style-type: none"> <li>- both intra-flow and inter-flow NC can be performed by CRSN nodes</li> <li>- decoding can be done in base station or in the cloud</li> <li>- only CR capability must be considered on top of the NC solutions in WSN</li> </ul>                                                                    |
|                                           | <i>Gateway</i>      | <ul style="list-style-type: none"> <li>- network coded packets by CRSN nodes must traverse the base station</li> <li>- the change in the network layers in the gateway causes packet structure change</li> </ul>                                                                                                                           |
|                                           | <i>TCP/IP</i>       | <ul style="list-style-type: none"> <li>- network-coded packets can be directly headed to the cloud</li> <li>- the NC is performed in network layer both in CRSN and the Internet</li> <li>- no packet structure change at the sink</li> </ul>                                                                                              |
| Topology-based integration                | <i>Hybrid</i>       | <ul style="list-style-type: none"> <li>- this is more compatible to the intra-flow NC due to one-hop access</li> <li>- single hop to reach the sink results in less error in NC</li> <li>- single hop means less exposure to PU activity</li> <li>- this approach is costly since uses more base stations</li> </ul>                       |
|                                           | <i>Access Point</i> | <ul style="list-style-type: none"> <li>- this is more compatible to the inter-flow NC due to network structure of trees with multiple roots</li> <li>- multiple hop to reach the sink results in less error in NC</li> <li>- multiple hop means more exposure to PU activity</li> <li>- the error in the route is more possible</li> </ul> |

### 10.4 Network Coding Applications for the CIoT

After the explanation of the integration approaches for CRSN with the Internet, we investigate the application of NC in CRSNs to highlight the open issues and challenges. The application of NC mainly depends on the dynamic radio environment. We present the NC applications which are applied in WSNs. Then, we state the possibilities of the application of NC in CRSNs while considering the dynamic radio environment and limited resource of CRSN nodes. In the following list, we explain the NC applications for CRSNs.

- **Distributed Storage:** Distributed storage is one of the main application areas in sensor networks. The nodes in sensor networks have limited battery power and memory. Hence, the nodes work collaboratively to achieve their goals. As the memory size is small, the extracted information by the sensor nodes is collected by an agent or a base station [175]. The data collection is expensive, hence, it is not performed frequently due to the resource-constrained nature of sensor nodes.

The base station selects randomly a number of nodes to extract the desired information. However, retrieving the information may not be successful. NC increases the possibility to extract the information and provides redundancy by dividing data packet into segments and storing the linear combinations of these segments. If data packet is divided into  $N$  segments and the base station collects  $N$  linearly combined data segments, it can decode the data packet [175].

The base station may not reach the sensor nodes in the network all the time due to harsh environments. The data may also become obsolete. The decoding operation must be carried out by the sensor nodes to eliminate the obsolete data segments. However, it may be difficult since the node should have  $N$  linearly combined packet to decode and eliminate the obsolete segments. The authors in [175] have proposed partial NC which enables some of the data segments to be combined.

Data collection in CRSN in the context of the CIoT needs special considerations. First of all, the integration of CRSN with the Internet in this data collection scenario must be investigated. The base station does not behave as in the conventional networks. Hence, the most convenient technique for the stack-based integration is front-end. The interaction of the base station with the sensor nodes are occasional, hence the simplest integration, access point solution, should be utilized for topology-based integration. Furthermore, opportunistic use of spectrum causes obstruction to complete necessary number of data segments.

- **Data Persistence:** Data persistence is defined to be the fraction of generated data in sensor networks that reached to the sink. The application of the NC provides resiliency to the failures. Hence, the authors in [176] use NC to provide the persistence of the data. Although there are unpredictable errors in sensor networks, the generation of the packets by the sensor causes congestion and delay for the nodes close to the sink, which also decreases the data persistence.

The sensor nodes employing the Growth Codes [176] encode the packets linearly. As the encoded packets are sent to the neighbor nodes to reach the sink, the neighbor again encodes the incoming coded packets. Hence, in the beginning of the session the sink receives low degree encoded packets, later on the degree of the encoded packets grows.

Data persistence is also very important for CRSN. From the perspective of the CIoT, the CRSN nodes must be connected to the Internet. The access point solution is the most compatible solution for this network configuration since the data packets are routed to the sink with multiple roots, and the packets are linearly encoded in the mean time. Furthermore, the NC overcomes the challenges of sensor network which are escalated by dynamic PU activities.

- **Data Reliability:** Reliability is degraded due to the packet losses in sensor networks. The redundancy to combat the data losses in sensor network causes

excessive energy consumption. Hence, the NC is used to manipulate the redundancy by NC, and the multi-path routing in [177]. They form tree whose root is the base station, and the nodes in the tree linearly combine their message with the other message coming from its child nodes.

Packet reliability in the harsh environment of CRSN is of utmost important. This problem is also intensified due to the licensed user activities. Furthermore, connecting CRSN to the Internet for the realization of the IoT causes problems. However, NC can be used to manage redundancy in the network, and multi-path routing can be utilized to increase the reliability. The hybrid and the access point solutions can be implemented to connect the CRSN to the Internet to enable the IoT.

- **Code Updates:** The sensor nodes are deployed in unattended areas such that the sensor nodes become inaccessible after the deployment. It poses challenges; one of them is limited battery power since we can not change the battery of the sensor nodes. Hence, power efficient solutions are introduced to overcome this difficulty. Another significant challenge is debugging sensor nodes. It requires upload of new codes to the sensor nodes and a broadcast from the base station to the sensor nodes. The data flow is not the same with the previous protocols. The flow in this scenario is downwards. The authors in [73] offers adaptive NC for code updates in sensor networks. The application of the NC for the code updates poses challenges such as limited memory and dynamic wireless channel conditions. Hence, the authors propose a coding scheme which depends on the neighbor of the sensor nodes.

CRSNs, which are elements of the IoT, also need code updates since the debugging is necessary process to eliminate errors due to software. NC needs to be studied in this scenario to offer reliable sensor code update. TCP/IP integration solution is beneficial for this scenario since the node will directly have contact with the Internet host for the code updates.

- **Interference mitigation in the CIoT:** In this section, we point out a possible application of NC for interference mitigation in CRSNs. Although CRSN nodes sense the spectrum periodically to be aware of the status of the spectrum use, the imperfections in the spectrum sensing and the sudden appearance of PUs on the channel during the transmission by the cause interference to the primary users. The interference to the PUs by CRSN nodes must be limited to not affect the operation of licensed users.

NC is used as a tool to shape the spectrum usage in primary networks [70]. It requires the batching the network packets in the buffer of the nodes. After the nodes receive the uncoded packets, they encode the packets via linear NC and transmit them. The buffering the uncoded packets and transmitting the resulting encoded packets organize the activity of PUs so that the spectrum is used by PUs become more predictable. This improves the performance of spectrum sensing and decreases the possible interference on PUs.

The NC may also be used in the secondary network side to decrease the interference to the PUs. However, the application of NC in the secondary network side, i.e., CRSNs, will not only shape the spectrum usage but it will decrease the total transmission effort to convey the packets to the destination. A CRSN node with NC capability decrease the number of transmission of packets since the receiver only needs  $N$  number of packets to decode the overall message, in which  $N$  is the number of source packets.

Table 10.2 outlines the application areas of NC and most possible integration approaches.

### 10.5 Open Issues

The IoT vision and CR require more attention while offering solutions for the CIoT. The challenges of CR and sensor networks are intensified in the IoT. NC is an important technique to address these strong challenges. Open issues can be outlined as

Table 10.2: Applications of NC and possible integration approaches

| <b>Network coding applications</b> | <b>Usable integration approach</b><br>Stack-based; Topology-based |
|------------------------------------|-------------------------------------------------------------------|
| Distributed storage                | Front-end; Access point                                           |
| Data persistence                   | Front-end, Gateway; Access Point                                  |
| Data reliability                   | Front-end, Gateway, TCP/IP;<br>Hybrid, Access Point               |
| Code updates                       | Front-end, Gateway, TCP/IP;<br>Hybrid, Access Point               |
| Interference Mitigation            | Front-end, Gateway, TCP/IP;<br>Hybrid, Access Point               |

follow in the context of the IoT.

- A holistic network architecture, which includes CR capabilities and the IoT vision with the application of NC, must be developed for sensor networks.
- The applications offering NC to the sensor networks must be reconsidered by taking into account the CR capability and the interconnection of sensor networks to the Internet. For instance, a NC solution could be developed to address the reliability of the data in sensor networks with a careful consideration of CR capability.
- CRSNs are mostly event-based systems such that many sensor nodes sense an event and the event readings are collectively conveyed to the sink or the gateway node. A new event reliability schemes could be developed by using NC.
- CRSN nodes in the IoT probably have multimedia packets since 5G communication would require high bandwidth applications such as video and image transmission from a monitored area. Hence, it is necessary to apply efficient NC schemes which avoid decoding delays since multimedia packets have time constraints.

- The effects of spectrum mobility on the NC should be investigated since spectrum mobility may degrade the benefits of NC.
- The use and effects of IPv6 in CRSN to connect it to the Internet should be clearly investigated for the NC by considering the resource constraint of CRSN nodes and dynamic radio environment.
- The mobility of CRSN nodes for the application of NC has not been investigated thoroughly. The spectrum mobility and node mobility in CRSN must be taken into account to offer efficient NC solutions.
- IPv6 application to CRSNs could be investigated to enable homogeneous IP layer for network systems in the IoT and 5G networks. The NC overhead in IPv6 packet could be studied considering the dynamics of CRSNs. Header compression techniques could be investigated.
- Depending on the application, CRSNs may be event-based such that an event is sensed by the nodes and the event samples are conveyed to the base station in a collective effort. However, the spatial and temporal correlations between the event samples require a careful consideration when applying NC in CRSNs.

## Chapter 11

# ENERGY HARVESTING COGNITIVE RADIO NETWORKING FOR IOT-ENABLED SMART GRID

### **11.1 Introduction**

The IoT paradigm provides connectivity to objects for information exchange from one remote place to another via the Internet [163, 162]. These objects sense the physical world and harvest information about it, and send the harvested data to remote users via the Internet. It provides the accessibility of information from anywhere in anytime. These objects form interconnected networks that are self-configurable and intelligent. Hence, the IoT is utilized in a number of applications such as e-health monitoring, transportation, environment monitoring, and logistic management [178].

As the IoT extends the wireless communication by providing connectivity among the objects, SG supports evolution of electrical power system by the utilization of next generation communication systems [179, 180]. It paves the road for more agile grid with increased efficiency, reliability and security. The energy demand, aging infrastructure of the electric grid and varying energy production due to renewable energy resources are some challenges of the SG. Furthermore, it provides real-time remote monitoring of the SG equipments for power provisioning, estimating failures, capacity limitations and blackouts [179], [181]. This provides an effective monitoring of the electric grid and control for safe, reliable and efficient power delivery in the SG [182]. Wireless sensor networks are main components of the IoT, and they form a digital skin the observed system. From this point of view, enabling the IoT in the SG is fundamental step towards the realization of it.

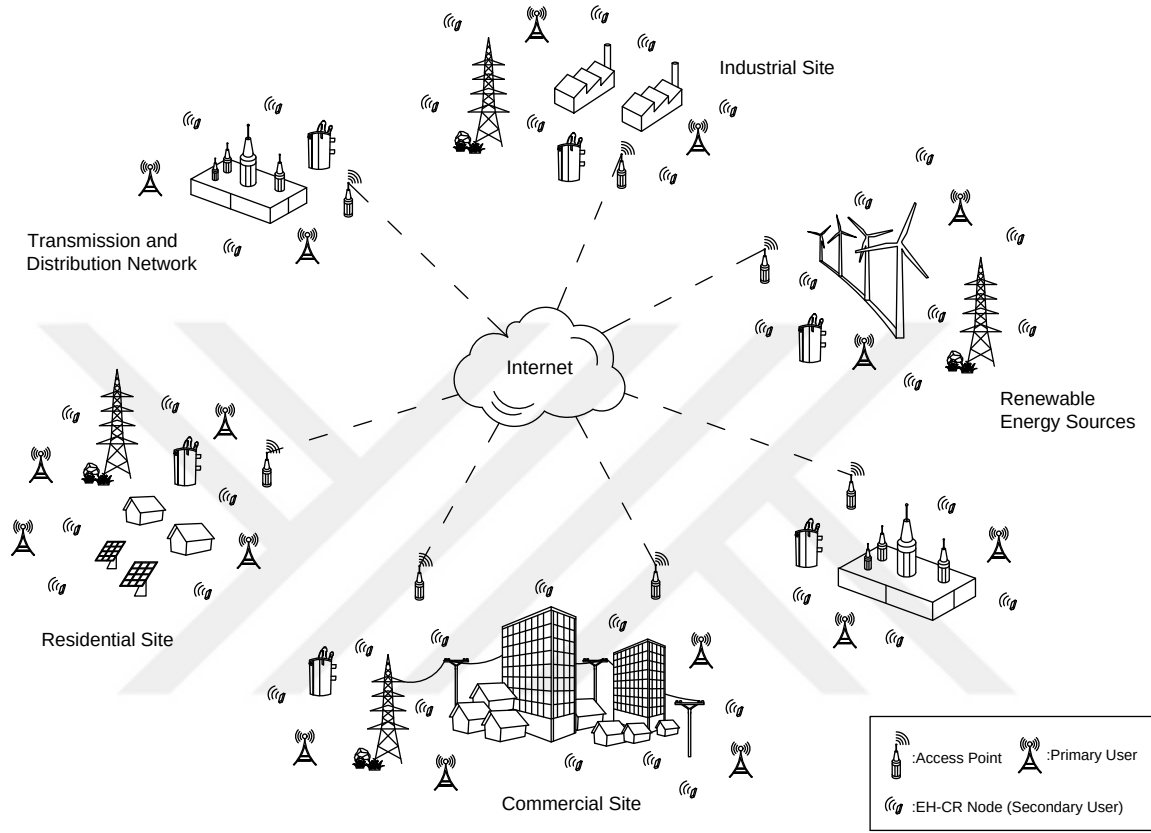


Figure 11.1: IoT-enabled SG Architecture.

The SG can benefit from the application of the IoT technology since the IoT enables smart monitoring of the environment, which is the main goal of the SG. Utilization of the IoT provides efficient management of resources by smart meters, home gateways, smart plugs and connected appliances via the Internet since it ensures efficient communication between consumers and utility providers, which provides efficiency in energy production and consumption [183]. Satisfaction of consumers' requirements and energy production from alternative resources cause a very dynamic environment and require efficient management of the electric grid. Autonomous monitoring, diagnosis and control, and efficient operation of the power equipments for the power generation, and distribution require monitoring and actuating devices [184]. Hence, the inclusion of the IoT in the SG is important. This will increase the utilization of information and communication technologies in the SG and provide effective

management of power grid system [185]. Empowering the SG with the IoT technology will lead a new paradigm, i.e., IoT-enabled SG. An IoT-enabled SG architecture can be seen in Fig. 11.1, which shows that the elements of the SG communicate over the Internet. The nodes, which are named as energy harvesting cognitive radios (EH-CR) in sequel, are our IoT wireless devices, and they access the Internet via access point. The condition of power grid elements, their energy production, the consumption of the energy are observed and measured via the IoT devices. The observations and measurements are sent over multiple hops to reach the Internet gateway, i.e., access point, to send them to remote areas for necessary actions to be taken in the IoT-enabled SG. Power consumption in industrial, commercial and residential sites can be monitored, and the power generated by renewable energy resources can be observed in real time via the Internet. For this architecture, SG benefits from the advantages of IoT, which are support for the communication of heterogeneous wireless devices, flexibility and context-awareness. This provides also better management of the grid with the Internet connection between SG components, which increases accessibility.

Enabling wireless technologies for the communication across the Internet are Wi-Fi, 3G, 4G, and satellite [186]. On the other hand, the standards used in the IoT environments are IEEE 802.11 and IEEE 802.15.4 for local areas. Hence, IoT devices to realize the SG operate mostly on ISM bands. However, these bands are heavily utilized. The over-utilization decreases the communication quality and increases the energy consumption of the resource-constrained wireless devices in the SG due to collisions. Furthermore, communication links have high packet error rates and variable link capacity due to the SG specific challenges such as electromagnetic interferences and equipment noise [184], [187], [188]. Hence, the channel conditions are generally harsh in the SG environment [187], which results in a dynamic delay and capacity variations in the SG networks. To overcome these challenges, CR technology can be utilized in the SG applications [189] so that the IoT nodes in the SG can access bands, which have better channel characteristics, in a dynamic manner. CR has special functionalities, which enables it to utilize licensed bands opportunistically, are

spectrum sensing, spectrum decision and spectrum hand-off [8]. With the spectrum sensing, idle licensed channels are determined. Afterwards, CR can resolve the problems of spatio-temporal variation on the channel characteristics, reliability, latency, harsh propagation conditions and collisions due to excessive use of certain channels by utilizing idle licensed channels [184].

Wireless nodes in the IoT-enabled SG are resource constrained. In spite of the recent advancements in ultra-low power transceiver and processor technologies, a conventional battery tends to deplete less than a year. This issue necessitates periodic replenishment and maintenance, however, the excessive numbers of the deployed elements, the tasks that are being fulfilled and the randomness of depletion times make this option impractical. Therefore, the need for a self-sustaining mechanism becomes more apparent to overcome limited power supply difficulty of IoT nodes. Although an auxiliary and/or a totally distinct source can contribute this aim sufficiently, energy harvesting methods come to the forefront as the energy that can be provided by these techniques is theoretically unlimited. As there are numerous potential alternatives, i.e, environmental and non-environmental, to gather energy, temperature and motion variations; electromagnetic fields, radio frequency signals; and light propagations can be regarded as the well-studied ones of these techniques. EH eases the problem of limited supply for IoT-enabled SG.

There are two fundamental problems in the domain of IoT, which are spectrum scarcity and resource constraint. They are intensified if the IoT is utilized in the SG since wireless channel conditions and environment in the SG are harsher than those of any other IoT domain. In this chapter, we propose a new networking paradigm, energy harvesting cognitive radio networking (EH-CRN) for IoT-enabled SG, which utilizes two important techniques, namely energy harvesting and cognitive radio. The contributions of this chapter are to provide a framework to merge these techniques to eliminate the problems of IoT-enabled SG and to introduce challenges, the potential advantages of this new paradigm, and to present network and node architectures. To this end, we first explain the usage of CR in the IoT-enabled SG. Afterwards, we

outline the existing energy harvesting techniques and how they can contribute to the realization of IoT-enabled SG. We overview the operation of the energy harvesting cognitive radios (EH-CRs), and explain their node and network architectures. We also state open issues and future research directions to realize EH-CRN for IoT-enabled SG.

## **11.2 Cognitive Radios in IoT-enabled Smart Grid**

The centralized management of the electric grid has experienced a paradigm shift towards the SG. It enables the two way communication, which connects the consumer side and the utility companies [180]. This paradigm provides an efficient management and control of the grid in a better way. SG brings the capability of monitoring of demand and supply in real time. Hence, SG adds new services to the customers, in which they can adjust their energy consumption according to the demand and supply balance.

To enable the concept of the SG, it should be integrated with the next-generation information and communication technologies having the ability of sensing and broadband wireless communication, supporting ubiquitous computing and adaptive control [190]. This will increase the stability of the electric grid, decrease unnecessary power consumption, predict communication blackouts, and provide security of the grid and power provisioning.

According to [190], sensing, transmission and control are the basic functionalities that are being offered by the SG infrastructure. Smart meters and sensors are the key components for sensing operations. Depending on the transmission scheme, sensed data reach to the controller or centralized coordinator/gateway via multiple hops. The SG covers a large geographical area, which makes the communication infeasible due to the harsh environmental conditions and the increased distance between communicating parties. Hence, the communication architecture of the SG is divided into three main groups, which are home/building area networks (HANs/BANs), neighborhood area networks (NANs), and wide area networks (WANs) [191], [192], [189], [190]. The

sensors in homes are essential parts of HAN. They send their readings to the local access points. HANs in a neighborhood constitutes a NAN, and a NAN connects the grid to the core utility systems [189]. SG's WAN is the network that covers the core network and the backhaul network [189]. For the connection of these networks wireless communication is utilized. When we look at the overall SG network, there is a hierarchical communication infrastructure [192].

Sensor nodes may be deployed in different parts of the electrical power system, which make them vital components of the SG. The deployment of the sensor nodes on the grid realizes the efficient and reliable power flow from the generation units to the end users [187]. These sensors provide monitoring of the power systems and diagnosing failures, which prevent the outages, and increase the reliability and efficiency of the electric grid [187], [193]. The SG benefits from the advantages of wireless sensor networks (WSNs), which are easy deployment, collaborative effort for sensing, support for increased coverage, flexible operation and low cost. This provides low-cost monitoring and diagnostic system for the SG [91].

The use of wireless sensor nodes poses some challenges in the SG. These challenges can be summarized as harsh channel conditions, reliability and latency requirements, bit error rate and channel capacity variation, and the limited power capability of the sensor nodes [187]. Conditions in SG may deteriorate the wireless channel by high humidity, dirt, dust and vibrations [194]. These environment-related parameters are also harmful for the sensor nodes. Furthermore, different SG applications would have various quality of service (QoS) requirements. For instance, monitoring a transformer vault demands a strict delay requirement to decrease the repair time by reporting the failure within a restricted time. Hence, the deployed sensor nodes should satisfy different levels of QoS. Also, the electrical systems in the SG cause variation in the noise level and interference in these environments may be high. These situations result in variation of the signal-to-interference-plus-noise ratio (SINR), which causes deviations in the channel capacity. Furthermore, limited battery power and processing capability require highly energy-efficient protocols. The most important challenge is

the collisions and resulting redundant energy consumption due to over-utilization of the unlicensed bands.

Although there are some studies to increase the context awareness of the SG, few of them consider the spectrum-awareness of the devices deployed in the SG [167]. These studies provide recognition in the spectrum usage. CR technology is proposed to support spectrum-awareness in wireless communications. The motivations behind this technology are to overcome the spectrum scarcity challenge and to dynamically use the underutilized licensed spectrum bands [33].

CR technology provides sharing licensed spectrum bands with primary users (PUs), which are the owners of these bands. In order to utilize these bands while the PUs are not active, CRs can change their transmitting parameters to operate on the vacant channel [93]. There are two main characteristics of CRs, which are cognitive capability and reconfigurability [33], [93]. With the cognitive capability, the idle spectrum bands are detected, and the best channel among these idle channels is selected for the communication without any interference to the PUs. With reconfigurability, CR can operate in different frequencies and reconfigure its parameters for the best performance. The use of the idle licensed spectrum bands increases spectrum utilization and decreases the traffic in ISM bands. Hence, collisions due to the excessive utilization of the unlicensed spectrum bands are decreased, which provides efficient spectrum usage and energy-efficiency.

The cognitive capability of the nodes is possible with cognitive functionalities. They are spectrum sensing, spectrum decision and spectrum hand-off. Spectrum sensing gives the ability of revealing the radio spectrum band usage in the licensed bands. Spectrum decision is the process that the band for the transmission is decided. Furthermore, a radio with CR capability must vacate the licensed channel if this channel become occupied. This process is performed by the spectrum hand-off functionality. Using these features, nodes with CR capability can coexist with the licensed users, which are the license holders of that spectrum band. Although CR provides advantages for the wireless communication, it poses challenges such as dy-

dynamic radio environment. If CR technology is utilized in the SG, it also intensifies the challenges posed by the SG itself.

The IoT paradigm has a goal to connect every electronic device to the Internet [163], [162]. It leads to the integration of different technologies and communication techniques. Hence, the devices within the IoT should communicate with different types of communication devices. The IoT is regarded as a union of wireless devices via the Internet to observe and sense the environment, and to monitor the surrounding. This paradigm has been evolving the way we communicate, most importantly, the standards of living since it finds many application areas such as transportation manufacturing, logistics, management of cities etc. [162].

With the emergence of the IoT, the Internet has been evolved in such a way that Network of Interconnected objects senses the environment and actuates accordingly by using Internet services for communication, data transfer and analysis of the sensed data [163]. From this point of view, the SG has the same characteristics since it covers the electrical grid to sense for providing intelligence on demand and supply side. Furthermore, the sensing from houses to the generation side provides less energy loss, immediate response to the grid failures and easy adaptation to new systems [195]. Hence, integration of the SG with the IoT helps better monitoring and management of the electrical grid. This integration will also provide IoT services such as broad connectivity, privacy, interoperability between the heterogeneous wireless devices and access to the cloud computing systems.

Internet connection of the SG and addressing the sensing and actuator devices in the Internet domain provide flexibility, reliability, efficiency and adaptation. Hence, SG can adopt the services provided by the IoT. However, the Internet connection via wireless links and the communication between the sensing and actuator devices in the SG suffers from the harsh channel conditions such as high path loss exponent and shadowing deviation [187] and changing spectrum characteristics over time and space [182]. Hence, CR may also be solution to overcome these challenges to provide unique reliability and requirements by dynamic spectrum access and decrease the

energy consumption of the wireless devices by avoiding the collisions with adapting its operating frequency according to the spectrum sensing.

### 11.2.1 Advantages of CR in IoT-enabled SG

Cognitive cycle operations provides awareness in frequency usage. Dynamic adaption to the frequency bands and opportunistic usage of the licensed channels increase the spectrum utilization and communication efficiency. The advantages of CR in IoT-enabled SG can be outlined as follows [182].

- *Adaptation to the environmental conditions:* The harsh conditions of a band can be eliminated by changing the operating frequency to channels with less noise level.
- *Accessing to underutilized licensed spectrum:* With the spectrum sensing, idle channels are utilized, efficiency of these bands is increased.
- *Resistance to the varying link capacity:* Due to varying channel conditions, CR can dynamically hop to the frequency bands with higher link capacity.
- *The ability of existence with different type of networks:* Due to the CR capability, they can coexist with different type of networks since they can opportunistically access to the spectrum. This advantage supports operation with different technologies due to IoT feature in SG.

### 11.2.2 Challenges of Cognitive Radio capable IoT-enabled SG

The challenges for the realization of the SG are empowered by inclusion in the IoT paradigm and the utilization of CR. The IoT requires scalable, energy efficient and flexible solutions. Furthermore, the solutions must support spectrum-awareness if CR is utilized. Hence, the challenges of CR capable IoT-enabled SG can be outlined as follows [187].

- *Excessive overall data transfer:* Since there is a large number of wireless devices in the IoT-enabled SG, the overall sensing data conveyed to the control center may result in huge amount. Opportunistic wireless transfer of this data will pose a great challenge without any excessive interference to PUs.
- *Balancing the energy resources:* Due to the variations between the demand and supply, balancing the energy resources and the determination of their share is a difficult task. Spectrum-aware communication between the demand and supply side with the harsh environmental condition of the IoT-enabled SG poses a challenge.
- *Dynamic licensed user activity:* Interference to the licensed users should be less than a certain threshold.
- *Variation in the traffic:* Due to the activities on the user side, the traffic flowing from the user side to the supply side varies.
- *Satisfying different levels of QoS:* SG can have a wide variety of QoS level due to diverse SG applications. Satisfaction of all the users in SG is a challenging task.

### **11.3 Existing Methods of Energy Harvesting**

Existing techniques of energy scavenging is broadly categorized into two groups as Harvest-Use and Harvest-Store- Use, where these can be further sub-categorized as controllable and uncontrollable [196]. By regarding this separation and the frequency of preference some leading EH methods are discussed below, and a detailed comparison is presented in Table 11.1.

#### **11.3.1 Energy Harvesting from Light Sources**

Power extraction from light sources is a well-known technique of energy harvesting in which the energy carried by photons is converted into utilizable electrical power with

respect to a chemical phenomenon, namely photo-voltaic (PV) effect [196], [197].

In outdoor, solar energy is efficiently exploited to power various systems and applications, thanks to its sufficient power rating, and implementation flexibility. One of the most well-established applications of sunlight EH, in terms of wireless networking, can be regarded as intelligent surveillance and advanced control of grid assets over the Internet since the electrical power grid related elements are in widespread. This aspect also contributes to the realization of SG and Smart City visions. However, as a corollary of being environmental, the energy that can be gathered by sunlight illumination is highly affected by ambient factors. For indoor applications, more specialized PV materials, which are better suited for diffused lights, are being developed for profiting from any kind of light propagation to build HANs/BANs [196]. Although the period of harvesting is much longer on the contrary of sunlight's daytime constraint, the energy that can be gathered by artificial lights is roughly one third of sunlight energy.

### 11.3.2 Thermal Energy Harvesting

Thermal EH is based on a physical phenomenon, i.e., Seeback Effect, which occurs between conductor pairs. In brief, due to a thermal difference the junction expands in a certain direction that results in utilizable electrical power. The attainable energy can be easily adjusted by changing connection of the pairs as series and/or parallel [196]. Thermo-electric generation (TEG) can be regarded as an innate method for SG communications, where the temperature gradients between the grid assets and the environment are being utilized for providing energy to the wireless devices attached [198]. In small scale, mostly peltiers and/or thermocouples are preferred for low-power requiring time-uncritical consumer electronics solutions. It is also possible to energize the circuitries that are obliged to monitor the human bodies or any body-attached control systems by using the very same approach. As the devices are more likely to operate self-sustainably, they may suffer from the quite low power extraction efficiency of the TEG process [196], [3].

### *11.3.3 Kinetic Energy Harvesting*

As the name suggest, kinetic energy conversion (KEC) means profiting from any mechanical stress and/or vibration resultant motion variation to gather power for wireless devices. KEC includes electrostatic, piezoelectric and electromagnetic methods to extract energy from mostly uncontrollable but somehow predictable environmental sources, as well as partly-controllable and mostly unpredictable man-made actions [197]. Airflow EH, in particular, can be considered as one of the well-established power provision methods for SG applications, in which the wireless autonomous devices destined to surveil the grid are powered by KEC-capable anemometer like mechanisms. As these systems provide longevity and maintenance-free operation for the networks to be built, the available power is highly threatened by many factors, such as day-time and weather conditions. Although the vibrations alternate the wind power in SG communications, they require specialized harvesters as the frequency of each vibrating element differs. For indoor applications, piezoelectric materials are mostly preferred to operate HANs and BANs intermittently [196], [3].

Table 11.1: Comparison of the existing EH techniques [3].

|                             | Type        | Characteristics                            | Power Density               | Advantages                                                           | Disadvantages                                                            |
|-----------------------------|-------------|--------------------------------------------|-----------------------------|----------------------------------------------------------------------|--------------------------------------------------------------------------|
| <b>Light</b>                | Solar       | Uncontrollable,<br>Predictable             | $15 - 100$<br>$mW/cm^2$     | Environmental,<br>Independent of grid,<br>High output voltage        | Not always available,<br>Sensitive structure,<br>Deployment constraints  |
|                             | Artificial  | Partly-controllable,<br>Predictable        | $10 - 100$<br>$\mu W/cm^2$  | Abundant in indoor,<br>Easy to implement                             | Low power density,<br>Sensitive structure                                |
| <b>Temperature gradient</b> | -           | Uncontrollable,<br>Unpredictable           | $\simeq 50$<br>$\mu W/cm^2$ | Environmental,<br>Low maintenance,<br>Scalable                       | Not always available,<br>Requires eff. heat sinking<br>Low power density |
| <b>Motion</b>               | Airflow     | Uncontrollable,<br>Unpredictable           | $100$<br>$mW/cm^2$          | Environmental,<br>Independent of grid,<br>Available day and night    | Big in size,<br>Hard to implement,<br>Requires construction              |
|                             | Human-based | Controllable,<br>Partly-predictable        | $200$<br>$\mu W/cm^3$       | No ext. power source,<br>Compact configuration,<br>Light in weight   | Charge leakage,<br>Brittle materials,<br>Highly variable output          |
| <b>EM Waves</b>             | -           | Partly-controllable,<br>Partly-predictable | $1 - 10$<br>$\mu W/cm^2$    | Abundant in urban lands,<br>Allows mobility                          | Scarce in rural areas,<br>Low power density,<br>Distance dependent       |
| <b>EM Fields</b>            | M-field     | Controllable,<br>Predictable               | $150$<br>$\mu W/cm^3$       | No ext. power source,<br>Easy to implement,<br>Non-complex structure | Requires high and<br>perpetual current flow,<br>Safety vulnerabilities   |
|                             | E-field     | Controllable,<br>Predictable               | N.A.                        | No need of current flow,<br>Easy to implement,<br>Always available   | Being capacitive,<br>Mechanical constraints                              |

### 11.3.4 Radio Frequency (RF) Energy Harvesting

With the unprecedented grow in wireless technologies in recent years, electromagnetic (EM) waves become more attractive for especially EH applications [196], [197]. Because of the nature of wireless communication, EM signals have the characteristics of being easily attainable and efficiently utilizable, which open up the potential of building battery-less WSNs that profit from ambient and underutilized RF waves. For urban areas, RF energy is about to unseat the conventional methods of EH that are destined to run remote services of Smart Cities. For indoor, EM waves emitted from modems, routers, smart phones, and laptops are first collected, then converted into AC and DC by using power receiving antennae, transducers, and rectifiers, respectively. Although the RF EH provides quite satisfying solutions regardless of the environmental parameters, being distortive for the communication; having strict deployment requirements; depending highly on an unpredictable source compel its utilization in mission-critical applications [3].

### 11.3.5 Energy Harvesting from Electromagnetic Fields

In addition to above-mentioned harvesting techniques, low-power operative wireless devices can be also powered by exploiting electromagnetic fields around the conductive materials energized at any level. Magnetic field (M-field) EH, in particular, is based on coupling the surrounding field flow of AC current carrying conductors by clamping them with current transformers [197], [198], [3]. This power transfer-based technique provides acceptable rate of stable power as long as there exist sufficient current flow on the conductor that is being utilized. Being bulky and requiring additional safety procedures due to the mechanical contact are the factors that restrict its employment in certain applications. However, for online condition monitoring of overhead power lines and environmental sensing around grid assets, it is the most efficient solution in contrast with the ambient sources such as sunlight and airflow.

Electric field (E-field), in similar, exploits the electric charges induced on a conductive material due to a voltage difference. The field that is being emitted is obstructed

by again a conductive material, where a displacement current starts to drain. The charges conveyed are first converted into DC and then accumulated in a storage element after regulated. As the source of this gathered energy is the ambient field, this method can be termed as E-Field EH (EFEH) [198], [3]. EFEH depends only on the existence of voltage potential. Since the voltage and the frequency are firmly regulated and exactly maintained, the E-field is stable and also predictable in its behavior. Therefore, it can be referred as the most promising way of composing long-term and self-operable communication services notwithstanding the environmental parameters.

#### **11.4 Energy Harvesting Cognitive Radios in IoT-enabled Smart Grid**

We separately investigate the usage of CR and EH in the IoT-enabled SG in prior sections. This section explains how the nodes operate by utilizing these technologies in the IoT-enabled SG. Spectrum-aware communication and energy harvesting capabilities of these nodes are the key elements for successful operation of the IoT-enabled SG. Hence, the wireless devices in an IoT-enabled SG are named as energy harvesting-cognitive radios (EH-CRs). As EH-CRs have additional capabilities, their node architecture would be different from conventional wireless nodes in the IoT-enabled SG. Furthermore, these capabilities require considering the network architectures of the IoT-enabled SG. Hence, we overview operation of EH-CRs, their node architecture, and the architectures of the network consisting of these nodes.

##### **11.4.1 Operation of EH-CRs**

Overcoming the spectrum scarcity challenges with CR and solving the limited energy supply problem with the EH techniques provide significant benefits in the SG domain. Furthermore, including the SG in the IoT results in very diverse application areas. This fact necessitates a clear understanding of operation of the IoT-enabled EH-CRs.

The SG is a visionary concept that connects the demand and supply sides by enabling two way communication. These connection is provided by the deployment of wireless sensing devices and actuators. Hence, the proper operation of these devices

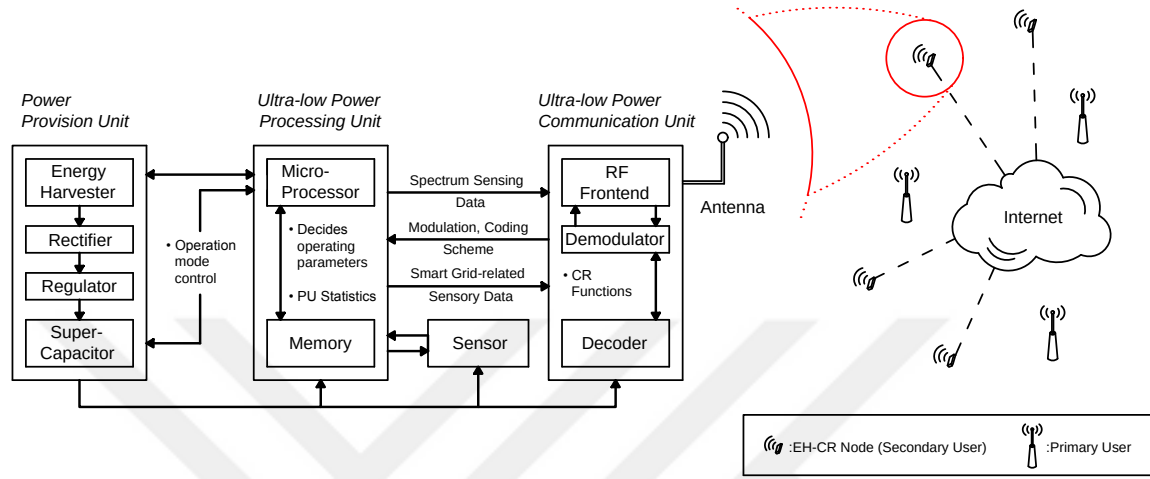


Figure 11.2: Node Architecture of EH-CRs.

is quite important. In the IoT-enabled SG, there are different operation schemes for the wireless devices. The deployed devices in homes may access directly to their gateways or they may reach their Internet gateways through multiple hops.

During the operation, EH-CRs use spectrum-aware communication techniques for the transmission, and EH methods to energize the device. Depending on the sub-network architectures, the packet generated by sensing are conveyed in one or multiple hops in dynamic radio environment to reach the Internet for realizing IoT-enabled SG. They utilize the licensed spectrum bands since they coexist with PUs. Furthermore, they scavenge energy by utilizing EH techniques.

#### 11.4.2 Node Architecture of EH-CRs

We propose a node architecture for IoT-enabled EH-CRs that supports energy harvesting and spectrum aware communications. In this architecture, we include three main units, which are ultra-low power (ULP) communication, ULP processing, and power provision units. A detailed structure is depicted in Fig. 11.2. The ULP communication unit performs channel switching, channel sensing, modulation and power control duties at the expense of milliwatts. Furthermore, sensory operations are performed in the sensor unit, which is controlled by the ULP processing unit. The

sensed information is processed in ULP, and it is transferred to the ultra-low power communication unit.

The power provision unit includes energy harvester, rectifier, regulator and energy buffer, i.e., super-capacitor, sub-units. As the name suggest, this unit is responsible for providing utilizable energy to the each part of the sensor node. In other words, profitable sources are captured, converted (if necessary), regulated and stored to be distributed to the rest of the system. The processing unit mainly decides on operating parameters and manages every process carried out by the sensor node. The ULP communication unit has an Internet-capable RF front-end, demodulator and decoder to provide the communication with CR functionalities. This node architecture is designed to support energy harvesting and spectrum-aware communications in the IoT-enabled SG.

### 11.4.3 Network Architecture of IoT-enabled SG

Using the node architecture of EH-CRs, we establish a network architecture for the IoT-enabled SG. Furthermore, we also utilize the general SG network architecture while establishing it for the IoT-enabled SG. The general SG network architecture has a multi-layer architecture and spread over a very geographical region, which poses challenges and limitations in wireless communications. Furthermore, this network architecture includes a number of sub-networks that have different QoS and other communication requirements.

There are three main components for the SG network architectures, namely, HAN, NAN and WAN as seen in Fig.11.3 [191], [192]. IAN in Fig. 11.3 refers to industrial area network, which is a sub-network of NAN located at industrial sites. BAN in Fig. 11.3 refers to building area network, which is again a sub-network of NAN consisting of wireless nodes located in buildings. In our architecture, we split the IoT-enabled SG network like in the conventional SG networks. However, we consider the capabilities of EH-CRs while proposing our network architecture. We investigate the sub-networks of the IoT-enabled SG in the following subsections.

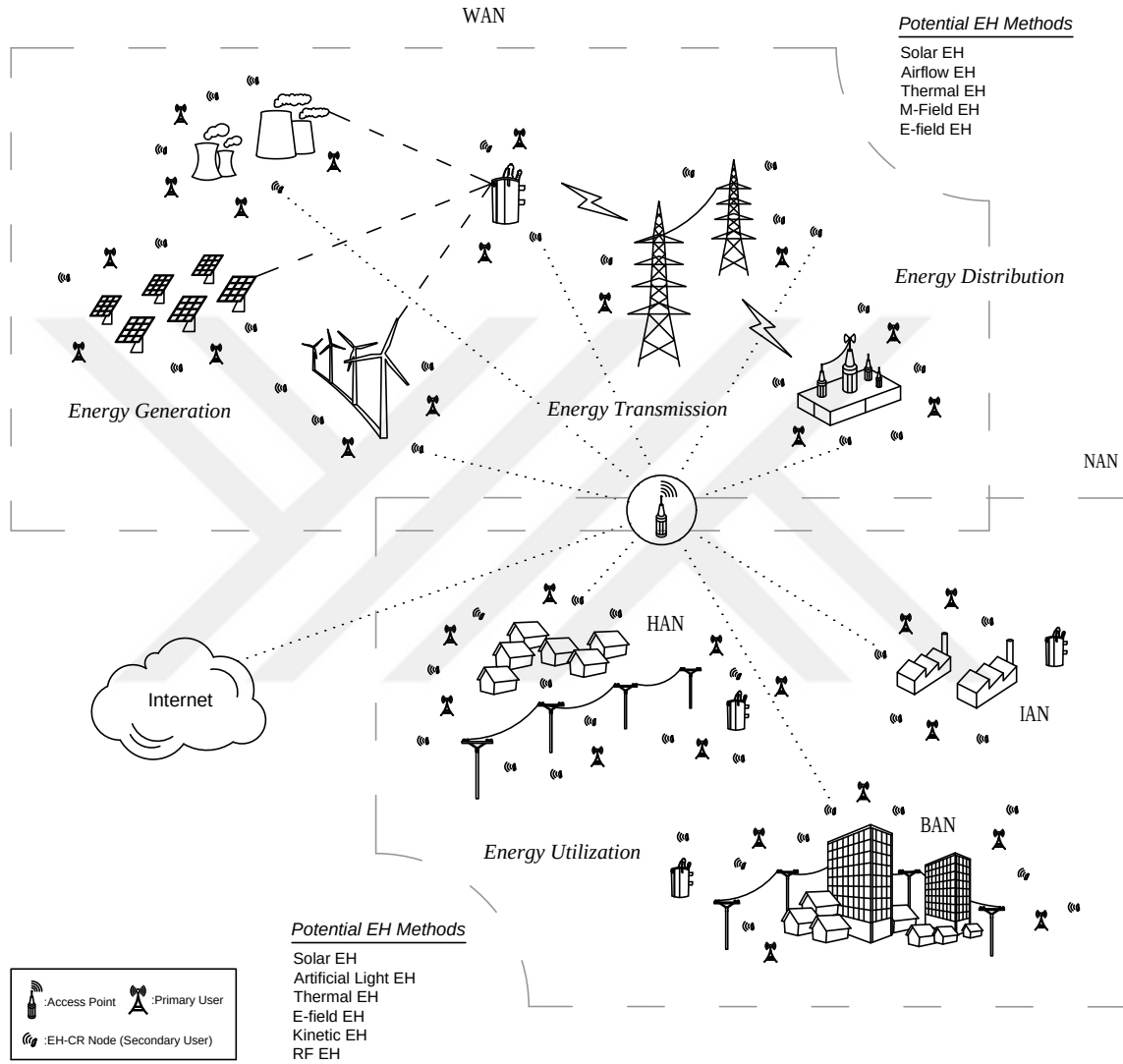


Figure 11.3: Network Architecture of IoT-enabled SG.

### Home Area Networks

HANs cover houses and buildings. They provide real time monitoring for adjustment of energy consumption. Furthermore, they have the capability of control, managing and track of the devices at homes and buildings. These networks bring intelligence to the houses, i.e., Smart Homes (SHs) [199]. Remote control and tracking, management of heat and light, and health-care monitoring are some of the applications of SHs. Home is the smallest part of the grid and provides context-aware services to the HAN

users.

The most important elements in HANs are smart meters, which have the capability of measuring the energy consumptions of the nodes [200]. WSNs are the key components to realize the SG in HANs that can be used home applications related to demand and energy management [201]. The collaborative nature of WSNs helps to exchange of the sensory information from the home appliances and systems, and makes this information accessible via the Internet with the inclusion of IoT.

The development of the SG have increased the usage of HANs, which utilizes protocols such as ZigBee, Wi-Fi, and 6LoWPAN. However, they use ISM (Industrial, Scientific, Medical) bands, which are highly utilized and become insufficient for the transmission. This also increases the collision and deteriorates the network performance. Hence, CR plays a key role to eliminate these problems in HANs. CR is also being utilized in the SG domain to manage high volume of data and to satisfy different QoS levels [190]. In our network architecture, the nodes in home communicates with the access point by dynamic spectrum access techniques to overcome the difficulties in the SG. This scenario is seen in Fig. 11.3 with exploitation of different EH methods such as harvesting from solar and thermal energy. The EH methods extend the lifetime of EH-CRs in HANs.

### *Neighborhood Area Networks*

Neighborhood Area Networks (NANs) provide the connection between HANs. These networks are also named as field area networks (FANs) due to their connection of field devices such as advanced metering infrastructures (AMI) and intelligent electronic devices (IEDs) [191]. NANs gather the energy consumption information from the homes in a neighborhood and sends it to utility companies via wide area networks (WANs) [190].

NANs also connect SHs and the utility companies. It provides real-time communication for pricing and control. Furthermore, main fields of NAN applications can be named as distribution automation, load management and so on. Depending on the

application, the network radius of NANs may be up to 10 km with a rate of 0.1 – 10 Mbps [192]. Multi-hop capable wireless nodes may be utilized such as ZigBee and Wi-Fi nodes [202]. Wireless sensor nodes may be utilized for this purpose. However, they may face the spectrum scarcity challenge in addition to the SG challenges such as harsh channel environment. CR again stands as a solution for these problems. In our networking paradigm, the nodes in NANs also access the licensed spectrum opportunistically. Gateway nodes are with cognitive radio capability. Their energy is supplied by the EH methods, which depend on the available energy resources in that neighborhood. Fig. 11.3 shows a NAN that gateway node is connected to the different sub-networks such as HAN, IAN and BAN. Furthermore, nodes in NANs need more energy since they communicate with the nodes in HANs. Hence, efficient EH techniques should be employed.

#### *Wide Area Networks*

WANs cover large areas and connects much smaller networks to form the communication backbone [203]. NANs forms WANs, the NANs communicates with the utility center via the Internet through WANs [190]. The observations and the real-time measurements of the substations and end users are conveyed to the control center traversing WANs, where the data from control centers is transmitted in the same manner [203].

IEDs are the sensor and actuator nodes, which are deployed in critical parts of the electrical grid such as transformers, circuit breakers, etc. [204]. The communication between the nodes of WANs requires high bandwidth and low delay due to the accumulated data from HANs and NANs. For instance, 5 Mbps data rate and 100 milliseconds delay is required for seamless communication [205]. The current WSN solutions may not satisfy these requirements due to inherent. CR provides the use of the licensed channels with high bandwidth to support the demands. If gateway nodes can not access base stations in WANs, they reach them in multiple hops by utilizing idle licensed bands.

#### 11.4.4 Open Issues and Future Research Directions

In this chapter, we have proposed a new networking paradigm, namely energy harvesting cognitive radio networking in IoT-enabled Smart Grid. The nodes have two capabilities, which are energy scavenging and spectrum-aware communications. Furthermore, these nodes operate in a very harsh domain, which is IoT-enabled Smart Grid. To enable EH-CR networking in IoT-enabled SG, we have explained the operation of EH-CRs, the node architecture and their network operation in a IoT-enabled SG. This new paradigm yields some open issues and future research directions, which are outlined as follows.

- Spectrum management frameworks must be designed according to the networking architecture of the IoT-enabled SG and the CR capability of the nodes. Furthermore, EH aspects of these nodes should be considered to enable efficient power consumption to support battery free operation.
- Energy harvesting and the energy consumption due to the cognitive cycle operations should be considered to balance the energy expenditure for perpetual lifetime. Furthermore, the spectrum-aware communication challenges such as arrival of PU during opportunistic communication should be considered in IoT-enabled SG with the intrinsic harsh channel conditions.
- Coverage and connectivity of the IoT-enabled SG should be studied according to the spectrum-awareness and energy harvesting points of view. New power control method can be utilized considering the harvested energy in IoT-enabled SG. Furthermore, the connectivity of IoT-enabled SG should be investigated in such a setup.
- The heterogeneity of IoT-enabled devices should be handled since these devices use different communication technologies. The compatibility with EH-CRs and the other IoT devices deployed in SG must be investigated in terms of communication.

- Spectrum-aware routing protocols should be designed to enhance the lifetime of the nodes with EH techniques. The routing techniques should also consider the different network architectures of SG such as HAN, WAN, NAN.
- Application specific EH methods should be offered to support battery free operations of EH-CRs. Furthermore, hybrid energy harvesting approach may be proposed to exploit different EH methods in EH-CR nodes.
- EH methods must be utilized in accordance with required operation in different parts of the IoT-enabled SG since different nodes in different subnetworks of the IoT-enabled SG uses different amount of energy for the communication due to different transmission ranges.

## Chapter 12

# ENERGY HARVESTING COGNITIVE RADIOS IN SMART CITIES

### 12.1 Introduction

Wireless communication has been experiencing tremendous advancements. These developments have triggered new wireless networking paradigms and communication services. For instance, 5G is being studied by the research community to provide mobile broadband communications in wireless networks. Recently, the concept of IoT [162] which is one of the key elements of 5G wireless networks, has been proposed to connect every device to the Internet, such as wireless sensor nodes, RFID tags, household appliances, etc. As these technologies grow, they have been applied to various real-world problems. One of the most important application areas is the management of cities in a more efficient and smarter way. The Smart City is a vision that extracts information from systems in the city to take measures for the management. This vision can be realized if information and communication technologies are employed in these systems to observe and manage them. Wireless sensors can be utilized as key elements for observing systems such as hospitals, highways, transportation networks, and power grids [206]. The transmission of the sensor observations about the city needs Internet connection to inform city officials. This fact leads to the utilization of the IoT since it can integrate all the facilities of the city with the Internet. Hence, the realization of the Smart City vision becomes possible since the systems can be sensed, analyzed and integrated with the use of communication technologies [207]. This enables the ability of managing the city in a cleverer and more efficient way in terms of city infrastructure, services, communication, business, energy, water etc.

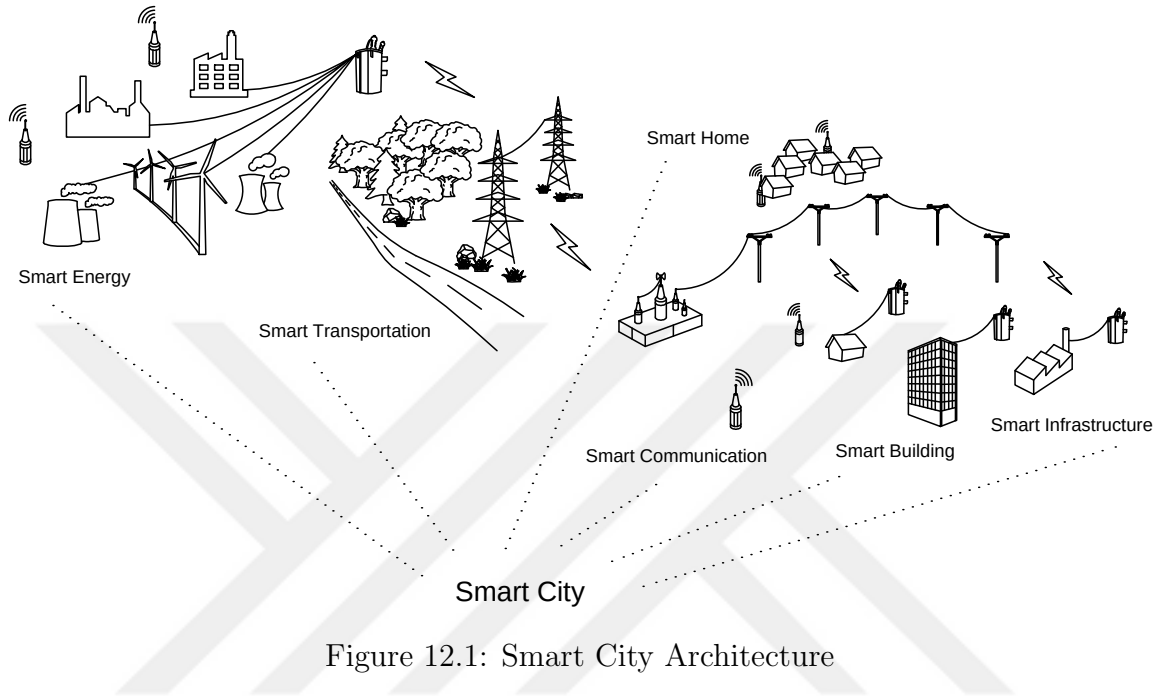


Figure 12.1: Smart City Architecture

The Smart City uses information and communication technologies to manage cities in an integrated manner [208]. The holistic view of the Smart City can be seen Fig. 12.1, where Smart Grid, Smart Transportation, Smart Communication, Smart Building, Smart Home and Smart Infrastructure are bound together. With the use of next generation information technologies, core systems are sensed, and the extracted information is analyzed for better management of the city and for improving quality of life in cities. To this end, it is envisioned that sensors are being deployed in different key areas of the cities, such as power grids, water and underground systems, oil and gas pipelines, railways, roads, schools, hospitals, stations, airports and so on. The application areas of the Smart City are diverse, and it connects every corner of the city to the Internet. This provides global intelligence over the management, and it paves the road for Internet + Internet of Things = Smart Planet [208]. The Smart City is the application of the concept of the Smart Planet to a specific region. The surveillance of infrastructure and environments of the city with the help of sensor technology achieves intelligent urban management and services [206]. The features of the Smart City provide development of efficient urban strategies such as construction

of smart homes, wireless cities, and smart transportation systems [206]. The use of IoT to realize the Smart City vision brings important challenges. With IoT technology, it is estimated that the number of devices connected to Internet will reach to 16 billion in 2020 [209]. Due to this increase, wireless data traffic that is being fulfilled in cities will surpass excessive levels, and the available spectrum will become scarcer. Ever-growing demand in wireless communications has also increased the spectrum scarcity problem. Furthermore, fixed allocation of the spectrum worsens the problem of inefficient spectrum use. While the licensed spectrum bands are underutilized, the unlicensed ones are crowded and the wireless communication is no longer feasible in these bands. To overcome the spectrum inefficiency and scarcity problems, CR technology is proposed [166]. CR capable wireless devices can access the licensed spectrum bands opportunistically, and hence increase the spectrum utilization efficiency [33]. On the other hand, wireless nodes in these systems are resource constrained. Even though the majority of sensor nodes have duty cycling, a conventional battery in a sensor node depletes in less than a year. Therefore, an auxiliary or even a completely distinct source, such as heat, light, motion, and electromagnetic (EM) waves must be exploited to ensure sensors' operation. In this regard, EH technologies come into prominence to build WSNs which are free from battery constraints [210]. Hence, these challenges promote novel methodologies for obtaining the spectrum efficiency and delivering the power to the wireless devices. The most promising answers that obviate these problems are CR and EH technologies.

### 12.1.1 Cognitive Radio

Excessive use of wireless devices has caused spectrum scarcity problem in industrial, scientific, medical (ISM) bands [165]. This problem has revealed a new access technology to the EM spectrum. The enabling technology is CR [166]. The most important feature of CR is the ability to adapt its operating frequency to certain frequency bands for wireless communication. Hence, this feature provides a scheme enabling dynamic access to the spectrum. With this feature, wireless devices can access to

the licensed spectrum bands opportunistically. Hence, CR nodes could coexist with license holders, which are primary users.

Dynamic spectrum access has one constraint, which is interference to the licensed users. There are two interference schemes. The first one is that CR must cause no interference to the primary users. The second one is that CRs may cause interference within a certain threshold. The interference is avoided with the help of cognitive cycle operations of CR-enabled wireless devices. These operations are spectrum sensing, spectrum decision and spectrum handoff, which are explained in detail as follows.

- **Spectrum sensing:** Spectrum sensing is the most important feature of CR due to the ability of getting information about the usage of the spectrum bands. It reveals unused spectrum bands, i.e., spectrum opportunity for the wireless devices. They share these spectrum bands without causing interference to the licensed users. There are different methods to identify the spectrum opportunities, which are energy detection, waveform detection, cyclo-stationary detection, and matched filter detection.
- **Spectrum decision:** After detecting the vacant spectrum bands, CR nodes should decide on which spectrum band to transmit their data. According to the requirement of the CR networks, the spectrum band for the communication is determined. The decision is performed in a centralized or distributed manner. However, the dynamic radio environment poses challenges since common control channel, which is proposed generally in literature, may not present most of the time. The exchange of spectrum sensing results may degrade the communication quality of CR nodes since the control packets may overwhelm the CR network.
- **Spectrum handoff:** This functionality prevents the interference caused by secondary transmission to the primary users. It provides the ability to stop the transmission of secondary users when a primary user arrives.

The features of CR increase overall spectrum utilization by utilizing the underuti-

lized licensed spectrum bands without causing any interference to the licensed users. Furthermore, they relieve the traffic jam in ISM bands. This also increases the energy efficiency since they decrease collisions among the secondary nodes, i.e., CR, by utilizing the underutilized licensed spectrum bands.

### 12.1.2 Cognitive Radio Sensor Networks

Wireless sensor networks (WSNs) have event-driven communication nature that results in bursty traffic depending on event characteristics. Dynamic spectrum access proposes a spectrum-efficient solution for the problems related to spectrum limitations of WSNs. Dynamic change of operating spectrum to utilize the unused licensed spectrum by the CR enabled sensor nodes improves the overall spectrum utilization. Hence, a new networking paradigm is proposed in [20], named as CRSNs. This networking paradigm has changed the fixed spectrum utilization adopted by the WSN nodes.

CR capability of the sensor nodes provides coexistence with the licensed users. Hence, this enables sensor observations to be conveyed in a multi-hop manner over the available licensed spectrum bands. The advantages of CR capability of sensor nodes are dynamic spectrum access, opportunistic channel usage for bursty traffic and adaptability for reducing power consumption. Hence, CR decreases the probability of collision and packet loss, which accordingly decreases the energy consumption of the sensor nodes.

The advantages of the CR usage in WSNs reveal a number of possible application areas of CRSNs. They may be listed as indoor sensing applications, multimedia applications, multiclass heterogeneous sensing applications, and real-time surveillance applications.

### 12.1.3 Energy Harvesting and Energy Harvesting Sensor Networks

Sensor nodes have an important constraint, which is limited battery power. This restricts the operation duration of sensor networks. Because of the CR capability,

the sensor nodes require more energy as the cognitive cycle operations are energy requiring processes. Hence, they drain the battery sooner, and the lifetime of the sensor network is decreased. One of the solutions to this problem is EH. It enables to power the wireless devices from natural resources such as light, temperature gradient and different ambient sources such as radio frequency signals and EM fields [211]. The practicality of this method comes from the fact that the sensor nodes no longer need to replace or recharge their batteries when they depleted. The harvested energy from the ambient resources is utilized to run the wireless devices autonomously. This provides more energy for the communication, which results in higher quality of service (QoS). Furthermore, cognitive cycle operations can be performed with higher precision due to increased energy budget thanks to harvesting. In this chapter, we overview all the mentioned solutions to overcome the challenges related to the realization of the Smart City, and therefore explore EH-CR wireless nodes. To this end, we first explain CRSNs, and how to combine the harvesting methods with them. The motivations for spectrum-aware and self-sustaining communications in the Smart City are revealed. Furthermore, challenges posed by the use of these methods in the Smart City are investigated. In the light of these discussions, we study a networking architecture for the IoT, i.e., Cognitive Energy Harvesting IoT. By using this architecture, we also overview a general implementation framework for EH-CRs.

## ***12.2 Motivations for using Energy Harvesting Cognitive Radios in Smart Cities***

The Smart City vision necessitates observing the key system elements in cities and extracting the information about these elements for better management of the cities. The most important aspect of this vision is the observation part, which is handled by the sensors that are deployed on different systems of the city such as hospitals, roads, bridges, and so on. This makes the city smarter, which means more efficient, sustainable, and livable.

The advantages of the Smart City motivate the utilization of information and

communication technologies. However, cities present harsh environment which poses challenges on the sensor technology. In the context of the Smart City, they are deployed in different remote geographical areas that make the sensor nodes inaccessible in case of battery depletion or failures. Hence, the utilization of EH-CRs has key importance in the Smart City. Motivations of using these radios are explained in detail in the following subsections.

### *12.2.1 Motivations for Spectrum-aware Communications*

A CR node can sense the spectrum, find vacant bands and change its transmission parameters to use these vacant bands for communication. This provides opportunistic spectrum access (OSA). Since the licensed spectrum is not fully utilized, these bands are used opportunistically. CRSN is a distributed network that senses the environment and collaboratively conveys their readings dynamically over available spectrum bands in a multi-hop manner to satisfy application-specific requirements [20].

The CR capability offers spectrum-aware communications. This type of communication provides licensed bands for the sensors by accessing the opportunistically. Spectrum-aware communications utilize the most favorable channel among the idle spectrum bands after spectrum sensing. This helps reducing transmission errors and the number of retransmissions, and increasing reliability of the communication. Furthermore, CR capability fulfills the delay requirement of the applications by utilizing the idle channels. This may reduce the number of hops to the destination in the network, which also decreases the total delay.

The Smart City applications require efficient and timely data transfer from the systems of the city. Since the unlicensed bands are heavily used in the cities, the spectrum-aware communications become the most important solution to overcome the spectrum scarcity problem. Furthermore, the advantages of the spectrum-aware communications such as increased reliability and decreased latency further motivate its utilization. Hence, it fulfills the requirements of the Smart City.

### *12.2.2 Motivations for Self-sustaining Communications*

Sensor technology is a key element for different IoT applications. Depending on the application, sensor nodes sense and transmit data either intermittently or in a periodic manner. Data transmission consumes a few milliwatts of power, and microwatts of it during sleep mode [198, 210]. However, a typical sensor battery even depletes in less than a year. If we consider the number of deployed sensors and their energy requirements in the Smart City domain, there is a clear need of an auxiliary or even a distinct source. However, this may or may not be an option for each application mostly due to size constraints, maintenance and/or deployment costs. Large number of sensor node utilization and their individual energy demands require energy-efficient solutions and sustainable use of resources. Hence, this also promotes energy-efficient solutions by encouraging battery-less systems.

EH resolves the problem of limited lifetime of wireless devices like sensor nodes [198]. This approach is very beneficial for the sensor nodes which have limited battery power. It exploits the ambient resources, namely radio frequency (RF) signals, heat and movement variations, vibrations, EM and sound waves, etc, and provides utilizable energy to the wireless devices.

Digital skin of the Smart City, which is sensor networks deployed in different parts of the city, performs periodical monitoring, and requires excessive amount of energy. The sensor deployment in large numbers and the difficulty in replacing the battery motivate the use of EH approaches for the Smart City. Hence, it stands as a way of providing more reliable, durable and profitable alternative for the proper system operation.

## **12.3 Challenges posed by Energy Harvesting Cognitive Radios in Smart Cities**

Sensor nodes have limited energy, memory and processing power. Furthermore, CR operation increases the energy consumption of these nodes with additional operations such as spectrum sensing and spectrum management. These challenges are intensified

by the Smart City. In the following subsection, we list these challenges.

- **Bandwidth:** Depending on the application, the sensors in the Smart City demand high bandwidth. For example, some applications require multimedia delivery. This poses an important challenge to overcome in a dynamic radio environment. The heterogeneity of spectrum bands and their dynamic availability change the bandwidth of the network, which requires flexibility in bandwidth of the licensed bands.
- **Quality of Service (QoS):** CR offers flexibility to satisfy QoS requirements of the Smart City. The QoS level depends on the application and the observed key elements of the cities. QoS is measured in terms of reliability, throughput and delay. The most important factor for the change of QoS level is the licensed user activities.
- **Coverage area:** The Smart City must provide coverage for very large geographical areas. However, the licensed user activity will vary spatially. This poses challenges for the coverage since the nodes in a region may not have any spectrum opportunity for some period of time due to licensed user activities. Hence, we cannot extract information from those regions which degrades the vision of the Smart City.
- **Scalability:** Monitoring such a large geographical area will be performed by large number of sensors. This requires scalable solutions to enable the Smart City. Furthermore, this forces the communication infrastructure to be flexible and adaptive to any change in the network.
- **Reliability and delay:** The sensory information from the elements of the city should be reliably delivered in real-time. However, the reliability of the communication may be degraded by the licensed user activities. This may distort the channel conditions, cause network outages and interference caused

by the transmissions of primary users. Furthermore, intermittent connectivity of the CR nodes causes an increase in the delay.

- **Computational Capability:** The computational capability of the CRSN nodes is limited, and this poses a challenge to perform complex tasks. The sensor nodes are also energy-constrained, which intensifies the limited computational complexity of the nodes.
- **Intermittency in available sources:** Consistency of available sources cannot be guaranteed. For example, in RF EH, the energy is harvested from the ambient RF signals. However, these signals are not always present, and hence, harvestable energy is not continuous. This is also the case for different EH resources such as wind and light.
- **Integration of the sensor networks to the Internet:** For the realization of Smart City, the extracted data should be delivered to the authorities of cities or the citizens. However, in such a large geographical area with varying deployment conditions, the connection of the sensors to the Internet poses a challenge.
- **Service differentiation:** ZigBee, IEEE 802.15.4, 6LoWPAN etc. technologies are utilized in the IoT domain. Various sensor types must cooperate with each other to achieve a desired goal in the Smart City. Different sensor nodes deployed in a system of a city must be compatible with one gateway, which provides the Internet connection to the system.

CR and EH pose some significant challenges. These challenges are intensified by the physical conditions in the cities. Furthermore, the harsh conditions in the elements of the city decrease the possibility to transmit the observed data to the cloud for the analysis and the evaluation of the critical data.

## **12.4 Energy Harvesting Cognitive Internet of Things**

### *12.4.1 Definition*

The advancements in wireless technology make interaction between people and digital world more powerful and sophisticated. The wireless communications technology plays a vital role for these advancements. In this respect, the IoT is one of the most innovative paradigm for next-generation wireless networks [163].

Every electronic will be connected to the Internet as a result of the notion of the IoT [163]. A clear definition has not been determined for the IoT despite the fact that concept of the IoT is obvious. It can be viewed as a union of next-generation wireless devices that sense the surrounding and gather information from the physical world [164].

Connection of the wireless devices with each other and to the Internet results in congestion and the high volume of traffic in the EM spectrum. As these devices in the IoT mainly use already crowded ISM bands, the problem of spectrum scarcity is intensified by the introduction of the IoT. Furthermore, the licensed spectrum bands are underutilized. To overcome the problems of spectrum scarcity in unlicensed spectrum bands and the under-utilization of licensed spectrum bands, CR technology has been proposed [209]. The wireless devices with CR capability can use the spectrum opportunistically. Unlicensed users, i.e. CR nodes, coexist with licensed users, i.e., primary users (PUs). Cognitive cycle operations enable CR nodes to use the licensed channels in an opportunistic manner. These operations provide scanning of the spectrum for an opportunity to transmit and ceasing the transmission if PU activities exist during communication. Hence, cognitive capability of devices increases the efficiency of the spectrum utilization and overcomes the spectrum scarcity problem. For instance, authors in [167] present the cognitive IoT (CIoT) to enable cognition in the IoT devices in terms of spectrum usage and the interaction with physical and social worlds.

The wireless devices in IoT are resource-constrained. Furthermore, cognitive cycle

operations deplete the battery of the wireless devices sooner. Furthermore, it is not possible to replenish the battery of them. Hence, EH is an efficient method to power the wireless devices in the CIoT. Hence, the networking paradigm of Energy Harvesting Cognitive Internet of Things, consisting of EH-CRs, would be a key enabler of the Smart City by satisfying its requirements.

#### 12.4.2 Energy Harvesting Methods in IoT

In this subsection, we overview the existing EH methods in IoT domain. Harvesting methods can be separated into two groups depending on the energy demand and availability in harvestable resources, named as Harvest-Use and Harvest-Store-Use, respectively [210]. Furthermore, the harvestable resources can be categorized according to their controllability and predictability. EH from light sources is a well-studied method of power provision that gathers energy from ambient lights, either from sun or artificial light sources, with respect to a phenomenon called as photo-voltaic (PV) effect [210]. Solar EH is performed by solar cell inlaid photo-voltaic panels in mostly outdoor applications for the monitoring of overhead power lines [198, 210]. For indoor applications, specialized photo-voltaic materials, which are better suited for diffused lights, are employed for taking advantage of the rays that are being emitted from ambient lighting elements. Although the PV modules are getting cheap, easy to use and sufficient each passing day, due to the dramatic fluctuations on the output power, and ongoing installation and maintenance costs, they have limited applicability in mission critical applications [212]. Another EH method, Kinetic energy harvesting (KEH), is the conversion of ambient movement energy into electrical power. Wind turbines and, on a smaller scale, anemometers are being utilized for exploiting air-flow energy to enable wide-scale communications structured in open space; however, their performance is highly threatened by the environmental variables similar to solar energy related techniques [198, 210]. Piezoelectric materials, in similar, are in great use for gathering energy from highly random and mostly unpredictable motion variations driven by external factors [196, 210]. KEH is frequently preferred in indoor and

outdoor domains, as there is a variety of sources that can be conveniently exploited to drive low power consumptive wireless autonomous devices. However, constituting a generalized harvesting system for especially vibrating sources is an ongoing issue, because the conversion efficiency highly varies with the resonant frequency of the vibration, which necessitates a specialized design for each sources [198, 210, 213]. Thermal energy harvesting, i.e., thermoelectric generation (TEG), is simply based on converting temperature gradients into utilizable electric power with respect to the Seeback Effect occurred in semiconductor junctions. TEG is an innate power provision technique for Smart Grid communications, in which temperature swings between the grid assets and the environment is used to extract energy [210]. Similar to environmental sources, i.e., solar and airflow, it strictly depends on the ambient variables, and therefore, may fail to satisfy providing stable power in some cases. For less power requiring sensor nodes; peltier/thermoelectric coolers and thermocouples are widely used for building delay-tolerant wireless networks. Although harnessing power by using temperature gradient between the systems sounds promising, there is a fundamental limit, namely Carnot cycle, to the maximum efficiency at which energy can be harvested from a temperature difference [212]. Regarding the intensive use of GSM networks in urban areas, Radio Frequency (RF) signals attracted both academia and industry in recent years [210]. RF EH simply targets RF signals emitted from base stations, network routers, modems, smartphones, tablets and any other wireless signal sources, and collecting them via large aperture power receiving antennae, and accordingly converting the gathered waves into utilizable DC power for the sensor nodes. An RF EH circuit includes a transducer for converting EM waves into alternating current (AC), and a rectifier for converting the AC power into the direct current (DC). In addition to them, RF filters, voltage multipliers and couplers can be also utilized for more advanced harvesting procedures. Even though this method serves reliable solutions regardless of the environmental variables, deployment inflexibility and low power provision efficiency compel its utilization in some applications [3, 210]. Wireless networks can be also powered by exploiting EM fields, i.e., magnetic and electric,

emitted from current carrying and/or tension holding conductive materials [210, 214]. Magnetic field (M-field) EH is based on coupling magnetic fields surrounding the AC current carrying conductors by simply clamping them with current transformers. This technique provides an adequate rate of power, and less complex utilization; however, the availability of energy is affected severely by the current density on the power line. As the M-Field occurs due to AC current, the line must be loaded to allow sufficient current flow. Furthermore, mostly due to space limitations, it might not be an efficient solution for such applications, in which it is not that practical to clamping the conductor. As the field density decreases exponentially by the distance from the field emitting source, this approach also requires very close placement for the most effective EH performance. In open-wide, such as Smart Grid and Smart City applications, this approach performs sufficiently in scavenging power from the targeted/attached assets to operate remote monitoring devices. However, it is still a challenging issue that gathering energy in a safe way from a high current carrying asset that has a physical contact with the harvester. To mitigate the safety concerns, M-field-based methods need to be equipped with advanced protection mechanisms and components. Similar to M-field related approaches, electric-field (E-field) EH is also targeting surrounding and unutilized field flow for operating miniscule of power requiring autonomous devices. E-field EH is simply based on obstructing the free charges that are being emitted by voltage implied conductor, and draining them via the displacement current. E-field EH is first tried on high and middle voltage overhead power lines by regarding the E-Field in abundance [198, 215, 216, 213]. First results revealed the potential of this method in powering wireless devices placed for condition monitoring procedures, and accordingly encouraged further efforts for building advanced Smart Grid services. It is then applied to low voltage systems as mounting single-phase AC power cords with metallic sheets [3, 217, 218, 219]. These efforts disclosed that, it is also possible to constitute an applicable EFEH methodology for applications in which E-Field intensity is considerably low. In short, E-field is the only source that is neither intermittent nor dependent on the load. As the voltage and the frequency

are firmly regulated and exactly maintained, the E-field is therefore stable and predictable in its behavior. Thus, it can be referred as the most promising way to compose long-term and self-sustainable communication systems notwithstanding the ambient factors [220].

### 12.4.3 System Architecture

In the system architecture, the nodes transmit their readings opportunistically to the access point or the sink that has the Internet connection. Furthermore, the sink or the access point has the CR capability. Topologies of the network may differ according to the application. These topologies are explained as follows.

*Ad hoc CRSN in the IoT:* In this architecture, there is no central entity for regulating the spectrum-aware communications. Hence, the nodes exchange control packets among themselves to perform interference free communication. The readings of the sensors are transmitted in multiple hops in an ad hoc manner. Spectrum management is performed cooperatively between the nodes.

*Clustered CRSN in the IoT:* In dynamic radio environment, the nodes can only communicate according to their spectrum availability. The nodes located within a neighborhood have similar vacant channels. It is highly possible that they have common channels among them. This provides a common control channel between the cluster members to exchange the control data for spectrum-aware communications. This is the most convenient architecture to support the communication.

*Heterogeneous CRSN in the IoT:* In this architecture, some special nodes are deployed, which have more power sources. These nodes may have special responsibilities such as spectrum bargaining [33].

*Mobile CRSN in the IoT:* In addition to the dynamic radio environment, the nodes are mobile in this CRSN architecture. This makes the operation of CRSN more dynamic. Solutions for dynamic spectrum access should also consider the mobility in this architecture.

#### 12.4.4 Integration of Energy Harvesting Cognitive Radios with the Internet

CRSNs are distributed networks having no central entity regulating the communication. Due to the large operation coverage of the Smart City, sensor observations are conveyed in a multi-hop manner. Furthermore, some nodes can reach the sink or access point in one hop. The CRSNs are the main components of devices that can extract information from the environment, hence they are the main pillar of the IoT. The harvested information by the CRSN nodes is important for the actions to be taken and the information processing. The integration of CRSN with the mobile networks or the Internet realizes the IoT, and manages the communications in CRSNs. To this end, we overview architectures [5, 219] to enable the connection of CRSNs with the Internet.

Stack-based [6] and topology-based [5] solutions are the two approaches that integrate WSNs to the Internet. The stack-based integration approaches require similarity between the network stacks of the sensor network and the Internet. Front-end solution, gateway solution, and TCP/IP solution are the stack-based integration approaches. There is independency between the Internet and the sensor networks in the front-end solution. In this approach, the sensor network uses its own protocol. On the other hand, the Internet uses TCP/IP. The gateway approach supports tunneling for the exchange of information and the integration between the sensor networks and the Internet. In the TCP/IP approach, sensor networks and the Internet uses the same protocol, which is the TCP/IP solution advocates the integration by utilizing the same networking protocols in both sides. On the other hand, the topology-based approaches depend on the deployment of the Internet-connected nodes in the sensor networks.

The spectrum awareness by CR capability makes an important difference for the stack-based integration solutions. The access point or the base station, which provides the Internet connection, must behave as a CR node and operate in an opportunistic manner. They are not resource limited, which make them capable of complex operations. In front-end solution, the base station has two interfaces: one for CRSN,

and one for the Internet connectivity. The packets from CRSN nodes are gathered at the base station by spectrum-aware communications. The base station sends the collected information to the cloud or to a user via Internet connection using TCP/IP. The Internet connection of the CRSN nodes is achieved by the base stations at the edge of the network. This architecture is the classical approach existing in literature.

The gateway approach supports the addressing of the CRSN nodes such that a user on the Internet communicates with specific nodes in the network. However, the bottleneck in this approach is again the base station since IP tunneling is implemented and the information must traverse the base station. This approach uses extra bits for the encapsulation of the IP packet. This degrades the benefits of this approach.

The full integration with the Internet is achieved by the TCP/IP solution. A user on the Internet can access to any node in CRSN. For this approach, IPv6 is very promising for sensor networks, which enables sensor nodes to be directly connected to the Internet [174]. The use of IPv6 can realize the TCP/IP solution for CRSNs and increase the possibility of usage CRs in the Smart City. It provides interoperability between CRSN and different network systems in the Smart City, which will emulate always-on link communication [174].

In the topology-based integration solutions, location and the deployment of the nodes, and the base stations that are directly connected to the Internet are important [6]. Multiple nodes have access to the Internet in hybrid solution, which is one of the topology-based integration approaches. These nodes are the neighbors of base stations. In access point solution, sensor nodes have direct access to the access points.

## **12.5 A General Framework for EH-CRs in Smart City**

### *12.5.1 Operation Overview*

As the definition of the Smart City implies, this concept emerges from the need of better management of the cities. Hence, many national governments are pushed to adopt information and communications technologies to provide better services in the cities, which realize the Smart City concept [221]. With the application of the Smart

City, city resources are efficiently utilized, costs of the city are reduced and the life quality of the city residents is increased [222].

The adoption of IoT in the Smart City also provides new services for the citizens and the governments. These services may be structural health, waste management, air quality and traffic congestion monitoring, and smart lighting and parking, to name a few [222]. IoT networks will find a number of deployment areas in the city to realize the concept of the Smart City. These areas include transport systems, bridges, electric grid, hospitals, schools, cultural sites, etc. Hence, with the IoT concept, the Internet becomes even more pervasive, which also helps realizing the Smart City. Every device will be connected to each other and the Internet.

The business side of the Smart City is studied in terms of the public actors and the city governments [223]. However, there are some open issues in the technical side of the Smart City. First of all, due to excessive increase in wireless communications, there are some challenges. The Smart City concept requires to sense the systems of the city and to report the application specific data to the city officials. This causes an enormous amount of data transfer from different part of the cities, which also increases wireless traffic in the city. Hence, new communication paradigms should be utilized. To this end, CR is an efficient solution to overcome the excessive wireless traffic in the city by opportunistic spectrum access. Secondly, wireless devices deployed in the Smart City are resource constrained. The reporting about the systems in the city causes energy depletion of the wireless nodes. Since the maintenance of these nodes is a difficult task, EH methods are perfect candidates to extend the lifetime of these nodes. To this end, the concept of EH-CRs becomes very important to address the technical challenges for enabling the Smart City.

From the holistic point of view, operation overview of EH-CRs in the Smart Cities can be explained as in Fig. 12.2. The EH-CR nodes deployed in the systems of the city report their sensing results to the city officials thanks to the approaches enabling integration of EH-CRs with the Internet. By using the spectrum opportunistically, they send their information in a more reliable manner. With the adoption of EH, they

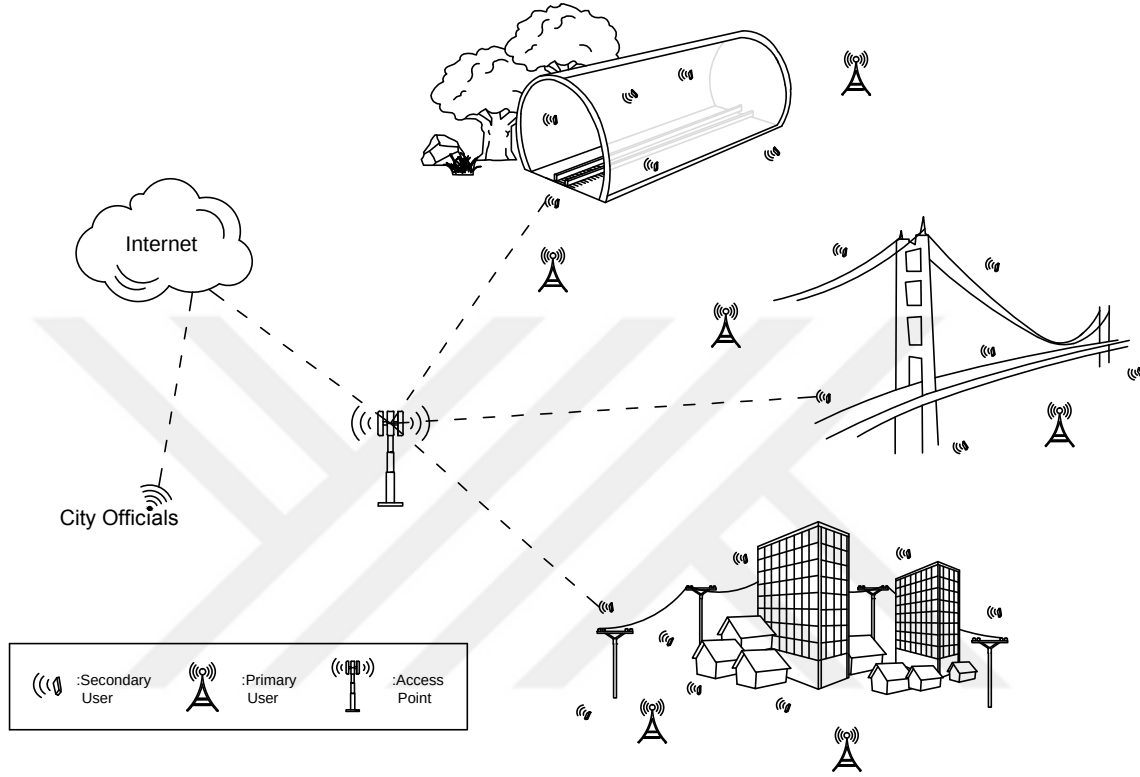


Figure 12.2: Operation overview of EH-CR in the Smart City.

do not face the shortages in the battery power. They increase the communication efficiency and power efficiency of the Smart City.

### 12.5.2 Node Architecture

Node architecture of an EH-CR node in the Smart City contains four main units as in Fig. 12.3, which are antenna unit, ultra-low power communication unit, ultra-low power processing and power provisioning unit. The ultra-low power communication unit provides the capability of channel switching, channel sensing, modulation and power control. The power provisioning unit has energy harvester, rectifier, regulator and super-capacitor. It provides energy to the antenna unit, communication unit and power processing unit. The aim of this unit is to convert an available resource into utilizable electrical power to operate the nodes. The processing unit decides the operating parameters, which consists of micro-processor and memory. Communication

unit has RF frontend, demodulator and decoder to provide the communication with CR functionalities.

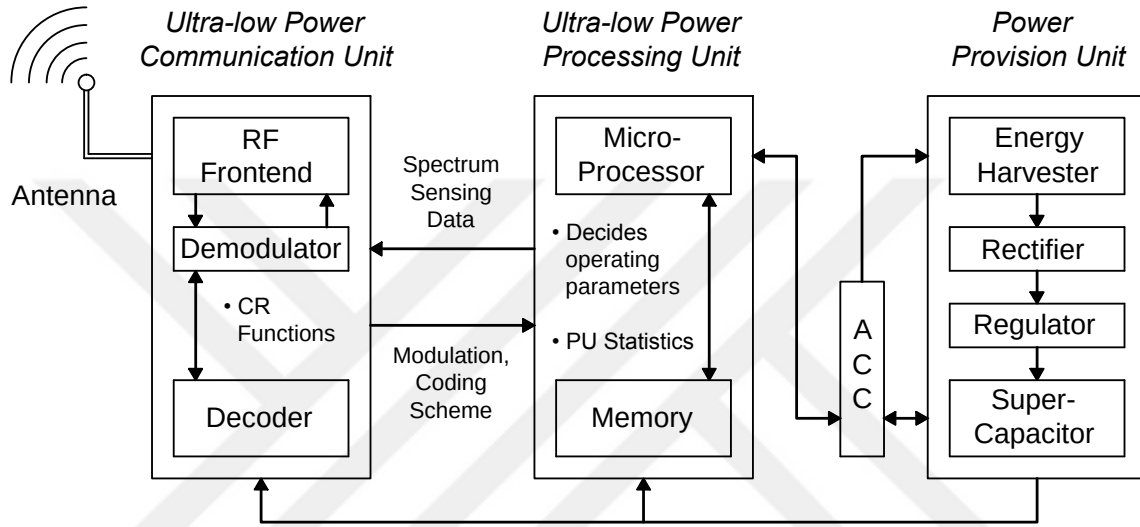


Figure 12.3: Node architecture of EH-CR node.

The block stated as ACC in Fig. 12.3, i.e., autonomous connection circuit, needs to be employed to switch between harvesting and nodal operation stages. This circuit simultaneously observes the voltage level on the storage element, i.e., super-capacitor, and accordingly enables charge transfer when the harvested energy is sufficient enough for sensory operations, and disengages the super-capacitor from the circuit to turn back the harvesting period when the voltage level descends below a certain threshold. This operation, held under the control of processing unit, not only prevents undesired discharge of super-capacitor, but also allows more frequent transmission cycles by shortening the time exerted for harvesting process [220].

### 12.5.3 Network Architecture

The networks consisting of EH-CRs have ad hoc and cluster-based architectures. The centralized architecture would be not feasible due limited harvestable energy. The harvestable energy cannot support the energy required for the transmission and the reception of the control data with the central entity regulating the communication.

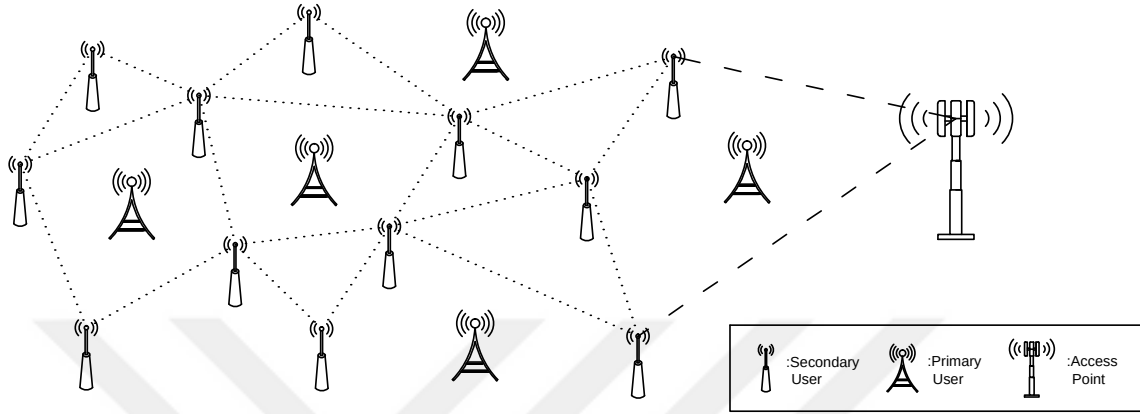


Figure 12.4: Ad hoc network architecture of EH-CR in the Smart City.

In ad hoc networks, each EH-CR nodes detects the vacant channels with the spectrum sensing. The sensing results are exchanged in the neighborhood to decide on which channel to operate for the communication. This may lead high power consumption for the nodes due to failures in the exchange of control data and false spectrum sensing results. Hence, cooperation between nodes is required to increase the reliability of the spectrum-aware communications; however, it may increase the amount of the control data. Ad hoc network architecture can be seen in Fig. 12.4.

The cluster-based architecture supports cooperation in the network more by enabling local coordinators in the network. These local coordinators are called cluster-heads, where the spectrum sensing results of the cluster members are gathered for determining the operating frequency among the cluster members. This increases the reliability since the nodes in a neighborhood reach an agreement on the parameters of the spectrum-aware communications.

However, the cluster-heads require more power since they are the most active nodes in their corresponding cluster. These issues make the cluster-head selection procedure important. The cluster-heads should have the highest number of available channel, since it should communicate as many neighbors as possible to increase its connectivity. Furthermore, the node exchanges information with its members that increases the power consumption of the cluster-heads in comparison to the ordinary

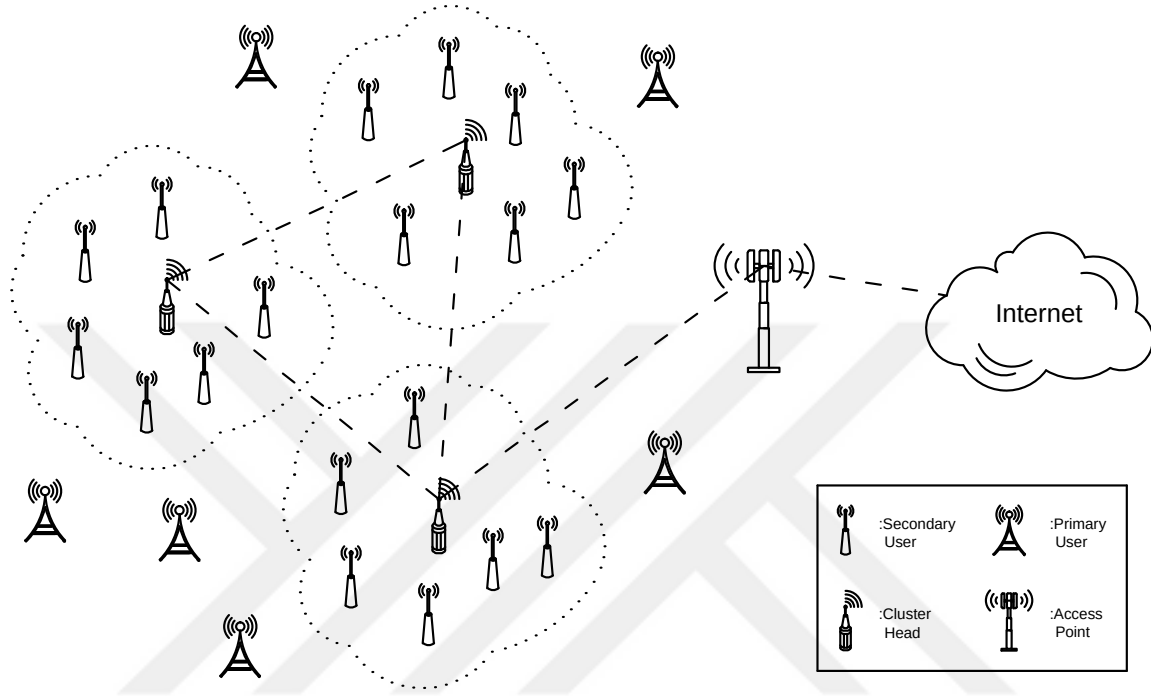


Figure 12.5: Clustered network architecture of EH-CR in the Smart City.

nodes. Hence, the selection of the cluster-heads in the network should depend on the harvested energy as well as the number of available idle channels. This architecture is illustrated in Fig. 12.5.

#### 12.5.4 Application Areas

The main application areas of the networks consisting of EH-CRs are the systems of cities. These application areas can be outlined as follows [224].

- *Transport systems:* Provisioning of traffic data by dynamic mapping, monitoring of parking lots, pollution detection in different parts of the city, monitoring of the transportation network
- *Hospitals:* Monitoring of hospital conditions such as temperature of vaccines and people with disabilities

- *Alert services:* Deployment of EH-CRs in different parts of the city for alerting services such as traffic control and communication services to alert citizen about critical situations
- *Energy systems:* Decreasing the outages and failures, and monitoring of water and gas consumption by smart metering systems.



## Chapter 13

### CONCLUSION

In this thesis, cognitive radio technology on different types of networks such as wireless ad hoc networks, wireless networked control systems, wireless multimedia sensor networks, Internet of Things and Smart Grid. The thesis clearly concludes that cognitive radio technology can be efficiently utilized to overcome spectrum scarcity and inefficient utilization challenges with the limited power supply problem by decreasing packet collision. The thesis proposes different communication techniques to enable spectrum-aware communications, which are clustering, network coding, and energy harvesting. The challenges, advantages and disadvantages to apply this technology in next generation wireless networks have been investigated in a detailed manner.

The findings in each pillar in next-generation cognitive wireless networks for this thesis can be summarized as follows.

- **Cognitive Radio Ad Hoc and Sensor Networks:** Utilization of spectrum opportunity is characterized to understand spectrum-aware communication in cognitive radio ad hoc and sensor networks. Event-driven spectrum-aware clustering is proposed for mobile wireless networks with cognitive radio capability. Its performance is analyzed extensively and compared with other related protocols. Optimal transmission range is found according to the energy per bit and primary user activity. Clustering in multi-channel cognitive radio ad hoc and sensor networks are analyzed and studied in terms of motivations, challenges and benefits. Network coded communication is performed and coding window size effect is studied on multicast throughput and interference.

- **Wireless Networked Control Systems:** I apply spectrum-aware communication in wireless networked control systems and find maximum coverage area and energy-efficiency under convergence constraint.
- **Wireless Multimedia Sensor Networks:** The adoption of cognitive radio in wireless multimedia networks is studied layer by layer. Challenges and open research issues are investigated.
- **Cognitive Internet of Things:** Network coding application in Internet of Things with cognitive radio capability is studied and integration of sensor nodes with cognitive radio is analyzed. Energy harvesting is studied if cognitive radio is applied in Internet of Things domain. IoT-enabled Smart Cities are investigated when cognitive radio technology is adopted.

The detailed conclusion reached in the chapters is given in the following.

### ***13.1 On the Utilization of Spectrum Opportunity in Cognitive Radio Networks***

In this chapter, we characterize the USOP probability under different network topologies. We find that this probability depends on the network topologies, the sensing performance of CRs, the channel conditions, and the PU activities. We observe the effects of them on the USOP probability in our numerical analysis. This probability can be used for proposing new solutions and protocols in medium access control, routing, transport and resource allocation schemes as it provides a probabilistic view of the spectrum-aware communication.

### ***13.2 Clustering in Multi-Channel Cognitive Radio Ad Hoc and Sensor Networks***

This chapter investigates clustering in multi-channel cognitive radio ad hoc and sensor networks. To this end, we define the requirement of these networks and design

considerations of clustering. The topologies for these networks are introduced, and motivations, challenges and functionalities of clustering are explained according to the network requirements. Existing solutions for clustering are studied. Furthermore, we explore how a clustering scheme must be in order to satisfy requirements of a realistic multi-channel cognitive radio ad hoc and sensor networks.

### ***13.3 Event-to-sink Spectrum-Aware Clustering in Mobile Cognitive Radio Sensor Networks***

In this chapter, we address the need for event-to-sink coordination scheme by presenting a clustering protocol for mobile CRSNs to minimize the energy consumption and to coordinate the communication between event and sink. We propose a two phase clustering algorithm which determines eligible nodes for clustering and performs clustering based on node weights according to some system parameters in mobile CRSNs [7]. Eligible node degree, number of available channels, remaining energy of nodes, the distance to the sink and the speed of the nodes are selected parameters to increase the energy-efficiency and connectivity of clusters. We further investigate the average re-clustering probability and how our approach decreases this probability. We obtain the maximum average event frequency to achieve energy efficiency for our protocol.

### ***13.4 Optimal Transmission Range for Cognitive Radio Ad Hoc Networks***

Transmission range is an important parameter in network where the nodes do not have power control capability and limited battery power. Hence, an energy optimal transmission range can be set up before the deployment of the nodes. This is the main motivation of this chapter. To this end, we first characterize the spectrum-aware communication and then find the cognitive hop advance distance accordingly considering the dynamic radio environment. To optimize the transmission range of the nodes, we define a cognitive hop advance-energy efficiency metric under reliable and unreliable link conditions. We find the energy optimal transmission range of the

nodes under the effects of system parameters and successful link probability due to primary user activities.

### ***13.5 On the Network-Coded Multicast Communication in Cognitive Radio Ad Hoc Networks***

In this chapter, we investigate the effect of NC in multicast communication for a cluster setting, where the communication is spectrum-aware. Multicast throughput and upper bound on average interference are two metrics we consider to characterize coding window size. We observe that there is an optimal coding windows size that maximizes throughput and minimizes the interference to the PU. Furthermore, the optimality depends on the system parameters such as packet length, field size, bit rate, and the PU activities. Hence, these results can be utilized to propose effective NC schemes in dynamic radio environment.

### ***13.6 Maximum Coverage Area of Cognitive Wireless Networked Control Systems with Maximum Cost-Efficiency under Convergence Constraint***

In this chapter, cognitive radio capable wireless networked control systems are investigated in terms of coverage. We find lower bound on the maximum coverage area under the Kalman filter convergence. We found critical hop diameter that guarantees the convergence. Afterwards, we find lower bound on the number of nodes providing maximum coverage area with maximum cost efficiency [90].

### ***13.7 Maximization of Energy-Efficiency under Convergence Constraint in Wireless Networked Control Systems***

In this chapter, we maximize the energy-efficiency of a WNCS consisting of  $N$  independent subnetworks having CR capable sensor nodes. We define an energy-efficiency function and formulate an optimization problem [225]. We solve it under the con-

vergence constraint of the Kalman filter. We characterized successful packet delivery probability and find a lower bound on the maximum coverage of the overall system which guarantees the convergence of the Kalman filter. We investigate the effects of system parameters and spectrum-aware communication parameters on the successful packet delivery probability, the energy consumption and the lower bound on the maximum total coverage area of the system.

### ***13.8 Multimedia Communication in Cognitive Radio Ad Hoc and Sensor Networks***

In this chapter, we surveyed the existing literature on multimedia communication in WSN, CRN, CRSN and WMSN [226]. We also investigate the protocols proposed for wireless networks and point out their advantages and disadvantages to realize the multimedia communication in cognitive radio ad hoc and sensor networks. Existing approaches are scrutinized from the perspective of network layers. The challenges posed by multimedia communication and cognitive radio ad hoc and sensor network paradigm are clearly indicated for each network layer. Open research avenues for realizing multimedia communication over cognitive radio ad hoc and sensor networks are determined.

### ***13.9 Network Coding for Cognitive Internet of Things***

In this chapter, we investigate the NC application for CRSNs, which can be considered as the main pillar of the CIoT in 5G wireless networks. We analyze the integration techniques to connect sensor networks to the Internet as 5G is a struggle to bring all devices in IP networks. We overview the applications of NC in WSNs and study how they can be modified for a dynamic radio environment. We also point out the challenges and open issues of the NC to enable the CIoT.

### ***13.10 Energy Harvesting Cognitive Radio Networking for IoT-enabled Smart Grid***

In this chapter, we propose a totally new networking architecture, namely, Energy Harvesting Cognitive Radio Networking for Internet of Things-enabled Smart Grid [227]. EH techniques are planned to be utilized for increasing the lifetime of wireless devices deployed in IoT-enabled SG. Furthermore, as the SG has harsh channel conditions and spectrum scarcity problems in its network architecture, we propose to use CR to overcome these issues. This new networking paradigm is investigated in terms of general operation, node and network architecture aspects. Open issues and future research directions are presented to realize EH-CR networking in the IoT-enabled SG.

### ***13.11 Energy Harvesting Cognitive Radios in Smart Cities***

In this chapter, we overview the joint use of two important techniques for the realization of the Smart City concept, which are CR and EH techniques. We discuss these techniques and their usage in the Smart City. We explain the motivations for spectrum-aware and self-sustaining communications. The challenges posed by utilization of these techniques in the Smart City are studied and IoT networks with CR and EH capabilities are discussed. According to these discussions, a general framework for EH-CRs is explained for the Smart City concept.

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