

Cognitive Communication Techniques for Next-generation Heterogeneous 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 Sefa and Zeki Ergül
and my sister Özge Ergül-Özçıtak...

ABSTRACT

Recently, cognitive radio emerged as a promising solution to spectrum scarcity problem. Cognitive radio introduces appealing features, such as improved spectrum utilization and increased communication quality, by making use of opportunistic and dynamic spectrum access. However, these capabilities impose additional tasks like spectrum sensing and spectrum management. In the following years, cognitive radio technology will inevitably be used in various network platforms, such as wireless sensor networks, smart grid, machine-to-machine communications, public protection and disaster relief networks, and vehicular networks.

In each of the areas where cognitive radio is to be introduced, optimal techniques that address the trade-off between additional capabilities and requirements of cognitive radio must be developed. The aim of this thesis is to intelligently exploit the characteristic of various network platforms to develop cognitive communication solutions tailored specifically to each of them. For the areas mentioned earlier, we provide a comprehensive discussion of how cognitive radio technology may be applied to alleviate the problems, mainly related to spectrum scarcity. Then we present solutions related to spectrum sensing, throughput maximization and achievable reliability for cognitive radio sensor networks as applied to some of these communication systems.

Specifically, we present our solutions for a two-stage spectrum sensing technique developed for resource constrained cognitive radio sensor networks. The first stage is to roughly determine a set of channels which are more likely to be available. In the second stage, a more accurate fine sensing scheme is used to locate vacant channels with higher precision.

We also present our analysis on throughput maximization for electromagnetic

energy harvesting cognitive radio networks, as well as an analysis of achievable reliability under opportunistic spectrum access for cognitive sensor-actor networks in smart grid. We target smart grid specifically for the later analysis, since reliability is a key requirement in both securing expansive backbone smart grid equipment and adaptive pricing using up-to-date demand response information.

We discuss the viability of using cognitive radio technology in public protection and disaster relief networks, and propose a network architecture based on cognitive radio. We present comparisons of our architecture with the state-of-the-art and give simulation results to emphasize the importance of cognitive radio when used properly in such systems.

Finally, we investigate the routing problem in cognitive vehicular networks. We list the challenges for routing in this network type, mainly due to its highly dynamic nature. We also lay out the advantages that are specific to vehicular networks. We present the state-of-the-art on both routing for vehicular and cognitive vehicular networks and discuss open research areas.

ÖZETÇE

Son dönemlerde bilişsel radyo tayf kısıtlılığı sorunu için umut vaadedici bir çözüm olarak belirmiştir. Bilişsel radyo, fırsatçı ve dinamik tayf erişimi yeteneği sayesinde gelişmiş tayf kullanımı ve artırılmış iletişim kalitesi gibi çekici özellikler sağlamaktadır. Ancak bu kabiliyetler tayf algılama ve tayf yönetimi gibi ek görevleri gerekli kılarlar. Önümüzdeki yıllarda bilişsel radyonun kablosuz algılayıcı ağlar, akıllı şebekeler, makineden makineye haberleşme, toplum koruma ve afet yardımı ağları ve araç ağları gibi alanlarda kullanılması öngörülmektedir.

Bilişsel radyonun kullanımı için her bir alandaki ek yetenekler ile yeni gereksinimler arasındaki dengeyi sağlayacak en uygun tekniklerin belirlenmesi gerekmektedir. Bu tezde amacımız farklı ağ platformlarının karakteristiklerinden faydalanan özel tasarlanmış bilişsel radyo tabanlı çözümler geliştirmektir. Önceden bahsedilmiş olan alanlardan herbiri için bilişsel radyonun, özellikle tayf kısıtlılığı sorununu aşmak için, nasıl kullanılabileceği ile ilgili kapsamlı tartışmalar sunulmuştur. Ardından, bilişsel radyo algılayıcı ağlar için tayf algılama, erişilebilir hız ve ulaşılabilir güvenilirlik için çözümler sunulmuştur.

Daha belirgin ifade etmek gerekirse, kaynağı kısıtlı bilişsel radyo algılayıcı ağlar için iki aşamalı tayf algılama çözümleri sunulmuştur. Birinci aşamada boş olma ihtimali yüksek olan kanallar kabaca kestirilmektedir. İkinci aşamada daha kesin bir algılama yöntemi kullanılarak boş kanallar daha yüksek bir hassasiyetle belirlenmektedir.

Elektromanyetik enerji depolayan bilişsel radyo ağları için erişilebilecek en yüksek hıza ilişkin analiz sunulmuştur. Ayrıca, akıllı şebeke ağları için fırsatçı tayf erişimi ile erişilebilecek en yüksek güvenilirliğe ilişkin inceleme de verilmiştir. Bu analiz için özel olarak akıllı şebeke ağlarını tercih etmemizin sebebi, gerek pahalı şebeke ekipmanını

korumak için, gerekse uyarlanabilir ücret belirleme için, güvenilirliğin bu ağlarda son derece önemli bir gereksinim olmasıdır.

Toplum koruma ve afet yardımı ağlarında bilişsel radyo kullanımının geçerliliği tartışılmış ve bilişsel radyo tabanlı bir ağ mimarisi önerilmiştir. Önerilen yapının literatürdeki alternatifleri ile karşılaştırılması sunulmuştur. Benzetim sonuçları, uygun kullanıldığında, bu sistemlerde bilişsel radyonun önemini göstermektedir.

Son olarak, bilişsel araç ağlarında yönlendirme konusu ele alınmıştır. Bu ağ türünün dinamik doğasından ortaya çıkan zorluklar ve bunun yanı sıra, bu ağlara has avantajlar listelenmiştir. Araç ağları ve bilişsel araç ağlarında yönlendirmeye yönelik literatürdeki çalışmalar incelenmiştir.

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NOMENCLATURE

CR	Cognitive Radio
OSA	Opportunistic Spectrum Access
WSN	Wireless Sensor Network
ISM	Industrial Scientific and Medical
PU	Primary User
SU	Secondary User
WLAN	Wireless Local Area Network
CRSN	Cognitive Radio Sensor Network
CRN	Cognitive Radio Network
WSAN	Wireless Sensor and Actor Network
SDR	Software Defined Radio
DSP	Digital Signal Processing
QoS	Quality of Service
FEC	Forward Error Correction
MAC	Medium Access Control
SNR	Signal to Noise Ratio
CC4C	Cooperative Coarse Sensing for CRSN
SPRT	Sequential Probability Ratio Test
ERL	Expected Run Length
ES	Energy Sensing
OFDM	Orthogonal Frequency-Division Multiplexing
MIMO	Multiple Input and Multiple Output
CSS	Cooperative Spectrum Sensing

AWGN	Additive White Gaussian Noise
ROC	Receiver Operating Characteristic
M2M	Machine-to-machine Communication
EM	Electromagnetic
PPP	Poisson Point Process
EM	Electromagnetic
DTV	Digital Television
DF	Decode and Forward
AF	Amplify and Forward
SG	Smart Grid
HAN	Home Area Network
NAN	Neighborhood Area Network
WAN	Wide Area Network
ARQ	Automatic Repeat Request
IED	Intelligent Electronic Device
PEV	Plug-in Electric Vehicle
DAU	Data Aggregate Unit
FAN	Field Area Network
AMI	Advanced Metering Infrastructure
DSL	Digital Subscriber Line
PLC	Power Line Communication
BLE	Bluetooth Low Energy
WRAN	Wireless Regional Area Network
MSE	Mean Squared Error
BLUE	Best Linear Unbiased Estimator
SINR	Signal to Interference plus Noise Ratio
FSK	Frequency Shift Keying

CSMA	Carrier Sense Multiple Access
PPDR	Public Protection and Disaster Relief
ENISA	European Network and Information Security Agency
UNDP	United Nations Development Programme
V2R	Vehicle-to-Roadside
SDN	Software Defined Networking
RPR	Resilient Packet Ring
AP	Access Point
UWB	Ultra Wide Band
SIR	Signal to Interference Ratio
NB	Narrow Band
DoA	Direction of Arrival
ICG	Intelligent Cognitive Gateway
TEDS	TETRA Enhanced Data Services
CVN	Cognitive Vehicular Network
VANET	Vehicular ad hoc Network
MANET	Mobile ad hoc Network
CCC	Common Control Channel
GPS	Global Positioning System
RSU	Roadside Unit
ETT	Expected Transmission Time
ETX	Expected Transmission Count
LOS	Line-of-Sight
DTR	Delay Tolerant Routing

Chapter 1

INTRODUCTION

In the near future, billions of wireless devices are expected to be operational. The overall wireless bandwidth requirement will be immense, giving rise to the spectrum scarcity problem. Cognitive radio (CR) has emerged as the key technology to address this problem with the capability of opportunistic spectrum access (OSA). A CR has the ability to sense the spectrum, identify the vacant bands and momentarily configure its transmission and reception parameters to be able to communicate in such bands. As such, main potential advantages introduced by cognitive radio can be listed as improving spectrum utilization and increasing communication quality.

These features are highly appealing for many wireless communication areas. One such area is wireless sensor networks (WSN). CR equipped sensor nodes can meet the unique requirements and challenges of resource-constrained multi-hop WSN. The number of applications that use industrial, scientific and medical (ISM) radio bands increase every day, creating interference problem for WSNs that generally operate on these bands. Furthermore, OSA stands as very promising and spectrum-efficient communication paradigm for WSN due to its event-driven communication nature, which generally yields bursty traffic depending on the event characteristics. In addition, ability to access multiple wireless spectrum bands may also help eliminate collision and excessive contention delay incurred by dense deployment of sensor nodes. Clearly, it is conceivable to adopt cognitive radio capability in sensor networks, which, in turn yields a new sensor networking paradigm, i.e., cognitive radio sensor networks (CRSN). In this thesis, one of our aims is to lay out the main design principles, potential advantages and application

areas, and network architectures of CRSN. The existing communication protocols and algorithms devised for cognitive radio networks (CRN) and WSN are discussed along with the open research avenues for the realization of CRSN [1].

Design of efficient spectrum sensing schemes is imperative for the implementation of CRSNs, since sensor nodes are energy-constrained devices. One of the proposed methods is to use a two-stage spectrum sensing scheme. A simple, coarse sensing scheme is used in the first stage to find channels that are more likely to be available. Once these channels are identified, a more complex, fine sensing scheme is used in the second stage to assess channel availability with higher precision. Based on this two-stage spectrum sensing idea, we propose a sensing scheme for each stage.

A novel cooperative coarse sensing scheme for CRSN, we call CC4C, is proposed as a coarse sensing scheme [2]. CC4C is based on sequential sensing, thus, it is simple and fast. Simulation results show that CC4C incurs less sensing delay and provides significant energy conservation compared to energy detection based coarse sensing schemes, and single stage sensing schemes where no coarse sensing is performed.

For the second stage, a cooperative spectrum sensing scheme (CSS), specifically designed for CRSNs, is presented [3]. CSS aims to minimize power consumption and delay during spectrum sensing, while meeting the performance requirements in terms of accuracy with minimal complexity. Simulation results indicate that significant power savings can be achieved with the proposed solution.

Another area where CR capabilities are highly desirable is machine-to-machine communications (M2M). The number of sensors with wireless transceivers are expected to be extremely high. To enable M2M, two major problems must be addressed. How to obtain the required spectrum efficiency, and how to deliver the required power to these devices. The most promising answers to these questions are CR and energy harvesting, respectively. Energy harvesting enables deployment of sensors and devices without having to worry about their battery lifetime. CR increases the utilization of spectrum by accessing unused spectrum dynamically. energy harvesting from electromagnetic (EM) waves is suitable for these low power,

low cost devices used in M2M, since only minimal additional hardware is required for such energy harvesting. With this idea as the starting point, we first present an analysis on how much throughput can be obtained from an EM energy harvesting CRN. Then, we show when and how cooperation among network nodes may increase performance. We believe that our results will provide insight for the development of future cooperative cognitive energy harvesting networks.

One of the largest applications of M2M is for the next generation electric grid, called the Smart Grid (SG). The vision for SG is to monitor the equipment in all areas of the SG, from generation to consumer end, by smart sensors. Since SG will cover a huge geographic area, some parts of the SG network are bound to have spectrum scarcity problem. Therefore, using CRSN in SG seems to be a fitting solution. We investigate the CRSN in SG, laying out advantages, disadvantages, challenges and how they can be met for each network layer. We also investigate how CR technology may be of use in different parts of SG such as Home Area Network (HAN) at the consumer side, Neighborhood Area Network (NAN) at the distribution side and Wide Area Network (WAN) at the generation and transmission side.

Reliability is one of the most important requirements in SG communications. Reliable detection of an emergency event enables timely response. Within the automated nature of SG, such detection and response are carried out by sensor and actuator nodes. Therefore, it is important to study the capabilities of wireless sensor actor networks. In this chapter, we first present an analysis of reliability in sensor actor networks, and lay out the factors that effect reliability. We then propose a scheme, where actor nodes cooperate to reach a global estimate, i.e. consensus, under interruptions due to licensed user interference. We show that consensus improves reliability compared to local estimation of event features. We further show that convergence rate depends on connectivity of actors. A simulation study is presented to support our analyses and demonstrate the performance of proposed scheme in achieving consensus and mitigating disagreement among actor nodes.

In the light of the recent natural catastrophes and terrorist activities it has

become evident that new architectural approaches are needed for the next generation Public Protection and Disaster Relief (PPDR) networks. These architectures should be adaptable to the conditions at the event site, resilient enough to operate under adverse conditions of the emergency. Furthermore, they should enable timely gathering of crucial event data and its delivery to the responder units at the site as well as the command and control center that are off-site. We first examine the state-of-the-art for areas related to communication in PPDR systems, and discuss the open research issues for each topic. Then, we propose a novel architecture that meets the aforementioned requirements which relies on a novel device called Intelligent Cognitive Gateway (ICG). ICG enables flexible use of the spectrum and facilitates data gathering from all lower tier devices and relays this data to the relevant units through the higher tier public or commercial backhaul networks. Finally, we provide some results that justify the need for these devices in emergency scenarios.

Finally, we examine viability of CR in vehicular networks (VN). Specifically, we focus on routing in cognitive vehicular networks (CVN). VN, like SG cover a huge geographic area. Therefore, like the SG case, spectrum scarcity will inevitably be a problem for certain parts of VN in the near future leading to the realization of CVNs. Compared to other wireless networks, VNs have a considerably more dynamic nature due to the speed of the vehicles. Connectivity changes rapidly as vehicles move around, as well as the channel properties due to the changes in the landscape. For the CVN, another consideration is the rapid change in channel availability; as vehicles move, they go in and out of transmission range of primary users (PU). Therefore, routing in CVNs is a very challenging task. We investigate conventional routing schemes in mobile ad hoc networks (MANET) and also VNs. We point out how they are not directly usable for CVNs and point out possible extensions to these schemes. We also lay out exploitable features of CVNs and indicate what can be done to take advantage of these feature. We investigate routing in CVNs according to various criteria such as communication paradigm, routing approach, etc.

To sum up, our contributions in this thesis can be listed as:

- Introducing the idea for cognitive radio sensor networks, discussing its viability and listing open research areas
- Design of a suit of (coarse and fine sensing) cooperative spectrum sensing schemes specifically for the cognitive radio sensor networks
- Analysis on achievable maximum throughput for electromagnetic energy harvesting cognitive radio sensor networks
- Discussion of viability of cognitive radio for smart grid communications, listing advantages, disadvantages and open research issues
- Investigation of reliability under opportunistic spectrum access for cognitive radio sensor networks in smart grid
- Introduction of a network architecture for public protection and disaster relief communication systems
- Examination of state-of-the-art for routing in cognitive vehicular networks, identifying open research issues

Chapter 2

COGNITIVE RADIO SENSOR NETWORKS

Increasing usage of wireless communications triggered the development of dynamic spectrum access schemes. The key enabling technology providing dynamic, i.e., opportunistic, spectrum access is the cognitive radio [4]. Cognitive radio has the capability to sense the spectrum and determine the vacant bands. By dynamically changing its operating parameters, cognitive radio can make use of these available bands in an opportunistic manner surpassing the traditional fixed spectrum assignment approach in terms of overall spectrum utilization.

With these capabilities, cognitive radios can operate in licensed bands as well as in unlicensed bands. In licensed bands, wireless users with a specific license to communicate over the allocated band, i.e., the primary user (PU), has the priority to access the channel. Cognitive radio users, called secondary users (SU), can access the channel as long as they do not cause interference to the PU. Upon the natural habitants of a specific frequency band, i.e., PU, start communication; the cognitive radio users must detect the potentially vacant bands, i.e., spectrum sensing. Then, they decide on which channels to move, i.e., spectrum decision. Finally, they adapt their transceiver so that the active communications are continued over the new channel, i.e., spectrum handoff. This sequence of operation outlines a typical cognitive cycle [5], which can also be applied over an unlicensed band by all cognitive radio users with the same priority to access the channel.

The capabilities of cognitive radio may provide many of the current wireless systems with adaptability to existing spectrum allocation in the deployment field, and hence improve overall spectrum utilization. Among many others, these features can also be used to meet many of the unique requirements and challenges of WSNs,

which are, traditionally, assumed to employ fixed spectrum allocation and characterized by resource constraints in terms of communication and processing capabilities of low-end sensor nodes. In fact, a WSN comprised of sensor nodes equipped with cognitive radio may benefit from the potential advantages of the salient features of dynamic spectrum access such as:

- *Opportunistic channel usage for bursty traffic:* Upon the detection of an event in WSN, sensor nodes generate a traffic of packet bursts. At the same time, in densely deployed sensor networks, a large number of nodes within the event area try to acquire the channel. This increases probability of collisions, and hence, decreases the overall communication reliability due to packet losses leading to excessive power consumption and packet delay. Here, sensor nodes with cognitive radio capability may opportunistically access to multiple alternative channels to alleviate these potential challenges.
- *Dynamic spectrum access:* In general, the existing WSN deployments assume fixed spectrum allocation. However, WSN must either be operated in unlicensed bands, or a spectrum lease for a licensed band must be obtained. Generally, high costs are associated with a spectrum lease, which would, in turn, amplify the overall cost of deployment. This is also contradictory with the main design principles of WSN [6]. On the other hand, unlicensed bands are also used by other devices such as IEEE802.11 wireless local area network (WLAN) hotspots, PDAs and Bluetooth devices as shown in Table 2.1. Therefore, sensor networks experience crowded spectrum problem [7]. Hence, in order to maximize the network performance and be able to co-operate efficiently with other types of users, opportunistic spectrum access schemes must be utilized in WSN as well.
- *Using adaptability to reduce power consumption:* Time varying nature of wireless channel causes energy consumption due to packet losses and retransmissions. Cognitive radio capable sensor nodes may be able to change their operating

parameters to adapt to channel conditions. This capability can be used to increase transmission efficiency, and help reduce power consumption.

- *Overlaid deployment of multiple concurrent WSN:* With the increased usage of sensor networks, one specific area may host several sensor networks deployed to operate towards fulfilling specific requirements of different applications. In this case, dynamic spectrum management may significantly contribute to the efficient co-existence of spatially overlapping sensor networks in terms of communication performance and resource utilization.
- *Access to multiple channels to conform to different spectrum regulations:* Each country has its own spectrum regulation rules. A certain band available in one country may not be available in another. Traditional WSN with a preset working frequency may not be deployed in cases where manufactured nodes are to be deployed in different regions. However, if nodes were to be equipped with cognitive radio capability, they would overcome the spectrum availability problem by changing their communication frequency.

Therefore, it is conceivable to provide wireless sensor networks with the capabilities of cognitive radio and dynamic spectrum management. This defines a new sensor network paradigm, i.e., Cognitive Radio Sensor Networks (CRSN). In general, a CRSN can be defined as *a distributed network of wireless cognitive radio sensor nodes, which sense an event signal and collaboratively communicate their readings dynamically over available spectrum bands in a multi-hop manner ultimately to satisfy the application-specific requirements.*

While the above potential advantages and the definition of CRSN stand as a significant enhancement of traditional sensor networks, the realization of CRSN depends on addressing many difficult challenges, posed by the unique characteristics of both cognitive radio and sensor networks, and further amplified by their union. Among many others, inherent resource constraints of sensor nodes, additional communication and processing demand imposed by cognitive radio capability, design

Table 2.1: Operating spectrum bands of commercial WSN transceivers and overlapping wireless systems.

Sensor node platforms	Radio chip	Operating bands	Overlapping wireless systems
<i>Bean, BTnode, Mica2, MANTIS, Nymph</i>	Chipcon (TI Norway) CC1000	315, 433, 868, 915 MHz	Fixed, Mobile, Amateur, Satellite, Radiolocation, Broadcasting, Telemetry, ZigBee
<i>IMote, MicaZ, SenseNode, XYZ, Sentilla Mini, TelosB</i>	Chipcon (TI Norway) CC2420	2.4 GHz	Fixed, Mobile, Amateur Radio as secondary, 802.11b/g/n, Telemetry, Bluetooth, ZigBee
<i>Mica, weC</i>	RF Monolithics TR1000	916.3 - 916.7 MHz	Fixed, Mobile, Broadcasting, Telemetry, ZigBee
<i>ANT</i>	Nordic nRF24AP1	2.4 GHz	Fixed, Mobile, Amateur Radio as secondary, Telemetry, 802.11b/g/n, Bluetooth, ZigBee
<i>EyesIFX v1 and v2</i>	Infineon TDA5250	868 - 870 MHz	Fixed, Mobile, Broadcasting, Telemetry, ZigBee
<i>Iris</i>	Atmel AT86RF230	2.4 GHz	Fixed, Mobile, Amateur Radio as secondary, Telemetry, 802.11b/g/n, Bluetooth, ZigBee

of low-cost and power-efficient cognitive radio sensor nodes, efficient opportunistic spectrum access in densely deployed sensor networks, multi-hop and collaborative communication over licensed and unlicensed spectrum bands are primary obstacles to the design and practical deployment of CRSN.

Despite the extensive volume of research results on WSN [6] and considerable amount of ongoing research efforts on cognitive radio networks [5], CRSN is vastly unexplored field. In [8], an energy-efficient and adaptive modulation technique is introduced for CRSN in order to achieve high power efficiency towards maximizing the lifetime of resource-constrained sensor networks. In [9], CRSN is discussed for

applications such as health care and tele-medicine, which require timely delivery of critical information. Authors propose a centralized spectrum allocation scheme with game theoretic approach in order to achieve fair allocation of spectrum bands with maximum spectrum utilization and energy efficiency. Potential of dynamic spectrum access in sensor networks is shown in [10] to achieve high power efficiency in sensing applications by reducing interference of concurrent transmissions through distributed channel selection and power allocation.

Clearly, only a handful of studies reviewed above do not suffice to open the road towards the realization of cognitive radio networks. The abovementioned fundamental challenges and many others need to be precisely determined and effectively addressed in order to exploit the potential advantages of CRSN. In this chapter, we introduce the main design challenges and principles, potential advantages and application areas, and network architectures of CRSN. The existing communication protocols and algorithms devised for cognitive radio networks as well as WSN are explored from the perspective of CRSN and the open research avenues for the realization of CRSN are highlighted. Our objective is to provide a clear picture of potentials of cognitive radio sensor networks, the current state-of-the-art and the research issues on this timely and exciting topic.

2.1 CRSN Architecture

Cognitive radio sensor nodes form a wireless communication architecture of CRSN as shown Figure 2.1 over which the information obtained from the field is conveyed to the sink in multiple hops. The main duty of the sensor nodes is to perform sensing on the environment. In addition to this conventional sensing duty, CRSN nodes also perform sensing on the spectrum. Depending on the spectrum availability, sensor nodes transmit their readings in an opportunistic manner to their next hop cognitive radio sensor nodes, and ultimately, to the sink. The sink may be also equipped with cognitive radio capability, i.e., cognitive radio sink. In addition to the event readings, sensors may exchange additional information with the sink including control data for

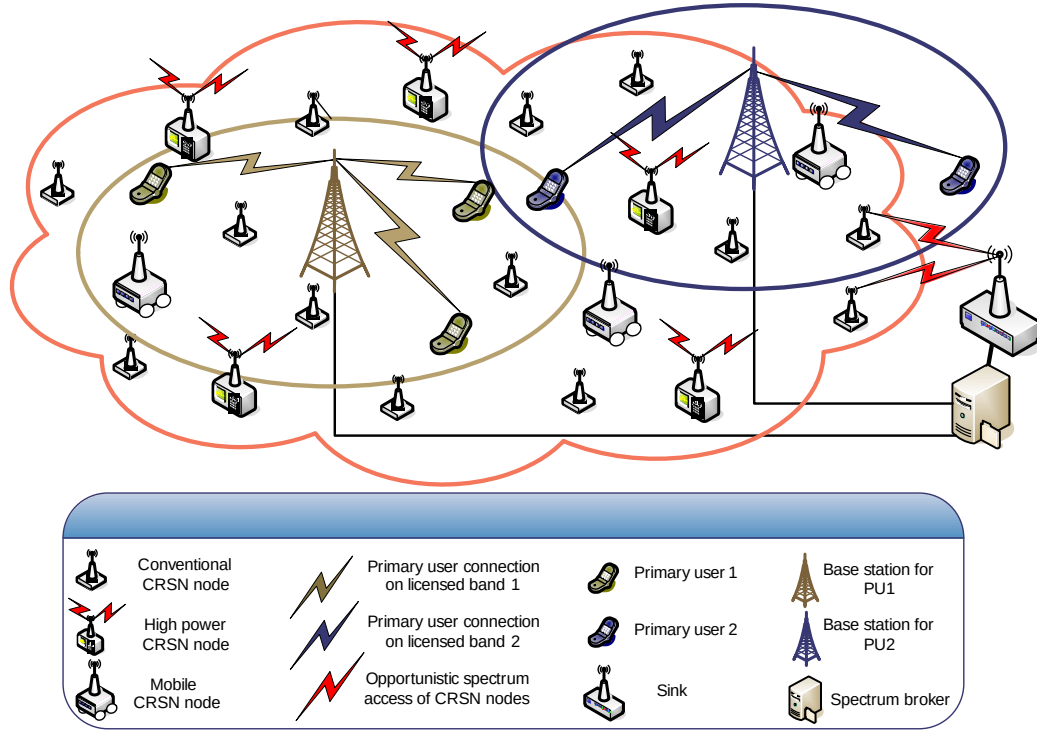


Figure 2.1: A typical cognitive radio sensor network (CRSN) architecture.

group formation, spectrum allocation, spectrum handoff-aware route determination depending on the specific topology.

A typical sensor field contains resource-constrained CRSN nodes and CRSN sink. However, in certain application scenarios, special nodes with high power sources, i.e., actors, which act upon the sensed event, may be part of the architecture as well [11]. These nodes perform additional tasks like local spectrum bargaining, or acting as a spectrum broker. Therefore, they may be actively part of the network topology. It is assumed that the sink has unlimited power and a number of cognitive transceivers, enabling it to transmit and receive multiple data flows concurrently.

2.1.1 CRSN Node Structure

CRSN node hardware structure is mainly composed of sensing unit, processor unit, memory unit, power unit, and cognitive radio transceiver unit as abstracted in Figure

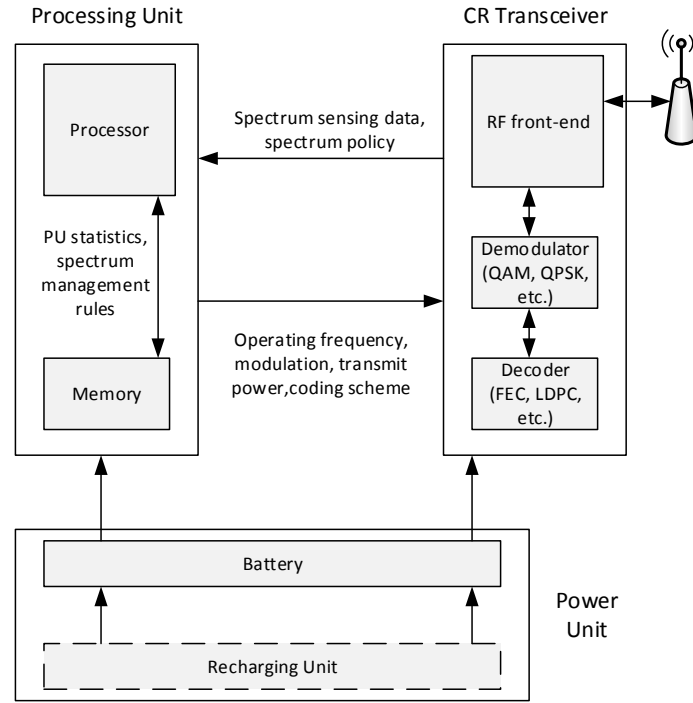


Figure 2.2: Hardware structure of a cognitive radio sensor node.

2.2. In specific applications, CRSN nodes may also have mobilization and localization.

The main difference between the hardware structure of classical sensor nodes [6] and CRSN nodes is the cognitive radio transceiver of CRSN nodes. Cognitive radio unit enables the sensor nodes to dynamically adapt their communication parameters such as carrier frequency, transmission power, and modulation.

CRSN nodes also inherit the limitations of conventional sensor nodes in terms of power, communication, processing and memory resources. These limitations impose restrictions on the features of cognitive radio as well. For example, as will be discussed in Section 2.3.1, CRSN nodes may perform spectrum sensing over a limited band of the spectrum due to processing, power, and antenna size constraints. Consequently, CRSN nodes are generally constrained in terms of the degree of freedom provided by the cognitive radio capability as well.

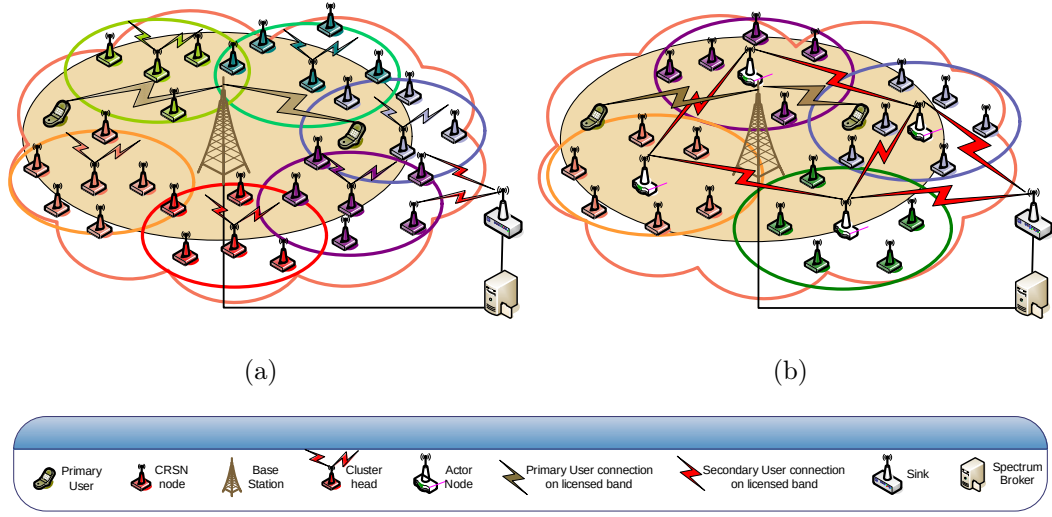


Figure 2.3: Possible network topologies for CRSN (a) Clustered (b) heterogeneous hierarchical.

2.1.2 CRSN Topology

According to the application requirements, cognitive radio sensor networks may exhibit different network topologies as explored in the following.

Ad Hoc CRSN

Without any infrastructural element, inherent network deployment of sensor networks yields an ad hoc cognitive radio sensor network as shown in Figure 2.1. Nodes send their readings to the sink in multiple hops, in an ad-hoc manner.

In ad hoc CRSN, spectrum sensing may be performed by each node individually or collaboratively in a distributed way. Similarly, spectrum allocation can also be based on the individual decision of sensor nodes. This topology imposes almost no communication overhead in terms of control data. However, due to hidden terminal problem, spectrum sensing results may be inaccurate, causing performance degradation in the primary user network.

Clustered CRSN

In general, it is essential to designate a common channel to exchange various control data, such as spectrum sensing results, spectrum allocation data, neighbor discovery and maintenance information. Most of the time, it may not be possible to find such common channel available throughout the entire network. However, it has been shown in [12] that finding a common channel in a certain restricted locality is highly possible due to the spatial correlation of channel availability. Therefore, a cluster-based network architecture as in Figure 2.3(a) is an appropriate choice for effective operation of dynamic spectrum management in CRSN.

In this case, cluster-heads may also be assigned to handle additional tasks such as the collection and dissemination of spectrum availability information, and the local bargaining of spectrum. To this end, new cluster-head selection and cluster formation algorithms may be developed for CRSN which jointly consider the inherent resource constraints as well as the challenges and requirements of opportunistic access in CRSN.

Heterogeneous and Hierarchical CRSN

In some cases, CRSN architecture may incorporate special nodes equipped with more or renewable power sources such as the actor nodes in wireless sensor and actor networks (WSAN) [11]. These nodes may have longer transmission ranges, and hence, be used as relay nodes much like the mesh network case. This forms a heterogeneous and multi-layer hierarchical topology consisting of ordinary CRSN nodes, high power relay nodes, e.g., cognitive radio actor nodes, and the sink as shown in Figure 2.3(b).

While the presence of capable actor nodes may be exploited for effective opportunistic access over the CRSN, the associated heterogeneity brings additional challenges. Among the others, sensor and actor deployment, increased communication overhead due to hierarchical coordination, and the need for cognitive radio capability over the actor nodes need to be addressed.

Mobile CRSN

When some or all of the architectural elements of a CRSN are mobile, this yields a more dynamic topology, i.e., a mobile CRSN. For example, the sensor nodes, actors if exist, and even the sink might be mobile depending on the specific application and deployment scenario.

Clearly, mobility amplifies the existing challenges on most of the aspects of CRSN. First of all, the dynamic nature of the topology requires mobility-aware dynamic spectrum management solutions over resource-constrained CRSN nodes. Moreover, cognitive radio communication protocols for CRSN must consider mobility as well. Therefore, this specific CRSN architecture needs a thorough investigation of the challenges and solution techniques.

In general, the physical characteristics of a CRSN node and diverse set of CRSN network topologies discussed above yield many open research issues outlined as follows.

- *CRSN node development:* Clearly, one of the fundamental issues for the realization of CRSN is the development of efficient and practical cognitive radio sensor nodes. Considering the basic design principles and objectives of sensor networks, and hence, the inherent limitations of sensor nodes, hardware and software design for sensor nodes with cognitive radio capability must be extensively studied.
- *Node deployment strategies:* In cases where primary user statistics are available, node deployment strategies considering spectrum availability characteristics may provide considerable improvements on the lifetime and transmission efficiency of the network. Therefore, the mathematical analysis for optimal node deployment in CRSN topologies, and hence, practical yet efficient deployment mechanisms must be investigated.
- *Clustering in CRSN:* Clustering and forming hierarchy incur additional

communication overhead in the network. This overhead may be amplified due to node mobility or spectrum handoff which vary the neighboring constellation of nodes. Hence, for the applications requiring cluster-based and hierarchical CRSN topologies, dynamic spectrum aware group formation and maintenance techniques must be developed.

- *Coordinated vs. uncoordinated network operation:* Spectrum sensing, spectrum detection and allocation, spectrum handoff as well as medium access may be performed either individually by the nodes or cooperatively in CRSN. A detailed efficiency analysis for the comparison of coordinated and uncoordinated schemes is required for various network topologies.
- *Optimal network coverage:* Spatial locations of CRSN nodes may vary even in case of manual uniform deployment due to node failures and primary user activities rendering some of the cognitive radio nodes disconnected. Hence, to maintain maximum network coverage, certain nodes may have to transmit with more radio power, which in turn, increases power consumption. On the other hand, connectivity at longer ranges may be achieved with lower frequencies which also help save transmission power. Therefore, optimal network coverage must be analyzed considering dynamic spectrum management, and new topology formation schemes which address the tradeoff between network lifetime and communication coverage must be introduced.

2.2 Potential Application Areas of CRSN

Traditional sensor networks already have a diverse range of application domains from smart home with embedded sensor and actuators to large-scale real-time multimedia surveillance sensor networks. With the ingress of cognitive radio capability to sensor networks regime, CRSN might be the preferred solution for some specific application domains explored below due to its potential advantages.

2.2.1 Indoor Sensing Applications

Indoor applications, e.g., tele-medicine [9], home monitoring, emergency networks, factory automation, generally require the deployment of many sensor nodes within a small area. In some cases, such as industrial operation automation, smart building, actor nodes may be also part of the deployment.

The main problem with indoor sensing applications is that the unlicensed bands, e.g., ISM bands, for indoor usage are extremely crowded [7]. Consequently, conventional sensor networks may experience significant challenges in achieving reliable communication due to packet losses, collisions and contention delays. Here, opportunistic spectrum access of CRSN may help mitigate these challenges due to crowded spectrum and extreme node density. For example, with the cognitive radio capability, emergency networks may coexist with other indoor wireless systems. Critical information, which requires real-time reliable communication, may exploit the potential advantages of dynamic spectrum management even in crowded environments.

2.2.2 Multimedia Applications

Reliable and timely delivery of event features in the form of multimedia, e.g., audio, still image, video, over resource-constrained sensor networks is an extremely challenging objective due to inherent high bandwidth demand of multimedia [13]. At the same time, the capacity provided by the sensor network varies with the temporal and spatial characteristics of the channel.

Unlike the traditional sensor networks, CRSN may provide the sensor nodes with the freedom of dynamically changing communication channels according to the environmental conditions and application-specific quality-of-service (QoS) requirements in terms of bandwidth, bit error rates, and access delay. Hence, for multimedia communication over sensor networks, CRSN may improve the performance of multimedia communication as well as overall spectrum utilization. For example, as the packet travels through multiple hops, each relaying node may

use higher frequencies and the highest possible data rate to provide required bandwidth.

Furthermore, when multiple nodes need to transmit at the same time, they try to acquire the same channel which increases the contention delay in WSN. However, nodes in a CRSN have access to multiple available channel and can send their data through different channels concurrently. Therefore, CRSN is more suitable to sensing applications that involve in multimedia communication.

2.2.3 Multi-class Heterogeneous Sensing Applications

Some applications may require multiple sensor networks with distinct sensing objectives to coexist over a common area [14]. Various information gathered from these networks may be fused to feed a single decision support. Similarly, in a single sensor network, different sensor nodes may be deployed over the same area to sample the event signal over multiple dimensions including scalar measurements, e.g., heat, humidity, location, motion, as well as audio visual readings of the target being monitored.

Clearly, readings of these heterogeneous sensor networks impose heterogeneity in terms of communication requirements as well. For example, a multimedia sensor node, providing streaming video data, has more bandwidth requirement and less delay tolerance compared to a magnetic sensor. With the help of dynamic spectrum management, multi-class heterogeneous sensor networks may overlap with minimum interference to each other. Furthermore, through the coordination and cooperative spectrum management among these multiple cognitive radio sensor networks, their individual performance as well as the overall spectrum utilization may be improved.

2.2.4 Real-time Surveillance Applications

Real-time surveillance applications like target detection and tracking require minimum channel access and communication delay. In traditional WSN with fixed spectrum allocation, this objective may not be always achieved, especially if the

operating spectrum band is crowded. Furthermore, additional communication latency may occur in WSN in case of re-routing due to a link failure caused by degrading channel conditions.

In CRSN, sensor nodes may opportunistically access to the available channel in order to maintain minimum access and end-to-end communication delay for effective real-time surveillance applications. As discussed in Section 2.4.3, with the development of new delay-constrained joint spectrum allocation and routing algorithms for CRSN, performance of real-time sensing applications may be further improved. At the same time, statistical information of primary user over the spectrum band in use can be exploited in order to minimize the probability of spectrum handoff so as to avoid increasing communication delay due to frequent spectrum mobility.

One typical real-time sensing application example is military surveillance applications which are highly delay-sensitive and also require high reliability. In general, tactical sensor networks are densely deployed to assure network connectivity and maximize reliability within a certain delay bound. As mentioned above, such dense deployment can also exploit the potential advantages of dynamic spectrum access. Furthermore, with the spectrum handoff capability, tactical surveillance CRSN may be less susceptible to interception and jamming threats.

2.3 Dynamic Spectrum Management in CRSN

The realization of cognitive radio sensor networks primarily require an efficient spectrum management framework to regulate the dynamic spectrum access of densely deployed resource-constrained sensor nodes. The major challenges and open research issues regarding such dynamic spectrum management framework for CRSN are explored in this section.

Table 2.2: Overview of spectrum sensing methods.

Spectrum Sensing Method	Disadvantages	Advantages
<i>Matched Filter [15]</i>	Requires a priori info on PU transmissions, and extra hardware on nodes for synchronization with PU.	Best in Gaussian noise. Needs shorter sensing duration (less power consumption)
<i>Energy detection [16]</i>	Requires longer sensing duration (high power consumption). Accuracy highly depends on noise level variations	Requires the least amount of computational power on nodes.
<i>Feature detection [17]</i>	Requires a priori knowledge about PU transmissions. Requires high computational capability on nodes.	Most resilient to variation in noise levels.
<i>Interference temperature [18]</i>	Requires knowledge of location PU and imposes polynomial calculations based on these locations.	Recommended by FCC. Guarantees a predetermined interference to PU is not exceeded.

2.3.1 Spectrum Sensing

Spectrum sensing is one of the major functionalities distinguishing CRSN from traditional WSN. Since nodes can operate on spectrum bands of the licensed primary users in an opportunistic manner, they must gather spectrum usage information via spectrum sensing prior to transmission. In the literature, there exist various spectrum sensing methods, which are examined below in terms of how they can apply to CRSN.

- *Matched filter:* It has been shown that the optimal spectrum sensing method for the cognitive radio with the presence of Gaussian noise is the matched filter method [15]. However, this approach requires a priori knowledge about the transmission of the primary user. Since it is a coherent detection method, it requires synchronization with the primary user. In cases, where PU transmission

characteristics are available, matched filter-based detection may be employed. However, most of the time, such assumption is unrealistic. Furthermore, CRSN nodes need additional dedicated circuitry for each encountered primary user type. This considerably increases the cost and complexity for low-end sensor nodes.

- *Energy detection:* Inherent constraints of CRSN nodes mandate for a simpler spectrum sensing technique such as energy detection method. This method is popular even in cognitive radio networks, where nodes are typically less power constrained and have more computational power [16]. The idea is to measure the received energy on the specific portion of the spectrum, i.e., channel, for a certain period of time. If the measured energy is below a threshold value, the channel is considered available. Its simplicity and low signal processing requirement make this method very attractive for CRSN. However, it has a number of drawbacks. Energy detection requires longer measurement duration to achieve a certain performance level compared to matched filter method. Furthermore, the performance of this method highly depends on variations of the noise power level. Therefore, in case of a small increase in detected energy, it is impossible to understand whether the reason is a primary user activity or an increase noise power level.
- *Feature detection:* This method can be used when certain features of the primary user transmission such as carrier frequency and cyclic prefixes are known [17]. Feature detection method takes advantage of the cyclo-stationary features of the PU signal. Unlike noise, the PU signal has spectrum correlation due to its inherent cyclo-stationarity. By making use of this correlation, the PU signal inside the noise can be detected. Thus, feature detection method is very robust against variations of noise. However, this additional capability comes with the cost of increased complexity, which typical CRSN nodes may not be able to provide. Hence, feature detection is more suitable to special CRSN cases where

the network includes nodes with greater computational power.

- *Interference temperature:* The sensing method introduced by the FCC is the interference temperature measurement method [18]. An interference temperature level above the noise floor is determined. CRSN nodes calculate how much interference they would cause at the primary user receiver. Then, they adjust their power such that their interference plus the noise floor is not greater than the interference temperature level. This method requires CRSN nodes to know the locations of the primary users for precise interference measurement. Furthermore, it may be too computationally intense for a low-end sensor node.

Following these main approaches above as outlined in Table 2.2, there is a substantial amount of work in literature on spectrum sensing methods for cognitive radio. Clearly, most of these methods are not suitable for CRSN as they are designed without considering the unique challenges posed by the resource constraints of sensor nodes as follows:

- *Hardware limitations* - It is not feasible to equip CRSN nodes with highly capable processors and A/D units. Thus, complex detection algorithms cannot be used. Spectrum sensing must be performed with limited node hardware.
- *Minimum sensing duration* - Keeping the transceiver on even just for spectrum listening causes excessive power consumption. While sensing accuracy increases with duration, spectrum sensing must be achieved in short sensing duration.
- *Reliable sensing* - Secondary users can operate on licensed bands, unless they do not interfere with primary users. For avoiding interference on primary user, spectrum sensing must be reliable.

The first two of these challenges are unique to CRSN. The last one is a concern for cognitive radio networks too; however, due to limitations of the cognitive radio sensor

node, techniques developed for cognitive radio networks cannot be directly applied to CRSN. Therefore, additional research must be conducted on spectrum sensing for CRSN along the following open research issues:

- *Hybrid sensing techniques:* A possible way to obtain spectrum information with minimum sensing duration and low computational complexity is to use hybrid sensing techniques, which is a balanced combination of the sensing approaches above. For example, energy detection may be used on a broader band to have an idea about which portions of the spectrum may be available. Based on this information, more accurate sensing methods can be performed over selected potential channels. Therefore, hybrid sensing techniques addressing the trade off between sensing accuracy and complexity must be investigated.
- *Cooperative sensing:* When nodes rely only on their own spectrum sensing results, they may not be able to detect the primary user due to shadowing. Spectrum sensing duty may be distributed among the nodes to increase sensing accuracy [16]. Achieving sensing in a distributed manner is called *cooperative sensing* [19, 12]. While cooperative sensing yields better sensing results, it also imposes additional complexity and communication overhead. New cooperative sensing method, requiring minimum amount of extra packet transmission and having minimum impact on the sleep cycles of the node, is an open research issue.
- *Sensing based on collaborative PU statistics:* If it is possible to obtain channel usage statistics of the primary users, it may be possible to develop more efficient sensing methods. Even if PU statistics are not available, nodes may collectively obtain these statistics by continuously sharing their distributed spectrum sensing results. Intelligent and collaborative methods, which estimate and then make use of primary user channel usage statistics, must be studied.

2.3.2 Spectrum Decision

CRSN nodes must analyze the sensing data and make a decision about channel and the transmission parameters, e.g., transmission power and modulation. Spectrum decision methods proposed for cognitive radio networks consider power consumption as a secondary issue and the amount of extra control packets to transmit is almost never taken into account. Furthermore, nodes in a cognitive radio network have more memory and computational power. More complicated schemes for coordination of spectrum decision, which incur higher communication overhead, may be used in cognitive radio networks. However, these solutions are not feasible for CRSN due to additional challenges posed by the ad hoc multi-hop nature as well as the inherent constraints of sensor nodes.

First, in any given locality, it has been shown that the spectrum sensing results will be similar [12]. Thus, most of the time, spectrum decisions of the nodes, which are close to each other, will be the same. If nodes try to access the channel depending only on their individual spectrum decision results, collision probability increases. Furthermore, since nodes run the same algorithm, when a collision occurs, they all try to switch to another channel, leaving the previous channel empty and colliding again on the new channel. This negates the advantage of multiple channel availability brought by the cognitive radio capability. Therefore, spectrum decision in CRSN must be coordinated to increase overall utilization and maximize power efficiency.

Coordination can be handled by a centralized method. Nodes send their spectrum sensing results to the sink along with their event samples and sink decides on optimal spectrum usage. Based on this decision, corresponding sharing rules are sent to the nodes. Furthermore, centralized methods are also suitable for hierarchical topology given in Section 2.1.2. Centralized methods may yield optimal spectrum utilization since central decision unit has global network information which enables it to perform global optimization methods over the multi-hop paths from the event field to the sink. However, the additional traffic imposed on the nodes may result in excessive power

consumption.

An alternate is to use distributed coordination approaches, where nodes share their spectrum sensing and decision results only with their immediate neighbors or within small clusters. Such distributed methods are more suitable for ad hoc and mobile topologies discussed in Sections 2.1.2 and 2.1.2. Based on shared local spectrum availability information, nodes follow simple rules to decide on spectrum usage on their own. Even though this method yields suboptimal utilization, compared to the centralized approach, it is considerably simpler to implement and incurs less communication and hence power overhead as data is shared among a small number of nodes. In [12], authors propose a distributed spectrum decision scheme based on a clustered architecture and show that the provided suboptimal solution is indeed close to the global optimal solution. This proves that properly designed distributed solutions may also yield performance close to the optimal.

Clearly, there exist many open research issues for the development of new spectrum decision techniques for CRSN as outlined below.

- *Spectrum decision parameters:* Determining which parameters to include in the decision process is essential. Parameters such as signal to noise ratio, path loss and channel capacity of the channel are easier to obtain. On the other hand, parameters such as wireless link errors, link layer delays and holding times of PU may be more challenging to obtain by constrained sensor nodes. Therefore, parameters to use in spectrum decision for CRSN must be explored and new algorithms, which yield optimal spectrum decision based on these parameters as well as application-specific requirements, must be developed.
- *New decision methods handling heterogeneity:* In heterogeneous networks with more than one sensor node type, some of the channel parameters may be more important than others. For example, for a multimedia sensor node which provides streaming video data, channel capacity is more important than path loss. Hence, novel decision schemes which consider heterogeneity in

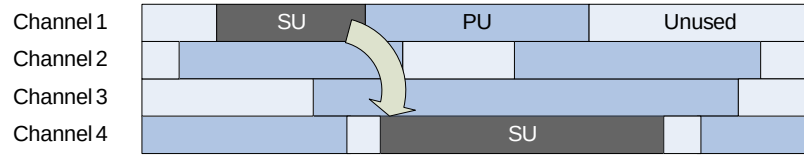


Figure 2.4: Spectrum handoff in CRSN.

energy-efficient manner must be developed.

- *Distribution of control data:* Coordinated spectrum decision schemes also need mechanisms to share essential control data. The method vastly used in conventional multi-channel networks is to use a common control channel. It was shown in [12] that most of the time, finding a channel that is available through the whole network may be impossible for a secondary user. On the other hand, finding such a channel within a given locality has a large probability and small local group based approaches, in which each group has its own local control channel may be more practical. Therefore, energy efficient central and distributed methods of sharing spectrum decision data must be investigated. Furthermore, analysis and comparison of these central and distributed methods must be studied.

2.3.3 Spectrum handoff

When a PU starts using a previously available channel, CRSN nodes must detect primary user activity within a certain time through spectrum sensing methods as discussed in Section 2.3.1. Then, as illustrated in Figure 2.4, they immediately move to another available channel decided by an effective spectrum decision mechanism as explored in Section 2.3.2, even if they have ongoing transmission. Nodes may also want to switch channels if channel conditions get worse, reducing communication performance. This fundamental functionality of cognitive radio is called as *spectrum handoff* [20].

When spectrum handoff is needed, first an alternate channel must be determined. Then, receiver-transmitter handshake must be performed on the new channel. Only then can nodes continue their transmissions. All of these additional operations incur long delays, and hence, buffer overflows which lead to packet losses, degradation in reliability, and ultimately resource waste in CRSN.

Various spectrum handoff methods have been proposed in literature for cognitive radio [21, 22]. There are also studies on the analysis of the effect of spectrum handoff on overall communication [23, 24]. However, none of these works consider the challenges posed by the inherent limitations of CRSN.

In [9], a central spectrum allocation scheme, which tries to minimize spectrum handoff, has been proposed for CRSN. However, this single work clearly comes short in addressing other fundamental issues pertaining to spectrum handoff in CRSN. First, minimizing the effect of spectrum handoff on various communication layers must be analyzed. For example, at the time of spectrum handoff queuing of packets in a memory limited node is an open issue to be researched. At the same time, the development of central and distributed spectrum handoff solutions for CRSN must be investigated. In addition, precautions must be taken to meet QoS requirements over multi-hop paths from the event field to the sink when spectrum handoff occurs. Hence, methods must be developed to move control traffic to another channel in case of primary user arrival to control channel.

2.4 Communication in CRSN

The performance of communication in CRSN is tightly coupled with how effectively dynamic spectrum management issues discussed in Section 2.3 are addressed. There exists a close relation and interaction between the requirements and functionalities of dynamic spectrum management and communication techniques in CRSN as illustrated in Figure 2.5.

In this section, we investigate the specific design considerations of each communication layer, and explore the existing networking solutions of cognitive

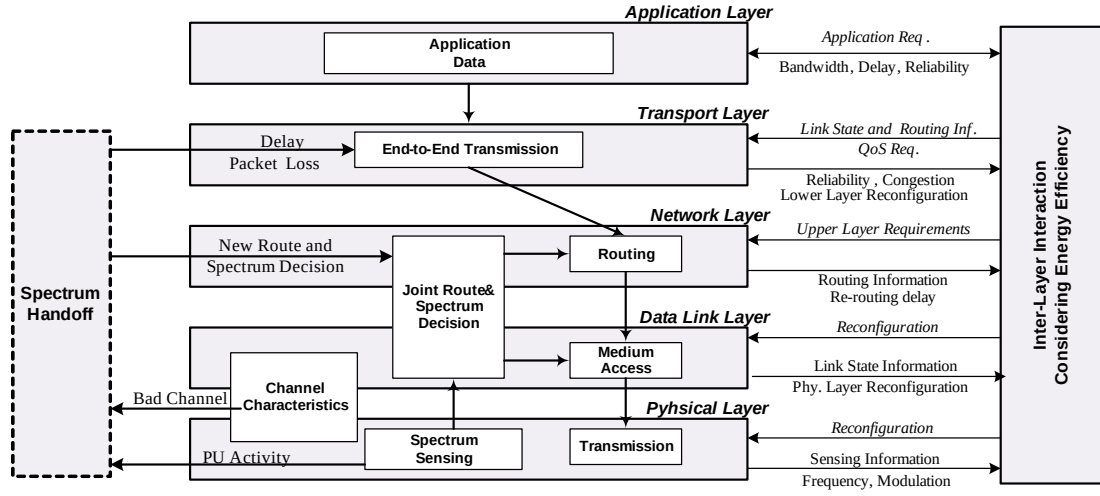


Figure 2.5: Interaction between the communication and dynamic spectrum management functionalities.

radio and wireless sensor networks along with the open research issues for effective communication in CRSN.

2.4.1 Physical Layer

Physical layer regulates interaction between data link layer and physical wireless medium. It is also responsible for spectrum sensing and reconfiguration of the transmission parameters according to spectrum decisions in CRSN.

A CRSN node can reconfigure its operating frequency, modulation, channel coding and output power without hardware replacement. This is the most significant difference between cognitive radio sensor network and wireless sensor network physical layer. Software defined radio (SDR) based RF front-end transmitters and receivers [25] are required for reconfigurability of cognitive radio sensor nodes. However, implementing RF front-end for cognitive radio sensor node is a significant challenge due to low cost and resource-constrained nature of sensor nodes.

On the other hand, limited capabilities of A/D converters used in the nodes and

heavy-weight signal processing algorithms, make spectrum sensing a challenging issue as well. Detecting weak signals, and hence, presence of PU, while there are secondary users, are significant sensing problems in CRSN [26].

Furthermore, unlike in conventional SDR, it is impossible to support different waveforms, since cognitive radio sensor node has limited memory and baseband signal processing capability. Similarly, wide-band spectrum sensing, advanced modulation schemes and cognitive learning capabilities cannot be fully realized in a CRSN node due to its limited computational power.

Clearly, the realization of CRSN depends on the development of effective, energy-efficient, and yet practical cognitive radio for sensor nodes. However, there exist many fundamental open research issues on the physical layer design for CRSN as outlined below:

- Software defined radio-based transceivers providing energy-efficient dynamic spectrum access must be designed for CRSN.
- Low-cost and practical digital signal processing (DSP) hardware and algorithms must be developed for wide-band spectrum sensing and reliable detection of primary user overlapping with CRSN.
- Since fully capable SDR is not feasible for CRSN, multiple waveforms cannot be maintained in hardware. Hence, design of an optimal waveform, which can be adaptively used in multiple channels with different transmission parameters, needs to be studied.
- Adaptive methods, which address the trade-off between transmission power and interference, must be designed to solve the interference problem that may arise in densely deployed CRSN.
- Methods to map application-specific QoS requirements to adaptable transmission parameters of the physical layer must be investigated.

2.4.2 Data Link Layer

Data link layer is responsible for reliable transmission and reception of frames between sensor nodes. In general, efficient medium access control (MAC), and error control and correction are the main functionalities of link layer to achieve its goals. In CRSN, these objectives must be achieved in accord with the principles of dynamic spectrum management and in an energy-efficient manner.

Error Control

The main error control schemes assumed by WSN are forward error correction (FEC), and automatic repeat request (ARQ). Despite the simplicity of ARQ approaches, its retransmission-based mechanism causes extra energy consumption and reduces bandwidth utilization. Therefore, similar to traditional WSN, FEC schemes are promising for resource-constrained cognitive radio sensor nodes.

In FEC approaches, a certain amount of redundancy is included in the packet so that the receiver can recover bit errors. The amount of error that can be corrected depends on the complexity of the error correction algorithm and the amount of redundancy. In addition to reduced channel utilization due to redundancy, CRSN have further challenges for error control because of its multiple frequency access ability. Since each channel may have different conditions, a fixed FEC scheme may not yield optimal results for all. Furthermore, when channel conditions are good, ARQ may yield better performance compared to FEC. Hence, the error correction method should consider this trade-off and may use a combination of both schemes.

Medium Access Control

In general, a MAC protocol aims to provide the sensor nodes with means to access the medium in a fair and efficient manner. This is a challenging objective considering the resource limitations of the nodes, dense network deployment, and application-specific QoS requirements.

In CRSN, according to the specific CRSN topology as explored in Section 2.1,

Table 2.3: Overview of MAC approaches developed for multi-channel ad hoc networks.

MAC approach	Disadvantages in CRSN	Reasons to adopt for CRSN	Open research issues
<i>On-demand negotiation</i> [27]	Contention due to single channel for all negotiations	On-demand reservation is suitable for bursty traffic	Coordination of multiple control channels required for heavy traffic
<i>Home channel</i> [29]	Multiple transceiver requirement	Does not require negotiation for each packet (helps power conservation)	Mechanisms to make this scheme work with single transceiver needed
<i>Time division-based negotiation</i> [28]	Requires network-wide synchronization for negotiation intervals	Simple and very few rules imposed on nodes	Need for network-wide synchronization must be eliminated

sensor nodes may perform handshake to negotiate on the channel before transmitting packets. Both topology forming and channel negotiations require some control packet exchange. Therefore, compared to conventional WSN, MAC layer of a cognitive radio sensor node must handle additional challenges due to the coordination of dynamic spectrum access as outlined below.

- *Silent periods* - CRSN nodes need to perform spectrum sensing in regular intervals. When a node performs sensing on a channel, other nodes must refrain from transmitting on that channel to avoid inaccurate spectrum sensing. Therefore, special control messaging may be employed to inhibit potential transmission of other nodes that are close to the node currently sensing the spectrum. These sensing periods are called *silent periods*. For efficient medium access control and spectrum sensing, these silent periods must be coordinated among neighboring nodes.

- *Broadcasting* - Due to opportunistic medium access in CRSN, broadcasting cannot be done by conventional means. At time of broadcast, neighbors may have their transceivers tuned to various other channels. Hence, acquiring the channel and successful transmission without collision do not necessarily imply the successful reception of the packet by the neighbor nodes. Second, as pointed out earlier, assumption of a common channel globally available throughout the whole network is not practical in cognitive radio networks. Thus, broadcast messages cannot simply be forwarded through the received channel. Clearly, an efficient MAC layer scheduling is imperative so that all nodes can switch to a local broadcast channel in the time of transmission.
- *Distribution of spectrum sensing and decision results* - If cooperative methods for spectrum sensing and decision mentioned in Section 2.3 are to be used to increase sensing accuracy and sharing efficiency, extra control information should be shared among nodes. In such cases, MAC protocol must include mechanisms to distribute sensing results and sharing information with higher priority.

Unfortunately, there exists no complete MAC solution which addresses above requirements for CRSN. The existing MAC solutions for WSN are not designed for dynamic spectrum access, and hence, they simply cannot address above issues. On the other hand, the previous work on ad hoc cognitive radio networks can be broadly divided into three categories based on how they perform channel reservation as outlined in Table 2.3.

In on-demand reservation approach, a channel, i.e., the *control channel*, is used to exchange channel reservation information on demand. Then, nodes switch to the negotiated data channel for transmission [27]. The main problem with this approach is that, it cannot handle cases where large number of nodes attempt to transmit in a short amount of time. Since a single channel is used for channel reservations, it gets congested very quickly. In fact, this is highly likely in CRSN due to its bursty

traffic nature and dense deployment. Furthermore, this approach causes a high end-to-end latency due to contention delay. Since CRSN generally operates in a multi-hop manner, this delay may exceed tolerable delay bound of some applications.

One of the challenges for on-demand approaches is to provide means to move control channels smoothly and in an energy-efficient manner in case of PU arrival. Having multiple control channels can also improve the performance for these cases such that the rest of the control channels can be used until a new vacant band is found for the effected control channel.

The second approach is to use each available channel as the *home channel* of one or several nodes [29]. This approach assumes nodes to have more than one transceiver. One of these transceivers is fixed to its home channel. When a node wants to send data to another node it switches its non-fixed transceiver to the home channel of the destination node and send the data. However, multiple transceiver assumption is not practical for CRSN. The main challenge for this approach would be to realize the core idea of the home channel method without multiple transceiver requirement.

The third approach is based on the use of time division techniques to divide time into frames, in which nodes transmit their data in a round-robin fashion [28]. Channel reservations are made at the beginning of each frame and nodes perform their transmission in their reserved slots. Due to network-wide strict synchronization requirement, this approach cannot be directly employed by a CRSN. Moreover, as the number of nodes increase the reservation time at the beginning of each frame increases, leading to overall performance degradation.

Clearly, none of these existing approaches can be directly employed in CRSN. Hence, the main open research issues for data link layer in CRSN are outlined as follows.

- When a degradation in channel conditions is detected, FEC schemes with more redundancy may be used to decrease the error rate. Therefore, dynamic spectrum FEC schemes with minimum energy consumption must be developed. Furthermore, impact of packet size on the transmission efficiency,

and hence optimal packet size for CRSN must be analyzed under varying channel characteristics.

- Adaptability to the channel conditions enable CRSN to employ novel error prevention schemes. For example, if channel availability permits, transmission bandwidth and constellation size can be changed, keeping the bit rate constant while decreasing error probability. Hence, dynamic spectrum access based novel error control mechanism must be investigated.
- Novel MAC solutions, which can handle the additional challenges above and make full use of the multiple alternative channel availability, must be developed.
- Home channel-based MAC seems to be promising as it requires minimum communication overhead for channel negotiation. However, it is not feasible for CRSN since it requires two transceivers. Methods to adopt home channel idea with a single transceiver in CRSN must be studied.
- Another issue that must be addressed by the link layer is the power saving methods as CRSN nodes have limited power like in WSN [5]. However, due to frequency agility of cognitive radio sensor nodes new challenges arise. One is the coordination of spectrum sensing with sleep/wake up cycles. Another challenge is to provide connectivity to a sensor node after it wakes up. Since there is no fixed channel to transmit, new duty cycle methods jointly considered with neighbor discovery, and spectrum sensing and allocation must be investigated.

2.4.3 Network Layer

CRSN inherits major network layer issues from WSN such as ad hoc and multi-hop networking, the need for energy-efficient data-centric routing, attribute-based addressing, and location-awareness.

Existing ad hoc cognitive radio routing schemes [38], [33], [20] aim to provide joint spectrum and routing decisions, however, do not consider the inherent resource

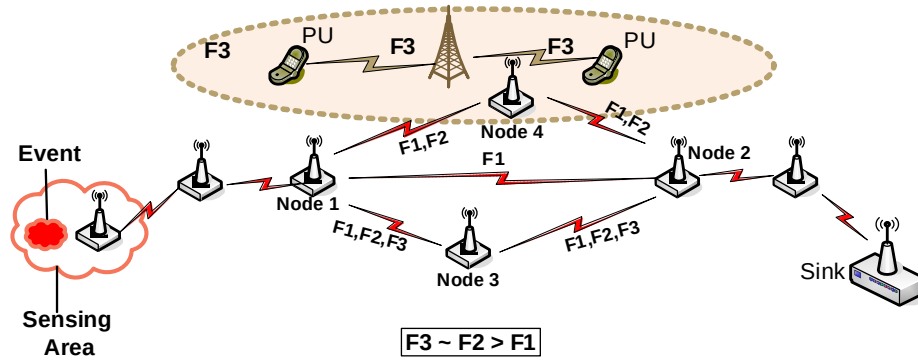


Figure 2.6: Effect of spectrum availability on potential routing paths.

constraints of CRSN. At the same time, routing schemes developed for WSN mainly aim to minimize energy consumption [32] and do not handle dynamic spectrum access.

In fact, there are various energy efficient routing algorithms proposed for WSN with fixed allocation scheme [32]. However, predetermined routing is not suitable for dynamic topology caused by opportunistic channel access. Hence, on-demand routing is advised for cognitive radio networks [33]. Despite the communication overhead and increased contention, dynamic spectrum-aware on-demand routing can be investigated for CRSN.

CRSN are also energy-constrained, hence, hop count is an important metric to be minimized in routing process. However, spectrum mobility introduces additional challenges. Hop-based channel characteristics like channel access delay, interference, operating frequency, and bandwidth are new metrics. Therefore, new route determination algorithms, which consider both opportunistic spectrum access and sensor networks metrics, are required. In addition, number of channel switches along a path between source to sink affects route decision since switching from one channel to another does not have zero delay. Hence, routing algorithms should select minimum channel switching paths [20].

On the other hand, spectrum decision can change neighboring status of CRSN node as path loss changes with operating frequency [30]. Therefore, spectrum decision and assignment is directly related to route determination. In [31], it is shown that

joint route and spectrum selection outperforms discrete route and spectrum selection in cognitive radio networks. In Figure 2.6 this situation is depicted, where primary and secondary users are in the sensing area. Here, 3 frequencies, i.e., F_1 , F_2 , F_3 , with different transmission ranges, R_1 , R_2 , and R_3 , such that $R_1 > R_2, R_3$, are available. F_3 is used by primary users. Hence, if node 1 selects F_1 for transmission, it connects to node 2 directly, or over nodes 3 and 4. However, if it selects F_2 , it can only connect to node 2 over nodes 3 or 4. If it selects F_3 , it connects to node 2 over node 3 as path over node 4 cannot be used due to PU activity. Therefore, unlike traditional WSN, frequency selection is directly related and must be jointly considered with route determination in CRSN.

In addition, spectrum handoff introduces re-routing challenges in CRSN. Due to spectrum handoff, routes may be obsolete during new spectrum sensing and assignment phases. After spectrum assignment, variation in channel characteristics mandates for re-calculation of routes according to the metrics in use. Unlike cognitive radio network, re-routing algorithms should also be highly energy-efficient in CRSN. For example, flooding over control channel during the spectrum handoff, or pre-determined route establishment with pre-spectrum handoff signaling may be incorporated into new network layer solutions for CRSN.

Furthermore, as discussed in Section 2.4.2, the absence of a global common channel makes neighbor discovery and messaging for route establishment quite challenging for CRSN. Therefore, heavy-weight and high maintenance routing algorithms may not be practical for CRSN.

Clearly, there is a need for extensive research for the development of effective network layer solutions addressing the challenges above for CRSN along the open issues outlined below.

- New energy-efficient cognitive radio multi-hop routing protocols as in Figure 2.5, which consider the requirements and challenges of both dynamic spectrum access and sensor networks such as spectrum mobility, resource constraints, dense deployment, must be developed.

- Unlike conventional WSN, on-demand routing may be employed in CRSN. Hence, energy-efficient on-demand multi-hop cognitive radio sensor network routing protocols must be investigated.
- Analytical framework for routing optimization in terms of efficiency and complexity in conjunction with opportunistic spectrum access must be studied, which would lead to optimal networking solutions for CRSN.
- Adaptive and priority-based routing schemes, which also consider application-specific QoS requirements for varying channel conditions, need to be designed for real-time multimedia surveillance CRSN.

2.4.4 Transport Layer

In sensor networks, transport layer is mainly responsible for end-to-end reliable delivery of event readings and congestion control to preserve scarce network resources while considering application-based QoS requirements. With the detection of an event, sensor nodes inject high and bursty traffic into the network. To achieve successful detection and tracking of an event signal, sufficient number of event readings must be reliably delivered to the sink. At the same time, if the capacity of multi-hop network is exceeded, this would lead to congestion which wastes power and communication resources in sensor networks.

Clearly, there is a delicate balance between reliability and energy-efficiency, which has been the main focus of transport layer solutions proposed for sensor networks thus far [34]. While the same balance is also inherited by CRSN, dynamic spectrum management brings additional factors affecting this trade-off as outlined below.

- There is no fixed frequency set over the path from the sensing node to the sink in CRSN, which may significantly vary the channel characteristics, e.g., link delay, channel bit error rate, capacity, over each hop.

- At the time of the spectrum handoff, performance degradation may occur due to extra delays, buffer overflows and packet losses. Furthermore, spectrum mobility during active communication or along the path may incur large variances and inaccuracy in end-to-end delay and packet loss measurements.
- CRSN nodes must sense spectrum periodically to control PU activity. Since, nodes in the spectrum sensing phase cannot transmit and receive; extra sensing delay and buffer overflows may trigger additional packet losses.

Furthermore, some applications such as target tracking and surveillance may also impose additional real-time delay bounds on the reliable communication requirements. Above challenges posed by opportunistic spectrum access render this objective extremely challenging. In addition to the event-to-sink forward path, effective transport layer solutions are also required for reliable delivery of packets in the reverse path, i.e., from the sink to the sensors, in CRSN. Delivery of queries, commands, and code updates may impose even tighter reliability requirements, which are difficult to handle with conventional fixed solutions due to large variations of channel characteristics over the entire CRSN.

Although there exist several transport layer solutions for WSN [35], [36], [37], which address reliable delivery with minimum energy consumption and congestion avoidance, none of them considers dynamic spectrum access. At the same time, there exists no transport layer solution for ad hoc cognitive radio networks either. Hence, all of the challenges elaborated above, which are inherited from WSN and amplified by cognitive radio, must be addressed through the design of novel dynamic spectrum-aware CRSN transport protocols. To this end, the open research issues for transport layer in CRSN can be outlined as follows.

- New reliability definitions, objectives, and metrics must be studied in order to incorporate the fundamental variables of dynamic spectrum access.
- Adaptive, energy-efficient spectrum-aware transport protocols, which can

effectively handle opportunistic spectrum usage challenges, must be developed for both event-to-sink and sink-to-sensor communication in CRSN.

- Analytical modeling of communication capacity, reliability, congestion, and energy consumption should be studied for CRSN. Furthermore, queuing and network information theoretical analysis of reliable communication must be explored for CRSN.
- Cross-layer interactions with spectrum management and congestion control mechanisms must be investigated to address large variations in channel characteristics over multi-hop paths.
- Adaptive real-time transport solutions must be developed to address real-time reliability requirements and application-specific QoS needs under varying spectrum characteristics.
- New mechanisms to exploit the multiple channel availability towards reliable energy-efficient communication in CRSN must be developed.

2.4.5 Application Layer

Application layer algorithms in sensor networks mainly deal with the generation of information and extracting the features of event signal being monitored to be communicated to the sink. Other services provided by the application layer include methods to query sensors, interest and data dissemination, data aggregation and fusion [5].

Clearly, each of these services must utilize the capabilities of cognitive radio sensor network while conforming to its limitations. Therefore, existing application layer protocols must be revisited with these capabilities and limitations in mind. For example, in a CRSN, solutions regulating queries must consider broadcast limitations of CRSN due to unavailability of a global common channel as discussed in Section 2.3.

As stated in Section 2.2, CRSN has a wide range of application areas. However, there is no application-layer protocol developed specifically for CRSN. One of the potential areas that needs an application layer protocol is overlay, multi-class heterogeneous sensor networks described in Section 2.2.3. In such applications, multiple kinds of sensor nodes coexist over the sensor field, each collecting data with different communication requirements. An application layer protocol that analyzes and organizes user queries in a heterogeneous network for efficient transmission is needed. Similarly, for multimedia sensor applications an open research issue is adaptive coding schemes which can employ various coding methods depending on the channel conditions and handoff rate.

On the other hand, there is a significant amount of research in the literature on data aggregation and fusion techniques for WSN [39, 40, 41, 42, 43]. Data aggregation and fusion techniques are employed to increase estimation performance at the cost of communication and computational complexity. The justification in terms of energy consumption is that computation at a node consumes almost always less energy than communication [44]. Since data aggregation and fusion reduce the number of transmissions or the transmitted packet length, these techniques help improve energy efficiency and network utilization.

However, in CRSN, transceivers of the nodes may be tuned to different channels, thus, a node cannot hear all transmitted data around it. This makes data aggregation and fusion a challenging task. New aggregation and fusion techniques which address CRSN limitations and take advantage of its additional capabilities must be investigated. Cooperative schemes, which let the node with aggregated data to use the best available channel, are example of such mechanisms taking advantage of CRSN capabilities.

Another open research issue is developing schemes to perform sampling of the event signal and to gather sensing data based on spectrum availability. If sensing results are sent to the sink periodically, mechanisms to schedule sampling and sensing based on spectrum availability must be investigated. If sensing data is sent based

on queries from the sink, new query methods which take spectrum availability into account must be developed.

For task-based applications and distributed data processing applications, work load on nodes can be distributed based on channel conditions of the nodes. The nodes with better channel availability can send and receive more data in a more reliable manner. Thus, these nodes can be assigned more tasks. In addition priorities may be assigned to the nodes based on their tasks and spectrum availability to achieve fairness enabling nodes with less channel availability to access better channels.

Chapter 3

COOPERATIVE COARSE SPECTRUM SENSING FOR COGNITIVE RADIO SENSOR NETWORK

In the recent years, demand for applications that use wireless communication increased exponentially. Most of the wireless traffic is generated by individuals, resulting in a highly dynamic spectrum activity that changes significantly in space and time. This trend also reflects on the ISM bands where WSNs generally operate. Since ISM bands are license-free, operating WSNs in these bands go in line with their low cost requirement. However, with the substantial increase of the interference from the surroundings, efficient utilization of conventional WSNs becomes harder every day. CRSN has been proposed as a promising solution to mitigate interference and increase spectrum utilization. In this chapter, we propose a coarse spectrum sensing method for CRSN.

3.1 Two-Stage Sensing and Previous Work on Coarse Spectrum Sensing

CRSN paradigm introduces the OSA capability to the WSNs. However, OSA comes with the added burden of spectrum sensing. In the early years of WSN development, adding spectrum sensing duty to the significantly resource constrained nodes would not make sense. Nevertheless, wireless sensor nodes have gone through considerable improvements over the years. Their memory sizes increased from a few kilobytes to tens of megabytes, their processing capabilities increased from 8-bit processors operating in the lower MHz range to 32-bit processors with dynamic clocks that can speed up to hundreds of MHZ and their power consumption is reduced through new power saving schemes [45].

Viability of CRSN has been investigated by various researchers [1, 46, 47]. A

common viewpoint was that in the near future, WSNs may need cognitive radio capabilities. As a result, recently there has been an increase in research related to CRSN [48, 49].

The most significant issue to address for the realization of CRSN is developing energy efficient spectrum sensing techniques. There is a large volume of research in the literature about spectrum sensing. However, research related to spectrum sensing for CRSN is limited. In [50], a medium access scheme that includes spectrum sensing is proposed. However, it does not utilize multiple channels. If the channel is sensed busy, sensors wait for the next opportunity. Furthermore, the sensing scheme is simplistic and assumes high signal to noise ratio (SNR) values. In [51], a spectrum sensing scheme which aims to minimize energy consumption due to spectrum sensing is proposed. However, the proposed scheme is not practical since it requires the nodes to solve complex optimization problems to obtain the optimal threshold values for sensing. In [3] we proposed a narrow band fine sensing scheme, CSS, specifically designed for the CRSN. The idea was to use correlation of environmental readings of the sensors to help with decisions related to cooperative spectrum sensing. Specifically, we developed a censoring scheme that only admits nodes with low correlation in order to reduce redundancy in cooperative sensing.

An important problem in spectrum sensing is to determine the most promising channels to perform spectrum sensing on. Most of the existing solutions do not address this question. Instead they assume that the most promising channels are known or predetermined, and focus on details about the specific detection scheme. However, PU activity patterns have a significant impact on spectrum sensing [52], [53], since nodes have to perform spectrum sensing over and over in different channels until an available channel is found. In case of ordinary CRN, nodes can afford to perform sensing consecutively until a vacant channel is found. On the other hand, since CRSN nodes are energy constrained devices, it is imperative that they keep sensing time to a minimum. Therefore, a mechanism to estimate the channels that are less likely to be occupied by the PU must be devised.

To this end, two-stage sensing methods have been proposed by various researchers. The first stage consists of a coarse sensing that is fast, but may not be very accurate. It is used to find the channels that are more likely to be available. Since coarse sensing is not accurate, a more accurate fine sensing scheme is used in the second stage for the final decision. The alternative is to keep using fine sensing on different channels, until an available channel is found. Since fine sensing requires more sensing time, and thus, more energy, the two-stage approach is generally more energy efficient.

The general approach in the literature on two-stage sensing is to use energy detection as the coarse sensing method [54, 55, 56]. There are other approaches, but they are either specific to a single PU network type, such as LTE [57], or make some unrealistic assumptions, such as predictable PU arrival process [58]. To the best of authors' knowledge, there is no coarse spectrum sensing scheme developed specifically for CRSN in the literature.

In this chapter, we introduce a novel coarse sensing scheme, CC4C. In the following section we give the details on CC4C operation. In Section 3.3, we lay out the details of our performance evaluation and simulation results.

3.2 Coarse Sensing Based on Sequential Detection

3.2.1 Motivation for Coarse Sensing

The cost of sensing increases as the probability of having PU on a channel increases. Assume that probability of a channel being available any given time is p . Let E_s denote the energy spent during sensing one channel. Then, the probability of finding a vacant band at the i^{th} sensing is $(1 - p)^{(i-1)} p$. Since a total of i bands are sensed, the total energy consumed is $i \cdot E_s$, thus, the expected energy consumption for sensing E_t^s can be written as $E_t^s = E_s \sum_{i=1}^{\infty} (1 - p)^{(i-1)} p i$. The sum is the expected value of geometric distribution, thus, $E_t^s = E_s / p$.

Therefore, the expected energy consumption for sensing is inversely proportional to the probability of having an available channel. This suggests that blindly picking channels to sense may have prohibitive energy costs, especially, in crowded spectrum

cases. One more issue of spectrum sensing is that CR nodes do not have any means of determining whether the detected signal is actually PU signal or not. Therefore, for example, even if the signal actually belongs to another CRN, it will be taken as PU activity. Considering this, and the expected increase in opportunistic access to spectrum in the future, it is reasonable to assume that spectrum will generally be crowded to a certain extent. Thus, CR nodes need a means to determine which channels are more likely to be available. To this end, we propose a simple coarse sensing technique, which yields approximate results for PU occupancy of the spectrum. Based on the results of this coarse sensing, nodes pick the channels which are more likely to be available and perform fine sensing on these channels.

For such a coarse sensing scheme to be viable, it should be simple, fast and energy efficient. Otherwise, just repetitive fine sensing would be more preferable. Our scheme is based on sequential probability ratio test (SPRT). It was shown in [59] that, for given false alarm (P_F) and miss probabilities (P_M), SPRT is the detector with the smallest average sample size. Thus, sequential sensing is very suitable for the purpose of a quick sensing.

3.2.2 Motivation for Sequential Detection

The core idea of our SPRT-based coarse spectrum sensing scheme is that, in SPRT, the average number of samples required to detect a PU depends on the SNR. As the SNR increases, detection of the PU can be made with smaller number of samples. So, if we were to perform detection on a group of contiguous channels instead of just one channel, as the total number of active PUs in those channels increase, the overall PU signal power increases. This means SNR increases with the number of active PUs.

Now consider a case where each node performs this coarse wideband sequential sensing in different groups of channels. Clearly, on average, the node which makes a decision with the smaller number of samples has the most crowded channel group, since on average SNR experienced by this node will be greater than the others. This is the main idea behind our coarse sensing scheme. In the following, we present the

theoretical details.

3.2.3 Theoretical Background

An SPRT has two threshold values, A and B. First, the ratio of conditional probabilities of the received samples, y , is formed as $\lambda = p(y|H_1)/p(y|H_0)$. A new sample, y_k , is taken as long as λ is between the lower (A) and upper (B) threshold values. If the ratio falls below A, H_0 is decided. If it exceeds B, H_1 is decided. An alternative is to take $\eta = \ln\left(\frac{p(y|H_1)}{p(y|H_0)}\right)$, then the lower and upper limits will be $a = \ln(A)$ and $b = \ln(B)$.

We first consider the following scenario. The received signal under the two hypotheses are,

$$\begin{aligned} H_0 : y(t) &= n(t) \\ H_1 : y(t) &= s(t) + n(t) \end{aligned} \tag{3.1}$$

where $n(t)$ is zero mean, additive white Gaussian noise with variance σ_n^2 . $s(t)$ is the combination of all PU signals residing on the entire wide band that we are attempting to sense. We do not assume a specific PU signal type, since the sensing scheme has to meet the detection criteria regardless of the PU signal specifics. Therefore, we analyze a general case where all PU signals are assumed to be Gaussian random process with zero mean and variance σ_s^2 . In practical cases, most of the digital modulation types have zero mean with a certain signal power as variance. Thus, our assumption is meaningful. Similar assumptions are made on various previous work in the literature (e.g., [67])

The first step in forming a SPRT is to calculate the thresholds for the desired $P_F = \alpha$

and $P_M = \beta$ values [61], $A \approx \frac{\beta}{(1-\alpha)}$ and $B \approx \frac{(1-\beta)}{\alpha}$.

One property of sequential tests is that the performance criteria, i.e., P_F and P_M requirements, can always be met if sufficient amount of samples are taken. However, the actual amount of samples needed to meet the criteria in any given time depends on the instantaneous SNR of the signal since, P_M at a given time instant depends on

instantaneous SNR. The expected number of samples to make a decision, also called expected run length (ERL), under H_0 and H_1 for a given $P_F = \alpha$ and $P_M = \beta$ are given as [61],

$$E\{N|H_0\} \approx \frac{1}{\sigma_0^2} \left[(1 - \alpha) \left(\ln \frac{\beta}{1 - \alpha} \right)^2 + \alpha \left(\ln \frac{1 - \beta}{\alpha} \right)^2 \right] \quad (3.2)$$

$$E\{N|H_1\} \approx \frac{1}{\sigma_1^2} \left[\beta \left(\ln \frac{\beta}{1 - \alpha} \right)^2 + (1 - \beta) \left(\ln \frac{1 - \beta}{\alpha} \right)^2 \right] \quad (3.3)$$

where σ_0^2 and σ_1^2 are the variances for a single sample under respective hypotheses. Without loss of generality, we take the first sample, i.e., $\sigma_0^2 = \text{Var}(\eta(y_1)|H_0)$ and $\sigma_1^2 = \text{Var}(\eta(y_1)|H_1)$.

$$\begin{aligned} \sigma_k^2 &= \text{Var}(\eta(y_1)|H_k) = E \left[\left(\ln \left(\frac{p(y_1|H_1)}{p(y_1|H_0)} \right) \right)^2 | H_k \right] \\ &= \ln(\sigma_n^2/\sigma_j^2) \frac{\sigma_j^2 - \sigma_n^2}{2\sigma_j^2\sigma_n^2} \text{Var}(y_1^2|H_k) \end{aligned} \quad (3.4)$$

where $\sigma_j^2 = \sum_{k=1}^j \sigma_{s_k}^2 + \sigma_n^2$, and $\sigma_{s_k}^2$ is the received signal power of PU k and j is the number of active PUs within the group of bands that we perform coarse sensing on. Finally, y_1^2 is chi-square distributed with

$$\text{var}(y_1^2) = 2 \text{var}(y_1|H_k) = \begin{cases} 2\sigma_n^2, & \text{under } H_0 \\ 2\sigma_j^2, & \text{under } H_1 \end{cases} \quad (3.5)$$

As a result, when the number of active PUs in the sensed wide band region is j , ERLs under respective hypotheses are,

$$E\{N|H_0\} \approx \frac{1}{K_0} [(1 - \alpha)a^2 + \alpha b^2] \quad (3.6)$$

$$E\{N|H_1\} \approx \frac{1}{K_1} [\beta_j a^2 + (1 - \beta_j)b^2] \quad (3.7)$$

where $K_0 = \frac{\sigma_j^2 - \sigma_n^2}{\sigma_j^2} \ln(\sigma_n^2/\sigma_j^2)$ and $\frac{\sigma_j^2 - \sigma_n^2}{\sigma_n^2} \ln(\sigma_n^2/\sigma_j^2)$, β_j denotes the P_M value when there are a total of j active PUs on the sensed group of channels, a and b are as defined at the beginning of this section.

Eqn. 3.7 indicates that ERL under H_1 depends on β_j , which depends on the number of active PUs, j . We calculate β_j as follows.

Let Z_0 be the region of samples for which H_0 is decided,

$$Z_0 = \{y \in \mathbb{R}^\infty | \eta_N(y_1, \dots, y_N) \leq a\} = \cup_{n=1}^\infty Z_{0n} \quad (3.8)$$

where N is the number of samples taken to make the decision, η is the log-likelihood ratio test, and

$$Z_{0n} = \{y \in \mathbb{R}^n | N = n \text{ and } \eta_n(y_1, \dots, y_n) \leq a\} \quad (3.9)$$

Therefore, Z_{0n} is the region of samples for which H_0 is decided with n samples, i.e.,

$$\eta_n = \sum_{i=1}^n \left(\ln \frac{p(y|H_1)}{p(y|H_0)} \right) = \ln(\sigma_n/\sigma_j)^n \left(\frac{(\sigma_j^2 - \sigma_n^2)}{2\sigma_j^2\sigma_n^2} (y_1^2 + \dots + y_n^2) \right) \leq a \quad (3.10)$$

Then,

$$Z_{0n} = \left\{ y \in \mathbb{R}^n \mid \sum_{k=1}^n y_k^2 \leq r^2 \right\} \quad (3.11)$$

where

$$r^2 = \frac{2\sigma_j^2\sigma_n^2}{(\sigma_j^2 - \sigma_n^2)} \ln \left(a \left(\frac{\sigma_j}{\sigma_n} \right)^n \right) \quad (3.12)$$

We see that Z_{0n} is the region inside of a hypersphere of n -dimensions. Z_{0n} can also be represented in n -dimensional spherical coordinate system with coordinates

$$r = \sqrt{y_1^2 + y_2^2 + \dots + y_n^2} \quad (3.13)$$

$$\theta_1 = \text{arccot} \left(\frac{y_1}{\sqrt{y_n^2 + y_{n-1}^2 + \dots + y_2^2}} \right) \quad (3.14)$$

...

$$\theta_{n-2} = \text{arccot} \left(\frac{y_{n-2}}{\sqrt{y_n^2 + y_{n-1}^2}} \right) \quad (3.15)$$

$$\phi = 2 \text{arccot} \left(\frac{\sqrt{y_n^2 + y_{n-1}^2} + y_{n-1}}{y_n} \right) \quad (3.16)$$

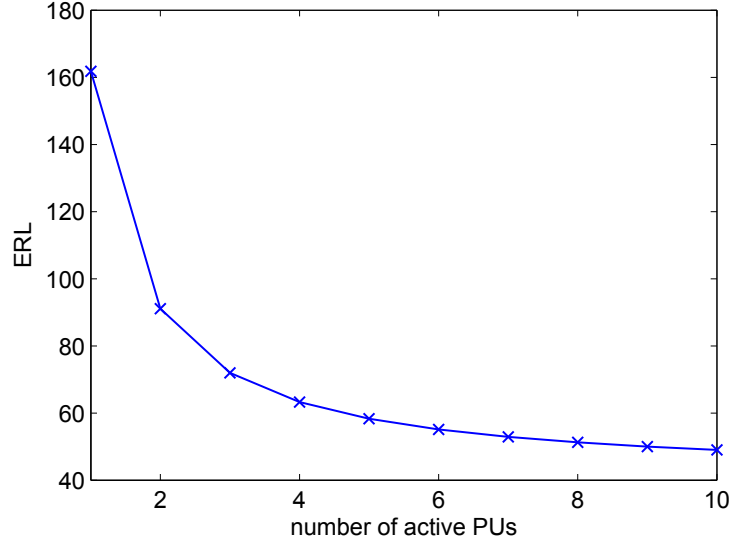


Figure 3.1: Expected run length for various number of active PUs.

Z_{0n} and Z_{0m} are mutually exclusive sets for $n \neq m$, therefore, α and β can be written as

$$\beta = \int_{Z_0} p(\bar{y}|H_1) d\bar{y} \quad (3.17)$$

$$= \sum_{n=1}^{\infty} \int_{Z_{0n}} \prod_{k=1}^n p(y_k|H_1) dy_k \quad (3.18)$$

Similarly,

$$\alpha = \sum_{n=1}^{\infty} \int_{Z_{1n}} \prod_{k=1}^n p(y_k|H_0) dy_k \quad (3.19)$$

where Z_1 and Z_{1n} are defined similar to Z_0 and Z_{0n} , i.e., $Z_1 = \{y \in \mathbb{R}^\infty | \lambda_N \geq B\} = \cup_{n=1}^{\infty} Z_{1n}$ and $Z_{1n} = \{y \in \mathbb{R}^n | N = n \text{ and } \lambda_n \geq B\}$

Probability of miss detection when there are j active PUs β_j can be written as

$$\beta_j = \sum_{n=1}^{\infty} \int_{Z_{0n}} (2\pi\sigma_j^2)^{-n/2} \exp\left(-\frac{1}{2\sigma_j^2} \sum_{k=1}^n y_k^2\right) dV_n \quad (3.20)$$

where $dV_n = dy_1 dy_2 \cdots dy_n$ is the differential volume element. In spherical coordinates

dV_n can be written as

$$dV_n = r^{n-1} \prod_{m=1}^{n-2} (\sin \theta_m)^m d\theta_m d\phi dr$$

As established in (3.11), the integral limits constitute the volume of a hypersphere, therefore, the integral in (3.20) can be written as

$$\begin{aligned} I(n) &= \int_0^R \int_0^{2\pi} \int_0^\pi \cdots \int_0^\pi \\ &\quad (2\pi\sigma_j^2)^{-n/2} \exp\left(-\frac{1}{2\sigma_j^2}r^2\right) r^{n-1} \prod_{m=1}^{n-2} (\sin \theta_m)^m d\theta_m d\phi dr \\ &= (2\pi\sigma_j^2)^{-n/2} \int_0^R \exp\left(-\frac{1}{2\sigma_j^2}r^2\right) r^{n-1} dr \frac{2\pi^{n/2}}{\Gamma(n/2)} \end{aligned} \quad (3.21)$$

$\Gamma(\cdot)$ is the gamma function given as $\Gamma(x) = \int_0^\infty t^{x-1} e^{-t} dt$. Evaluating the final integral, we have,

$$I(n) = 1 - \frac{\Gamma\left(\frac{n}{2}, \frac{r^2}{2\sigma_j^2}\right)}{\Gamma\left(\frac{n}{2}\right)} \quad (3.22)$$

where $\Gamma(a, x) = \int_x^\infty t^{a-1} e^{-t} dt$ is the upper incomplete gamma function. Thus,

$$\beta_j = \sum_{n=1}^{\infty} I(n) = \sum_{n=1}^{\infty} 1 - \frac{\Gamma\left(\frac{n}{2}, \frac{r^2}{2\sigma_j^2}\right)}{\Gamma\left(\frac{n}{2}\right)} \quad (3.23)$$

By placing β_j in Eqn 3.7 we can obtain the ERL for j active PUs. The relation between expected run length and the number of active PUs is shown in Figure 3.1, for $P_F = 0.01, P_M = 0.01, \sigma_n = 1$ and $\sigma_s = 1$, i.e., normalized noise power and an SNR of 0 dB. As clearly seen here, the number of samples taken before the decision is made, gives us an approximate idea about how many of the channels within the sensed wideband are occupied.

3.2.4 The Near-PU Problem

CC4C has one weak point. Since it depends on overall SNR to be an indication of the number of active PUs, if one of the PUs is too close to the secondary network, CC4C may yield undesired results. For example, if a PU in one group of channels has twice

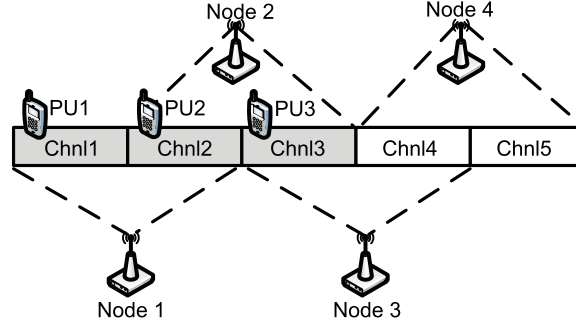


Figure 3.2: A sample scenario depicting overlapped sensing idea to overcome near-PU problem.

the received power of another PU in another group of channels, when only these two are active in their respective channel groups, on average CC4C concludes that the group with the higher PU power has twice the number of PUs in that group., where, in fact there is only one PU active in each group.

One way to overcome this problem is to use averaging methods. We propose two averaging method. One is to pick two nodes that are furthest away from each other to perform CC4C on the same channel group, then take the average of ERLs reported by them. With nodes chosen this way, a PU that is close to one will be further away from the other, and averaging results of such two nodes will *smooth* the effect of near PU problem.

Another averaging method is to use the previous method along with choosing channel groups in an overlapping manner. The idea is illustrated in a simplistic case in Figure 3.2. There are a total of five channels in the entire spectrum. Four nodes perform CC4C coarse sensing, each covering two channels, with one channel overlapping. The ERL at each channel is determined by averaging the ERLs of nodes that performed coarse sensing for that channel. For the presented example case, if PU2 presents the near PU problem for node 2, node 1 will smooth that effect, since it is further from the PU and ERL of channel 2 is determined by averaging.

The remaining problem is how to determine the nodes that are furthest away from

each other. A good approximation of this would be to use correlations of spectrum sensing samples of the nodes. Since the probability of having more shadowing objects between two nodes increases as the distance increases, correlations of spectrum sensing samples for the furthest away node pairs is more likely to be closer to zero. However, exchanging thousands of samples with multiple nodes every time spectrum sensing is performed to calculate this correlation is not realistic. The data is huge, the number of transmissions is n^2 , if number of total nodes is $n + 1$, moreover, available channel(s) to transmit this information is not yet known since spectrum sensing is yet to be performed. However, in a CRSN we can instead use the idea that we proposed in [3]. It is to use correlations of environmental sensing data instead of sharing spectrum sensing data. Sensors' environmental reading are already regularly sent to the sink node as the normal operation of the CRSN. All of the neighbors overhear it these reports. Therefore, in a CRSN, nodes can continuously keep track of their correlation with their neighbors, which can be used as an estimate to determine the nodes that are far away from each other. This is what makes CC4C a very suitable coarse sensing scheme for CRSN.

3.3 CC4C Performance Evaluation

In this section, we present our result on the performance of CC4C with comparison to the energy sensing (ES) based coarse sensing schemes. We do not include schemes that are specific to a certain PU type since those schemes would have the additional information and be specifically tailored to that PU, the comparison would not be fair. In the simulations we use a two-stage sensing for both cases. For coarse sensing, we determined the threshold (and the number of samples for the ES case) for desired parameters of probability of false alarm, $P_{FA} = 0.1$, and probability of detection, $P_D = 0.9$. The performance of fine sensing is not the focus of this chapter, therefore, the chosen method is not very important as long as same fine sensing method is used in both compared schemes. For both methods, we used energy detection with much tighter desired parameters, i.e. $P_{FA} = 0.01$ and $P_D = 0.99$. We also include the case

where no coarse sensing is performed and available channel is found by repetitive fine sensing in different channels until an available channel is found. We label this case as NoCS in the figures.

For both CC4C and ES cases, if an available channel was not found at the end of the fine sensing stage, we assume that the node which has data to transmit has to wait till the next round of sensing. We assume that one round of sensing is performed at each 1 ms interval (for example, LTE has a scheduling interval of 1ms). We take the delay due to spectrum sensing to be the interval between the beginning of coarse sensing and the time when the node finds a channel to transmit.

We use the parameters given in [62] for energy consumption. Namely, we take consumed energy for spectrum sensing to be $E_s = I_r V t_s$, where $I_r = 19.7mA$ is the receive mode current, $V = 3V$ is the supply voltage and t_s is the total amount of time spent in spectrum sensing including both stages.

We assumed the whole usable band to have 40 channels. CC4C divides the spectrum into equal size chunks and performs coarse sensing on these chunks concurrently. To present a fair delay comparison, we assumed that in the ES case, multiple nodes perform coarse sensing concurrently on different portions of the band with equal size. For both methods we assumed 8 nodes performing coarse sensing concurrently on 5 channels each. In each simulation, we used an interval of 100 spectrum sensing rounds. We ran the simulations 1000 times and present the average of the results of these runs.

In Figure 3.3, we present the delay incurred by the sensing schemes as the spectrum gets more crowded. We see the advantage that two-stage sensing schemes provide clearly. The single stage scheme causes up to 69.7% delay compared to CC4C. CC4C and ES have similar performances under low PU occupancy, but CC4C has lower delay as the occupancy rate increases up to a 20.75% improvement.

In Figure 3.4, delay comparison for increasing SNR values is given. Single stage sensing scheme performs extremely poorly in low SNR regions, so much so that we had to zoom the plot to see the difference between CC4C and ES. However, as the

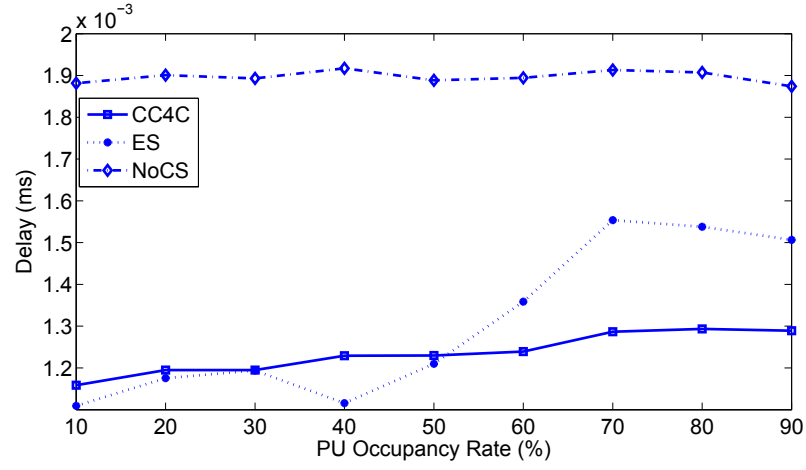


Figure 3.3: Average delay vs PUs occupancy rate

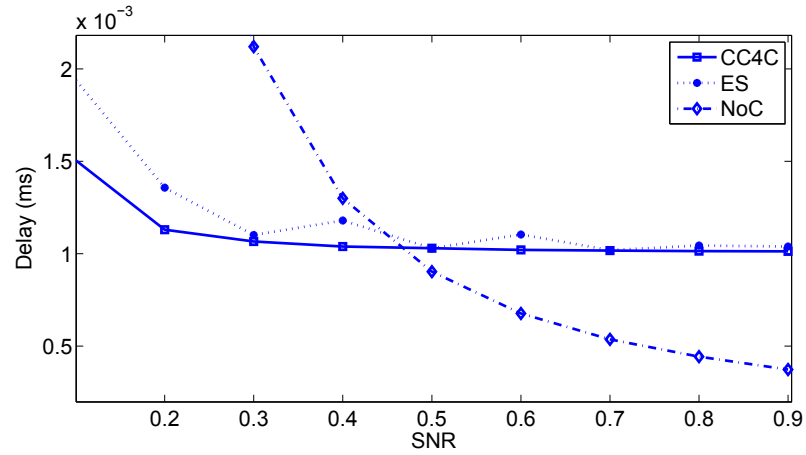


Figure 3.4: Average delay vs SNR

SNR increases, single stage scheme performs better and actually proves to be more advantageous for SNR values greater than 0.5, i.e., -3 dB. This is expected because the number of required samples to meet detection criterion rapidly drops as SNR increases. At about -3 dB, the required number of samples for fine sensing becomes so low that repetitive fine sensing incurs less delay. However, keep in mind that obtaining desired results in high SNR regions is easy. In real life scenarios CRs generally operate in low SNR regions and the real challenge is to meet sensing requirements at SNR values as low as -20dB. In this low SNR region, CC4C causes less delay compared to other

schemes with up to 10.3% less delay compared to ES.

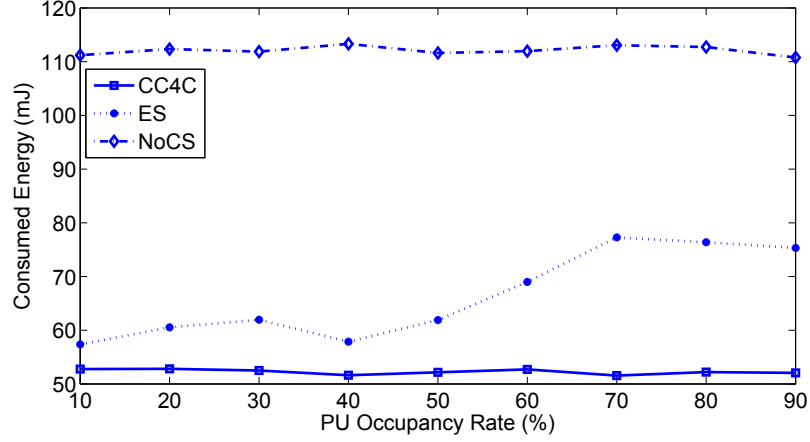


Figure 3.5: Average energy consumption vs PUs occupancy rate

Energy consumption comparison as PU occupancy rate increases is given in Figure 3.5. Here also, there is a large difference between two-stage schemes and the single stage scheme. Single stage scheme consumes 119.4% more energy compared to CC4C. ES also consumes more energy than CC4C, difference up to 49.89% difference between the two schemes.

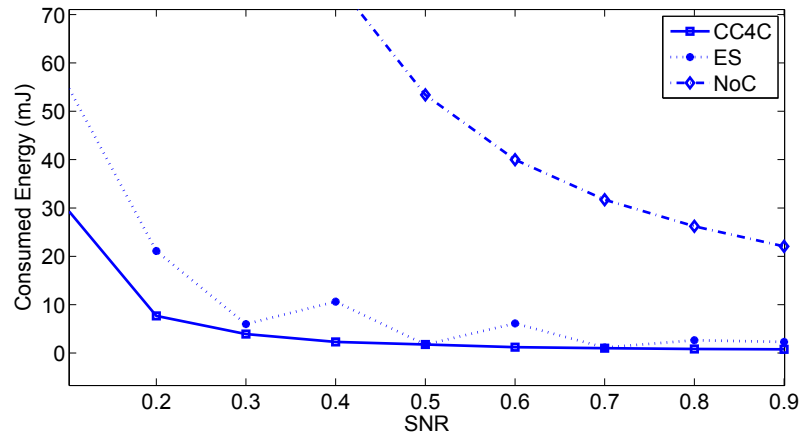


Figure 3.6: Average energy consumption vs SNR

In Figure 3.6, we present energy consumption as the SNR increases. Once again, the single stage scheme performs very poorly in low SNR regions. CC4C performs better than the other schemes, enabling up to 85.95% conservation compared to ES.

Chapter 4

ENERGY-EFFICIENT COOPERATIVE SPECTRUM SENSING FOR COGNITIVE RADIO SENSOR NETWORKS

In this chapter, we present our solution for cooperative fine spectrum sensing. Our solution is tailored to CRSN and makes use of the sensing data of the sensor nodes in determining the nodes that will participate in the cooperative spectrum sensing. To the best of our knowledge, this is the first solution in the literature that proposes the correlation of sensor data to be used in spectrum sensing. We first lay out the state-of-the-art in CRSN spectrum sensing. Then, we detail our proposal.

4.1 Previous Work on Spectrum Sensing in CRSN

There is a large volume of research in the literature about cooperative spectrum sensing. On the other hand, there are only a few solutions specific to CRSN. In [50], authors propose a medium access scheme which includes spectrum sensing. However, the proposed scheme does not utilize multiple channels. If the channel is sensed busy, sensors wait for the next opportunity. Furthermore, the sensing scheme is simplistic and assumes high SNR values. In [51], a spectrum sensing scheme which aims to minimize energy consumption due to spectrum sensing is proposed. However, the proposed scheme is not practical since it requires the nodes to solve complex optimization problems to obtain the optimal threshold values for sensing.

A cooperative sensing for orthogonal frequency-division multiplexing (OFDM) based on energy detection in multiple input multiple output (MIMO) CRSN is proposed in [63]. The solution assumes that PUs use OFDM. Furthermore, it requires multiple antennas on sensor nodes, thus, it is not a realistic solution. Also it requires all nodes to participate in sensing, therefore, it is wasteful of resources.

Another cooperative sensing is proposed in [64]. The solution is based on the spatial spectral estimation. It assumes all SUs use spread spectrum. There is no PU detection. Rather, amount of interference to PUs are controlled. It requires very complex calculations since it is based on direction of arrival estimation. In [49], a distributed wideband sensing scheme for CRSN is presented. Its major problem is that since it is based on compressive sensing, it assumes sparse use of spectrum, which is contrary to the current status of wireless spectrum. Therefore, it performs poorly in crowded bands. Moreover, it requires all nodes to participate.

All of the previously proposed solutions approach CRSN spectrum sensing problem as if it the underlying network was a generic cognitive radio network. None of them make use of the inherent advantages of the sensors. The novelty of our scheme is the idea of exploiting the actual sensing data of the sensors to develop a more efficient spectrum sensing mechanism as follows:

An important consideration for cooperative sensing is which nodes to include in the sensing. It was shown in [66] that, although sensing performance increases with the increasing number of cooperating nodes, this increase has diminishing returns, and the contribution of highly correlated nodes is very limited. However, having every node send its spectrum sensing data to each other node to calculate correlations is clearly a very demanding task in terms of resource consumption. It will also increase the delay caused by spectrum sensing considerably. Instead, we propose that nodes use actual sensing data of their neighbors that they overhear. Here we emphasize the difference between spectrum sensing data and the data of actual sensing performed by the nodes, such as heat, humidity, etc.

There are a number of justifications for using actual sensing data instead of spectrum sensing data. First, the sensor nodes will send their sensing results regardless of spectrum sensing operation. Therefore, it is logical to make use of this information instead of having nodes additionally transmit their spectrum sensing samples. Second, building a moving average of this correlation gives a good idea about the attenuation introduced by the current obstacles between nodes. Thus, it

is viable to use this correlation within the spectrum sensing mechanism to overcome the adverse effects of shadowing. This is the main idea behind our scheme called CSS. Simulation results also support our claim.

4.2 System Model

CSS is based on energy detection, since it is the most suitable detection type for sensor nodes due to its simplicity. We first consider the following scenario. The received signal under the two hypotheses are,

$$\begin{aligned} H_0 : y(t) &= n(t) \\ H_1 : y(t) &= s(t) + n(t) \end{aligned} \tag{4.1}$$

where $y(t)$ is bandlimited to the spectrum channel that is being sensed, $n(t)$ is zero mean, additive white Gaussian noise with variance σ_n^2 , and $s(t)$ is the PU signal. We do not assume a specific PU signal type, since the sensing scheme has to meet the detection criteria regardless of the PU signal specifics. Therefore, we analyze a general case where the PU signal is assumed to be Gaussian random process with zero mean and variance σ_s^2 . In practical cases, most of the digital modulation types have zero mean with a certain signal power as variance. Thus, our assumption is meaningful. Similar assumptions were made in various previous work in the literature (e.g., [67]).

For energy detection, the following statistic is formed using the N observations obtained by each node

$$r_j(r) = \sum_{k=1}^N y_k^2 = \sum_{k=1}^N (y_{k(i)}^2 + y_{k(q)}^2) \tag{4.2}$$

where $y_{k(i)}$ and $y_{k(q)}$ indicate the in-phase and quadrature components of the k^{th} sample of the bandpass signal y_k . $r_j(r)$ is the summation of chi-square distributed random variables for the j^{th} node [68]. Central limit theorem indicates that for large N , $r_j(r)$ approaches a Gaussian distribution.

4.3 Analysis of Correlation Based Node Selection

Detection performance is maximum when observations (i.e. spectrum sensing data) of the nodes are independent. However, independence assumption is not realistic. There is almost always a certain degree of correlation among the nodes. CSS aims to choose nodes with the least correlation to minimize the adverse effects of correlation in sensing. To illustrate the idea, consider the following two cases. In the first case, we have two independent observations. In the second case we consider observations which are correlated with a correlation coefficient of ρ . The general expression for sufficient statistic for two correlated readings can be expressed as

$$l(\vec{r}) = \frac{1}{2}(\vec{r}^T - \vec{m}_0^T)Q_0(\vec{r} - \vec{m}_0) - \frac{1}{2}(\vec{r}^T - \vec{m}_1^T)Q_1(\vec{r} - \vec{m}_1) \quad (4.3)$$

where Q_j indicates the inverse of the covariance matrix $K_j = E[(\vec{r} - \vec{m}_j)(\vec{r}^T - \vec{m}_j^T)]$ under hypothesis j , and $\vec{m}_1$ and $\vec{m}_0$ indicate the mean values under respective hypotheses.

For normalized noise power and assuming noise samples are independent we have,

$$l_{uncor} = \frac{1}{2}(r_1^2 + r_2^2) \frac{\gamma}{1 + \gamma} \quad (4.4)$$

and,

$$l_{cor} = \frac{1}{2}(r_1^2 + r_2^2) \left[1 - \frac{1 + \gamma}{(1 + \gamma)^2 - \rho^2} \right] + r_1 r_2 \left[1 + \frac{\rho}{(1 + \gamma)^2 - \rho^2} \right] \quad (4.5)$$

where, l_{cor} and l_{uncor} are the sufficient statistic for the correlated and two uncorrelated cases, respectively. Here, $\gamma = \sigma_s^2 / \sigma_n^2$ is the SNR and ρ is the correlation coefficient between r_1 and r_2 .

The larger the correlation, the greater the different between two sufficient statistic. Since l_{uncor} represents the ideal case, we want to choose nodes with the least correlation so that the sufficient statistic, l_{cor} , is as close to the ideal as possible.

In our solution we propose the following method to choose the nodes which will take part in cooperative sensing. We define a distortion metric, D , that indicates

the difference in contribution between two uncorrelated nodes and two nodes with correlation ρ . We take D to be the MMSE error between the sufficient statistics of these two cases, i.e.,

$$D = E [(l_{uncor} - l_{cor})^2] \quad (4.6)$$

Placing Eqn. (4.4) and Eqn. (4.5) in Eqn. (4.6), expanding the expectation and making algebraic manipulations, D can be expressed as

$$D = (1 + \gamma)^2 P^2 + \rho^2 (1 + \gamma)^2 Q^2 - 2\rho^2 (1 + \gamma)^4 PQ \quad (4.7)$$

where

$$P = \frac{\gamma}{1 + \gamma} - 1 + \frac{1 + \gamma}{(1 + \gamma)^2 - \rho^2} \quad (4.8)$$

and

$$Q = 1 + \frac{\rho}{(1 + \gamma)^2 - \rho^2} \quad (4.9)$$

It is unrealistic to calculate the correlation coefficient of spectrum sensing data. In a wireless sensor network, sensor nodes overhear their neighbors' reported sensing data all the time. Since this data is readily available, we propose to calculate correlations using these actual sensor data. As justified by the results in Section 4.4 this is a perfectly exploitable aspect of wireless sensor operation, and it is unique to CRSNs.

The distortion, D , for various SNR and correlation values is shown in Figure 4.1(a). We see that in low SNR regions the distortion due to correlation is lower. In addition, more cooperating nodes are needed to obtain the required sensing performance in low SNR regions. Thus, the number of nodes to take part in cooperated sensing can be determined by SNR and correlation parameters as explained below.

Ideally, each node would check to see if it will yield a distortion larger than the required minimum for its instantaneous SNR value, and refrain from participating in sensing if that is the case. This would correspond to any SNR-correlation pair in

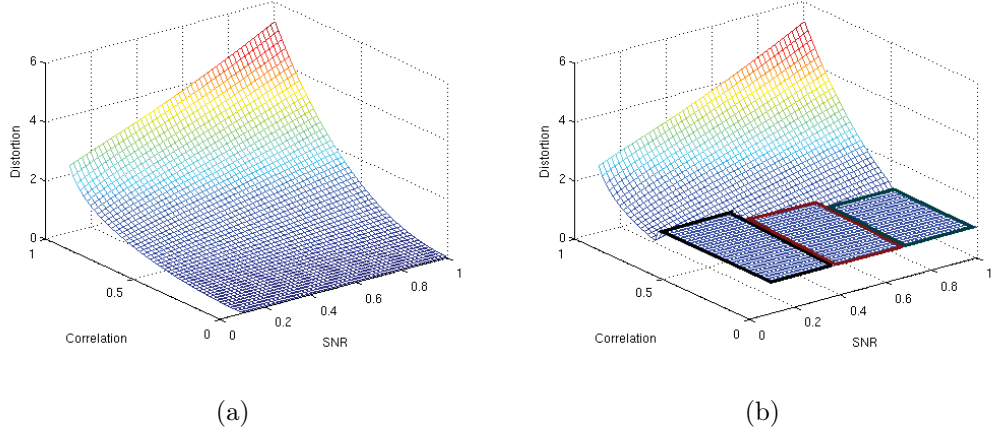


Figure 4.1: Distortion in sufficient statistics and corresponding admittance regions

Figure 4.1(a), for which, the distortion is higher than the required minimum. However, it is not realistic to expect resource constrained nodes to perform the involved calculations each time. Instead, we propose forming predetermined *admittance regions* for which corresponding SNR and correlation ranges are below the distortion threshold. If node SNR and correlation is within these regions they will participate in the cooperative sensing. The idea of admittance regions is illustrated in Figure 4.1(b) with relation to Figure 4.1(a). The flattened three regions are the so called admittance regions for which D is below a certain threshold (1 in this case). Each of these regions can be defined by two snr-correlation pairs, each defining one of the upper corners of the region. These pairs are pre-calculated and hardcoded into the nodes. Each node checks to see if its SNR and correlation values are within one of these regions. If not, it concludes that its distortion value is too high, does not participate in spectrum sensing and goes to sleep. Otherwise, it participates in sensing. This considerably reduces the number of nodes that perform sensing while still meeting the spectrum sensing performance constraints as supported by the simulations given in the next section.

4.4 CSS Performance Evaluation

In order to make an assessment about the proposed scheme, we performed extensive simulations. We ran each simulation 5000 times. Results presented in the figures are the average numbers of these 5000 trials. In each run, a random topology is created. First, a large number of events at random locations are generated. In a real life scenario, sensor nodes gather this data over the time of their normal operation. Then, correlations between nodes for these sensing data are computed. The channel is AWGN with log-normal shadowing. A path loss exponent of 3.7 and a shadowing variance of 3.65 dB is used since these are typical values. Thresholds were calculated for $P_{FA} = 0.1$.

To the best of our knowledge there is no generic (i.e. that works without assumptions about PU signal) and non-complex (e.g requiring multiple antennas, etc.) cooperative spectrum sensing method developed for CRSN to compare CSS with. Therefore, we choose a cooperative scheme that is designed for CR networks [69]. This scheme is chosen because, like CSS, it also employs a kind of censoring strategy to choose nodes. In this scheme, nodes which have sufficient statistic that is close to the threshold value are not included in the sensing, i.e. only nodes that have very high or very low SNR are chosen. The idea is to include nodes that are more “sure” about their decision. Since threshold is calculated assuming a noise floor, this method performs poorly in noise fluctuations. We call this method the SNR-based censoring method. When deciding which nodes to censor, our method also uses the correlation between nodes. Therefore, we expect CSS to yield better performance.

In the simulations, additive white Gaussian noise (AWGN) channel model with log-normal shadowing. A path loss exponent of 3.7 and a shadowing variance of 3.65 dB is used. First simulation is performed to compare the performance of CSS with other methods by means of receiver operating characteristic (i.e. ROC) curves. In the figures, the solid line represents CSS. The dotted line is for the case where all nodes participate in the sensing, the dot-dash line is the sufficient statistic-based censoring method designed for CRNs. The threshold offset values of sufficient statistic based

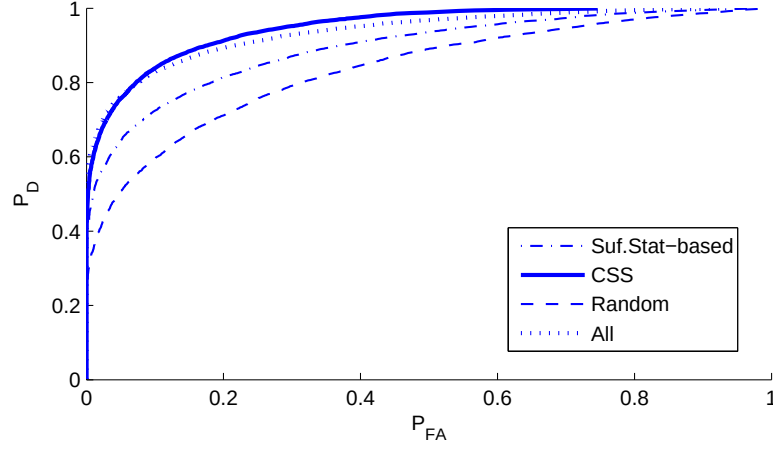


Figure 4.2: Detection and false alarm probabilities for varying threshold values.

method and D value of CSS are chosen such that average number of nodes that participate in the cooperation are equal. For ROC simulations, we also added the case of random node selection. This is represented by the dashed line. Random node selection has the same number of average nodes. This case was included to make comparisons about the effect of intelligent node selection on performance. As seen in Figure 4.2, CSS has the best performance except for a very narrow region where threshold is very high. Here CSS has slightly lower P_D than the case where all nodes are included in sensing.

In the second simulation we compare the energy spent in different sensing cases. Transmission power values of the PUs are 50 mW. Their locations are picked randomly with a mean distance that corresponds to the desired average SNR for each case.

We calculate energy consumption as

$$E_s = n_s t_s I_r V \quad (4.10)$$

and

$$E_t = l_p t_b I_t V \quad (4.11)$$

Here, E_s and E_t are energy spent in sensing and energy spent for transmission of sensing results for one node, respectively. n_s is the number of samples takes for

sensing, t_s is the time it takes to obtain one sample, t_b is byte transmission time, l_p is the packet length in bytes, I_r and I_t are the transmit and receive mode currents, and V is the supply voltage of the sensor nodes. Since the sensing data reported by the nodes is a single measurement (i.e. 1 or 2 bytes), packet size is small. We assume a packet length of 100 bytes including the protocol headers for spectrum sensing result reports. Note that this is not a limit on ordinary communication packets of the sensor network, but rather only an estimate for packets that are used to report sensing results. Furthermore, with regard to comparisons among the sensing methods presented below, the determining factor is the number of packets transmitted in each method, and not so much the size of these packets.

For the rest of the parameters typical values [62] given in Table 4.1 is used .

The results given in Figure 4.3 focus on the low-SNR region where cooperative sensing is used to increase detection performance. CSS provides more than 100 % energy saving compared to the cases where all nodes participate up to about -9.5 dB SNR. It is also considerably more energy efficient than the sufficient statistic-based method, which only makes use of SNR. The performance difference between these two cases clearly demonstrate the importance of using correlation in node selection.

Finally, we investigate the delay incurred by sensing for different sensing methods. Presented delay in Figure 4.4 includes the delay during spectrum sensing as well as

Table 4.1: Values used in the simulations for energy consumption

l_p	100
t_s	$4 \mu s$
t_b	$32 \mu s$
I_r	19.7 mA
I_t	17.4 mA
V	3 V

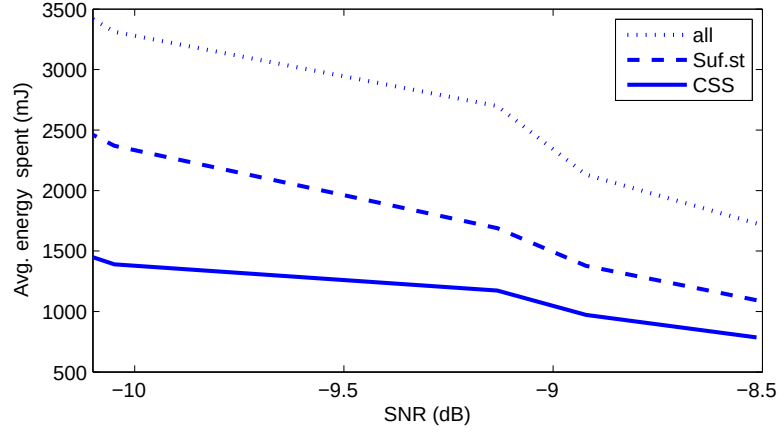


Figure 4.3: Energy spent under various SNR

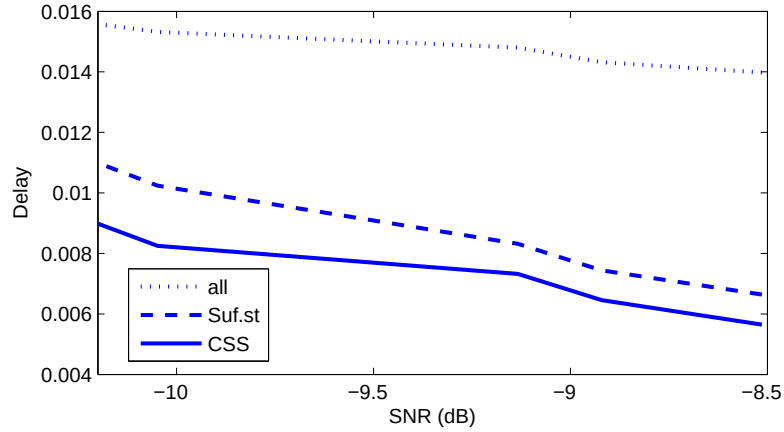


Figure 4.4: Delay incurred by sensing under various SNR

the delay due to packet exchange of the spectrum sensing results. The typical values used in the second simulation are also used here (i.e values in Table 4.1). As the number of participating nodes increase, the number of required samples to meet the sensing accuracy decreases, however, with diminishing returns. On the other hand, the number of packet exchanges increase. The overall delay for different SNR values is given in Figure 4.4. As SNR increases, the required number of samples to meet sensing performance decreases. The delay in CSS is less than half of the case where all

nodes participate. CSS also causes 15% to 18% less delay compared to the sufficient statistic based method.

Chapter 5

THROUGHPUT MAXIMIZATION IN ELECTROMAGNETIC ENERGY HARVESTING COGNITIVE RADIO NETWORKS

Energy harvesting techniques considerably increase the lifetime of wireless devices. Theoretically, energy harvesting enables infinite energy gain. However, since this gain is obtained at a limited rate, i.e., harvesting power, energy efficiency is still one of the major concerns for energy harvesting devices. Even though there is an extensive amount of work in the literature on energy efficient communication schemes, they generally address conventional battery operated devices. There is a key difference between them and energy harvesting devices. While the former is restricted by energy inside the battery, the latter has infinite energy, but, is restricted by harvesting power. Since their restrictions and abilities differ from conventional battery operated wireless devices, energy harvesting devices need solutions tailored specifically for them. In this chapter, we present an analysis on maximum achievable expected throughput for EM energy harvesting CRNs.

5.1 Previous Work on EM Energy Harvesting CRNs

Energy harvesting in wireless communications has, in fact, been a hot topic in the recent years. Related research is mostly focused on finding optimal methods under certain assumptions on network conditions. Some of these works assume perfect knowledge of EH profile at the transmitter and present optimal resource allocation methods for various objective functions [70] - [72]. Others assume statistical knowledge of the energy harvesting profile and try to optimize with regard to

stability regions, in which, both data and energy queues are kept bounded so that the system can keep on operating [73, 74]. Natural sources such as sun, wind underwater currents and acoustic waves are considered for energy harvesting in these works. With their infinite energy, natural sources are good targets for energy harvesting. However, energy harvesting from these sources require additional equipment to be placed on the nodes. Moreover, these sources are not consistent on the amount of energy they provide due to day-night cycles, seasonal changes and overall dependency on environmental conditions.

More recently, energy harvesting from electromagnetic (EM) waves has been considered as an alternative to these natural sources. Since harvesting can be done via the existing antenna of the node, this method offers a significant advantage in terms of cost, size, weight, and ease of implementability. However, since the amount of energy harvested from EM waves is lower than the energy that can be harvested from natural resources [75] - [77], EM harvesting is more suitable for low energy devices such as sensor networks with simple sensing tasks. Densely deployed sensor networks with low transmission distances and tolerance for long sleep cycles, during which, energy harvesting can be performed, are suitable platforms for EM harvesting.

Machine to machine (M2M) communications is currently a very hot topic for the research community. The number of devices connected to the Internet is predicted to reach billions by 2020 [78]. M2M communication is considered to be the means of controlling, configuring, maintaining and obtaining data from these devices. It will be very impractical to empower such huge number of devices by standard batteries. Furthermore, for cases like wireless sensor networks, nodes are distributed over a large area and battery replacement is not feasible most of the time. EM energy harvesting is a very promising means to provide power for such devices.

The main limiting factor in the implementation of EM energy harvesting networks is the higher power dissipation of the transceivers in reception and transmission modes compared to energy harvesting power that can be harvested.

Fortunately, there are ultra low power chips that require much less power compared to conventional sensors. In [79] a wireless sensor node designed specifically for low energy applications is reported to have 61 times improvement in overall energy consumption compared to the MICA sensor for a one day run of environmental data collection. The author also mentions an on-chip receiver they are developing that only consumes 0.9 mW. Ultra-low power transceivers with similar power consumption are now commercially available. One such transceiver draws only 0.9 mA with a 1 V supply while transmitting at -6 dBm [80]. In [81], an ultra-low power transceiver which draws only 15 μ A from a 15.5 V source during transmission is reported. Compared to MICA, which has a power consumption of 15 mW in receive mode, these are very promising developments.

Even though transceiver is generally the unit that has the most power consumption, other units such as the sensor itself, CPU and RAM should also be considered. There are also very promising improvements in all of these areas. In [82], a temperature sensor that only requires 3.6 nJ to achieve a resolution of 63 mK with a conversion time of 6 ms is presented. In [83], an ultra-low power CPU that dissipates 297 nW in active mode and 29.6 pW in sleep mode is introduced. There are other similar work with similar power consumption for both sensors [84] - [87] and CPU [88, 89].

With potentially infinite energy, additional capabilities can be introduced to wireless devices. Opportunistic spectrum access is one of the most promising capabilities due to the increasing demand for wireless spectrum and the arising need to dynamically access it. By adding CR capability to the wireless devices, spectrum utilization can be increased [1].

Various aspects of cognitive energy harvesting networks have been analyzed in the literature. In [90], optimal times for energy harvesting and transmission is investigated based on the amount of interference on the channel. A dynamic channel selection problem in a multi-channel RF-powered CRN is examined in [91]. Most of the previous work assume that the energy harvesting rate is constant, or its distribution is known.

Furthermore, most assume that there is a separate unit for energy harvesting on the node, thus, energy harvesting and transmission can be done concurrently. However, the main motivation for EM energy harvesting is that existing antenna can be used as energy harvesting unit and no additional equipment is needed. Moreover, to the best of our knowledge, none of the previous work lay out an analysis of the effect of cooperation in cognitive EM energy harvesting networks.

Even though cooperation is thoroughly investigated for conventional, battery operated wireless networks, the cost of cooperation differ between these networks and energy harvesting wireless networks. In conventional networks, the main concern is the trade-off between the gain obtained by cooperation and the extra energy spent. In energy harvesting networks consumed energy is not important as long as the harvesting rate is high enough to cover the power dissipation. In this regard, cooperation in EM networks is constrained by power, rather than energy.

In this chapter, we provide analysis on various aspects of Cognitive EM energy harvesting networks. We provide analysis on how much throughput is realistically achievable on average. Our contribution can be listed as follows:

- Contrary to most of the previous work, we do not assume exact or statistical knowledge of energy harvesting profile. Neither do we assume a separate antenna unit for energy harvesting. Assuming energy is harvested from the PU network, we first examine the average power that can be harvested by a single SU node. We assume a stochastic network geometry for the PU network. We use a model that is widely used in the literature for modeling wireless node distributions, i.e. Poisson point process (PPP).
- We model node operation as a Markov chain, in which, certain energy levels of the battery corresponds to states of the Markov chain. Then, we find the maximum average throughput that can be obtained for different PU channel occupation probabilities. This gives us an insight on how feasible a secondary energy harvesting network is for crowded and uncrowded spectrum

cases. The trade-off is, for a crowded spectrum, higher energy harvesting rates are expected. However, transmission opportunities are low. Vice versa for the uncrowded case.

- We also derive the equations for the durations of spectrum sensing, transmission and energy harvesting for achievable expected throughput.
- Then we focus on the cooperative case. We show that cooperation is not always the best choice to increase the expected throughput. We find the threshold transmission distance, when cooperation increases the expected throughput.

5.2 System Model

We consider a 2-D primary wireless network. There are N_{PU} PU nodes, distributed in a circular area of radius R_{PU} , according to PPP of intensity λ . The secondary network, i.e., the cognitive EM energy harvesting network is co-located with the PU network but is not necessarily limited in the same circular area. We focus our investigation on a single SU node, that is assumed to be at the origin, without loss of generality [95]. We assume that the investigated node communicates with another SU node that is at a distance d_x . We provide analysis on how this transmission distance effects the viability of cooperation.

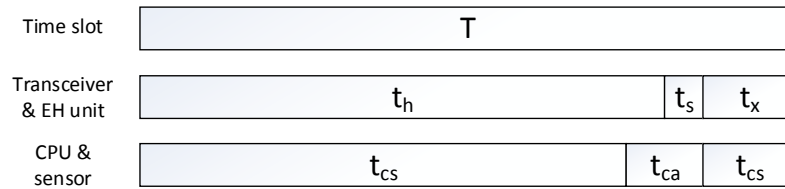


Figure 5.1: Time slot structure

We assume that each SU transceiver has a single antenna and can perform only one task at a time, i.e., energy harvesting, spectrum sensing, transmission or reception. The frequency range of interest is comprised of C non-overlapping

contiguous channels, each with a bandwidth of B . Time is assumed to be slotted. For the transceiver and the energy harvesting units, each time slot, T , consists of 3 phases. The first phase is for energy harvesting and lasts for t_h . In the second phase spectrum is sensed for s channels for a total duration of t_s . In the final phase, data transfer takes place on an available channel for t_x seconds. The CPU and the sensor units spend most of the time in sleep mode, t_{cs} , and only wake up for spectrum sensing and to take a sensor measurement and store it, which lasts for t_{ca} . The time slot structure from the transceiver and energy harvesting units and the CPU and sensor units is shown in Figure 5.1.

The energy harvested in the first phase plus the amount of energy inside the battery should at least be sufficient to cover energy spent in the second and third phases. We take T as constant. We calculate t_s according to spectrum sensing performance criteria and analyze how t_h and t_x should be chosen to increase expected throughput.

The amount of time spent on spectrum sensing is determined according to the spectrum sensing accuracy requirements, i.e. the node is required to have a detection probability (P_d) greater than δ , even in very low SNR values such as -20 dB, to protect the PU network from extreme interference of SU network. Furthermore, false alarm probability (P_f) should be below β to assure a certain level of spectrum utilization.

At the beginning of a spectrum sensing phase, a channel is assumed to be busy with probability P_{PU} . Given a channel is busy, the PU that is using it may be any one of the total N_{PU} PUs with probability $1/N_{PU}$. During energy harvesting, the EM energy received from the whole band is sent to the energy harvesting unit which performs the RF to DC conversion as well increasing voltage with voltage multipliers to bring it to levels required to operate circuit boards. Each SU node is equipped with a battery that is charged by this energy harvesting unit.

In the cooperative case, the time slot is divided into four phases. First, phase is energy harvesting. Then, all nodes perform spectrum sensing in a cooperative manner. Overall spectrum sensing decision is made by an OR fusion rule. Each node

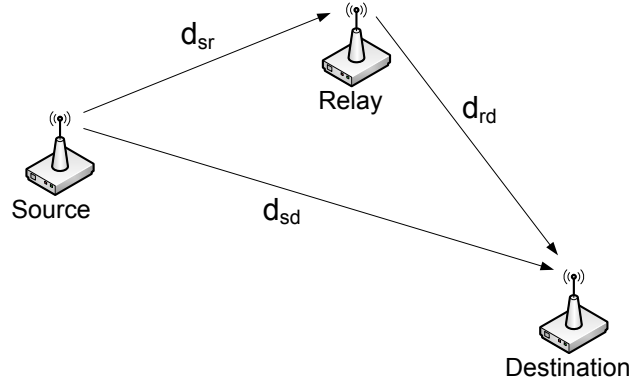


Figure 5.2: Structure of the cooperative relaying

sends its individual spectrum sensing result and PU existence is decided if one or more of the nodes detect PU. Complex spectrum management schemes are out of the context of this chapter. We assume that each node sends its results in a single bit to others by taking turns in a pre-arranged manner through a control channel. For data transmission, cooperating nodes act as relays as shown in Figure 5.2. In the third phase, the source node transmits its data and the destination node and cooperating nodes, acting as a relays, receive this data. Final phase is the relaying phase in which relay nodes take turns to transmit the data to the destination.

We assume fading to be as in [96, 97] in which channel gains are affected by both small-scale fading and large-scale path loss, however amount of received power is dominated by the path loss [98, 99]. Under this model fading power is an exponential random variable with unit variance. The path loss is proportional to $d^{-\alpha}$, where d is the Euclidean distance and $\alpha > 2$ is the path loss exponent.

5.3 Analysis of Non-Cooperative Communication

We aim to determine the maximum expected throughput, Γ , in a EM harvesting CRN.

$$\max \Gamma = R(P_d, P_f, t_s, t_x, P_x, E_i) \cdot t_x / T \quad (5.1)$$

s. t.

$$P_d \geq \delta \quad (5.2)$$

$$P_f \leq \alpha \quad (5.3)$$

$$T = t_s + t_h + t_x \quad (5.4)$$

$$E_i + E_h \geq E_{cs} + E_x + E_s \quad (5.5)$$

where, R is the optimal transmission rate that maximizes throughput, P_x is the corresponding optimal transmission power, E_i is the amount of energy that is left in the battery from the previous time slot, and E_h is the harvested energy. E_{cs} is the amount of energy dissipated by the CPU and the sensor. The first two constraints are related to spectrum sensing. the third constraint is about the periodic time slot operation. The final constraint is the energy causality constraint. It is to make sure we do not try to spend more energy than we have.

To reach a conclusion, we seek the answers of the following questions:

1. What should be the spectrum sensing time for one channel to meet $P_f \leq \beta$ and $P_d \geq \delta$ for minimum SNR i.e. γ_{min} ?
2. What is the expected amount of power that can be harvested under these conditions?
3. What should be the transmission time and the transmission power to obtain achievable expected throughput under these conditions?

We lay out the answers in the following analysis.

5.3.1 Spectrum sensing time

The detection and false alarm probabilities for a single node performing sensing on an AWGN channel is given as [100]

$$P_d = Q\left(\frac{\zeta - N(\sigma_n^2 + \sigma_s^2)}{\sqrt{2N}(\sigma_n^2 + \sigma_s^2)}\right) \quad (5.6)$$

$$P_f = Q\left(\frac{\zeta - N\sigma_n^2}{\sqrt{2N}\sigma_n^2}\right) \quad (5.7)$$

where, ζ is the detection threshold, N is the number of required samples, σ_s^2 and σ_n^2 are the signal and noise power, respectively. $Q(\cdot)$ is the q-function, i.e. $Q(x) = 1/2\pi \int_x^\infty \exp(-u^2/2)du$.

The detection threshold, ζ , that satisfies $P_d \geq \delta$, can be found by replacing P_d with δ in Eq. 5.6, and solving for ζ ,

$$\zeta = Q^{-1}(\delta)\sqrt{2N}(\sigma_n^2 + \sigma_s^2) + N(\sigma_n^2 + \sigma_s^2) \quad (5.8)$$

To find the required number of samples to meet $P_d \geq \delta$ under γ_{min} , we substitute (5.8) in (5.7). Assuming the sampling rate is equal to the Nyquist rate, after algebraic manipulations we obtain the required spectrum sensing time for one channel,

$$t_{s1} = \frac{1}{B} \left(\frac{Q^{-1}(\beta) - (1 + \gamma_{min})Q^{-1}(\delta)}{\gamma_{min}} \right)^2 \quad (5.9)$$

where, B is the channel bandwidth. Note that bandwidth is inversely proportional to the spectrum sensing duration. Therefore, as the channel bandwidth decreases, spectrum sensing time increases. In fact, when channel bandwidth is lower than a threshold value, t_s may increase so much that there isn't enough harvesting time and transmission becomes impossible.

This is shown in Figure 5.3, where the continuous line is the energy spent on spectrum sensing for various channel bandwidth values and the dotted line is the amount of energy that can be harvested in the remaining time. At around 9 KHz

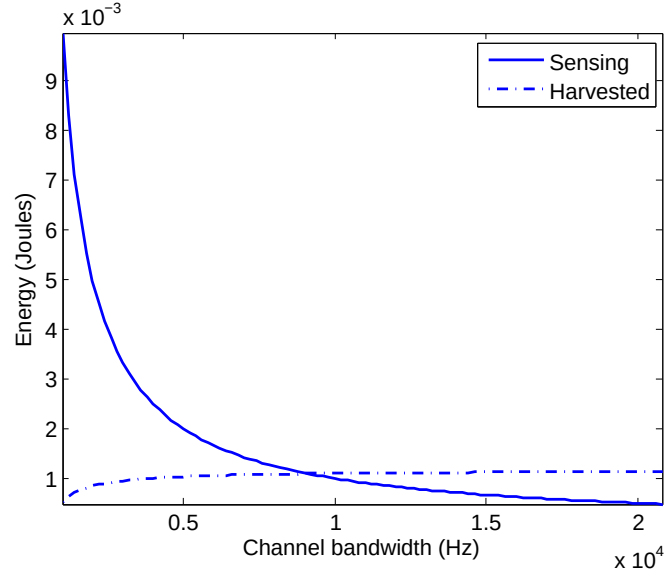


Figure 5.3: Harvested energy and energy spent on sensing

bandwidth, spectrum sensing consumes all of the harvested energy and no transmission can be done. As the bandwidth goes lower, the harvested energy cannot even cover the spectrum sensing phase. As seen here, for a system with specs given in Table 5.1, bandwidth should be higher than 9 KHz. An alternative is to use compressive sensing and use sub-Nyquist samples. However, we note that compressive sensing requires sparsity and is more suitable for mostly vacant spectrum, which is not very fitting for energy harvesting networks.

Unless otherwise stated we use the typical values given in Table 5.1 for this and all of the following figures. Power dissipation values are chosen as in the related references. We assume execution of 2000 instructions is required to take one sensor measurement as used in [83]. With a 106 KHz CPU as in [83], this corresponds to an approximate active duration of $t_{ca} = 18.8$ ms.

PU transmission power is chosen as 250 mW. This is half of the maximum allowed transmission power for power class 2 UEs [92]. Taking into account the power control mechanism, we didn't use the maximum allowable power. Taking an even lower transmission power would mean that the base station is nearby and it is possible to

harvest energy from it. While this is also a possible case, we took the worse case by not assuming a nearby base station.

In IEEE 802.22 standard, DTV protection at -114 dBm corresponds to an SNR of -19 dB for equivalent receiver noise figure of 11 dB and 22 dB safety margin at edge of coverage [93]. We took minimum SNR as -20dB. Also, minimum detection probability of $\delta = 0.9$ and maximum false alarm probability of $\beta = 0.1$ is required.

Table 5.1: Typical Values Used in Analysis and Simulation for the Network Environment and EM Energy Harvesting Nodes

Parameter	Meaning	Value
B	Bandwidth	200 KHz
R	Radius of PU network area	35 m
T	Time slot duration	120 sec
δ	Required detection prob.	0.9
β	Required false alarm prob.	0.1
α	Path loss exponent	3.4
γ_{min}	Minimum SNR	-20 dB
P_t	PU transmission power	250 mW
d_x	Transmission distance	35 m
V	Sensor supply voltage	1.55 V [80]
I_s	Current drawn in sensing mode	15 μA [80]
P_{ca}	Active power dissptd. by CPU	297 nW [83]
t_{ca}	Time CPU spent in active mode	18.8 ms [83]
P_{cs}	Passive power dissptd. by CPU	29,6 pW [83]
E_{sa}	Energy dissipated by the sensor	3.6 nJ [82]

The radius of the PU network is taken as 35 m. Due to practical considerations, a certain minimum received power is required for energy harvesting to be possible. As an example, in [94] a minimum of -22 dBm is reported as minimum received RF

power requirement. Using our channel model and a PU transmission power of 250 mW, 34 m is the maximum distance from which -22 dBm power can be received.

5.3.2 Harvested Power

The average harvested power can be written as $E[P_h] = \sum_{p=1}^{N_{PU}} \eta_{eh} E_p[P_r] P_p$, where η_{eh} is the harvesting efficiency, $E_p[P_r]$ is the expected received power when p PUs are active, P_r is the received power and P_p is the probability of having p PUs active. P_p can be written as $P_p = P_{PU}^p (1 - P_{PU})^{(N_{PU}-p)} \binom{N_{PU}}{p}$.

To find $E_p[P_r]$, we form a list, $\mathcal{P}$, of the PUs, in the order of their distance to the investigated energy harvesting node. When PUs have a PPP distribution, the density function of the distance (d_n) between the n^{th} PU in $\mathcal{P}$ and the energy harvesting node is given by [95]

$$f_{d_n}(r) = e^{-\lambda\pi r^2} \frac{2(\lambda\pi r^2)^n}{r\Gamma(n)}, \quad r \in \mathbb{R} \quad (5.10)$$

where $\Gamma(\cdot)$ is the Gamma function. The expected value of the distance to the n^{th} closest neighbor can be expressed as [95]

$$E[d_n] = R \sqrt{\frac{n}{N_{PU} + 1}} \quad (5.11)$$

Furthermore, let $\mathcal{A}_p$ be the set that consists of p combinations of PUs in $\mathcal{P}$, and $|\mathcal{A}_p|$ be the size of the set. Then,

$$E_p[P_r] = \frac{1}{|\mathcal{A}_p|} \sum_{k=1}^{|\mathcal{A}_p|} \sum_{n \in \mathcal{A}_p} P_t E[d_n]^{-\alpha} \quad (5.12)$$

The inner sum is the combined received energy when a certain p -combination of PUs are active. Since all PUs have the same probability to be active, all p -combinations are equally probable for a given p . Therefore, average over all possible p -combinations gives the expected received power when p PUs are active. Combining all,

$$\begin{aligned}
 E[P_h] &= \sum_{p=1}^{N_{PU}} \frac{1}{|\mathcal{A}_p|} \sum_{k=1}^{|\mathcal{A}_p|} \sum_{n \in \mathcal{A}_p} P_t R^{-\alpha} \left(\frac{n}{N_{PU} + 1} \right)^{-\alpha/2} \\
 &\quad \eta_{eh} P_{PU}^p (1 - P_{PU})^{(N_{PU}-p)} \binom{N_{PU}}{p}
 \end{aligned} \tag{5.13}$$

5.3.3 Maximum expected throughput

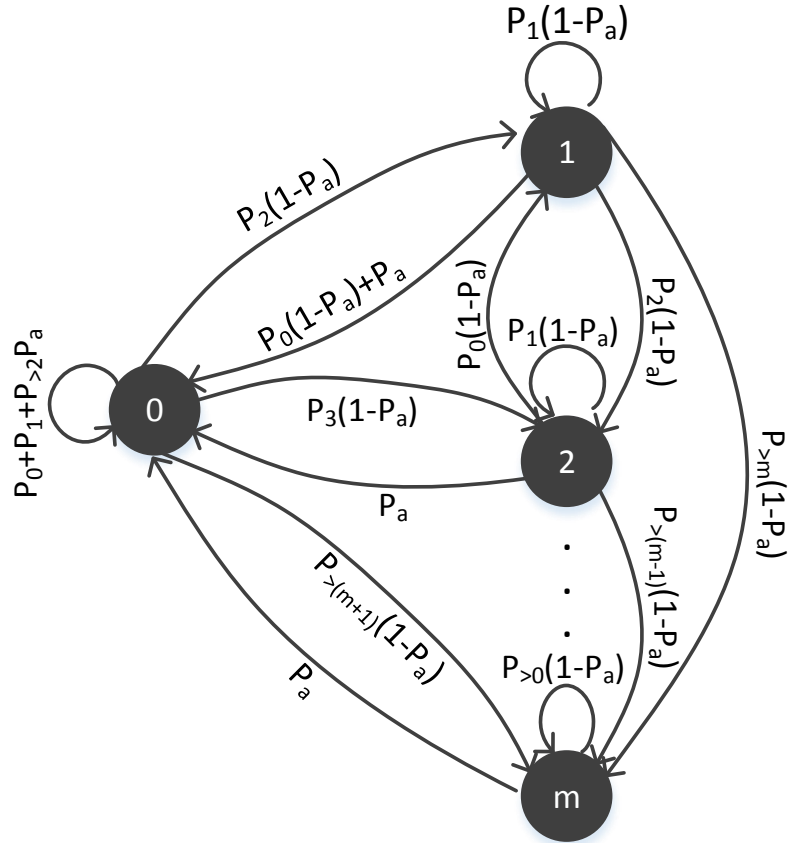


Figure 5.4: Markov modeling of node operation

Node operation in a time slot, T , begins with energy harvesting, then spectrum is sensed and finally transmission takes place. However, sometimes an available channel may not be found and the harvested energy remains in the battery, ready to be utilized in the next time slot. Throughput calculations should take this into account.

To achieve this, we model the node operation as a Markov chain, where each state corresponds to the amount of energy remaining in the battery from the previous time slot. If the amount of energy in the battery remaining from the last time slot is not sufficient to supply one environment and spectrum sensing phase, the system is in state 0. If remaining energy is sufficient to cover one environment and spectrum sensing phase, but not two sensing phases, the system is in state 1, and so on. Our Markov chain model is depicted in Fig 5.4. If we find an available channel we spend the remaining energy in transmission and go to state 0. If no available channel is found, there are three possibilities. If the harvested energy is not sufficient to cover the sensing tasks (i.e. environment and spectrum sensing) in that slot, we move down one state. If it is only sufficient to cover sensing in that slot, we stay in at the same state. Otherwise, we move to one of the higher states.

Associated transition probabilities are written in terms of:

$$\begin{aligned}
 P_a: & \Pr(\text{at least one available channel decided in } n \text{ channel senses}) = 1 - (P_{PU}P_d + (1 - P_{PU})P_f)^n \\
 P_0: & \Pr(\text{harvested energy is not sufficient for even one sensing phase}) = \Pr(E[P_h] < E_{s1}) \\
 P_i: & \Pr(\text{harvested energy is sufficient for } i \text{ sensing phases but not } i+1) = \Pr(E_{si} \leq E[P_h] < E_{s(i+1)}) \\
 P_{>k}: & \Pr(\text{harvested energy is sufficient to cover more than } k \text{ sensing phases}) = \Pr(E[P_h] \geq E_{sk})
 \end{aligned}$$

In calculation of P_a we take into account two cases. Either PU is active and we detect it, or there is no active PU but sensing raises a false alarm. E_{si} , is the amount of energy consumed in i spectrum sensing phases.

The maximum throughput can be written as AWGN channel capacity times the ratio of time spent in transmission to the time slot duration when moving from state i to state j .

$$\Gamma = \sum_{i=0}^m \sum_{j=0}^m B \log_2 \left(1 + \frac{\eta_x d_x^{-\alpha} P_x(i, j)}{P_n} \right) \frac{t_x(i, j)}{T} \pi_i S(i, j) \quad (5.14)$$

where, d_x is the transmission distance, α is the path loss exponent, $\pi_0 \cdots \pi_m$ are the steady state probabilities of the Markov chain and $S(i, j)$ are the state transition

probabilities for moving from state i to state j . The state transition matrix is given in (5.15). The actual amount of power transmitted as RF power depends on the transmitter efficiency. A transmitter radiates $\eta_x P_x(i, j)$ amount of power when operation moves from state i to state j .

$$S(i, j) = \begin{bmatrix} P_0 + P_1 + P_{>2}P_a & P_2(1-P_a) & P_3(1-P_a) & \cdots & P_{>(m+1)}(1-P_a) \\ P_0(1-P_a) + P_a & P_1(1-P_a) & P_2(1-P_a) & \cdots & P_{>m}(1-P_a) \\ P_a & P_0(1-P_a) & P_1(1-P_a) & \cdots & P_{>(m-1)}(1-P_a) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ P_a & 0 & \cdots & P_0(1-P_a) & P_{>0}(1-P_a) \end{bmatrix} \quad (5.15)$$

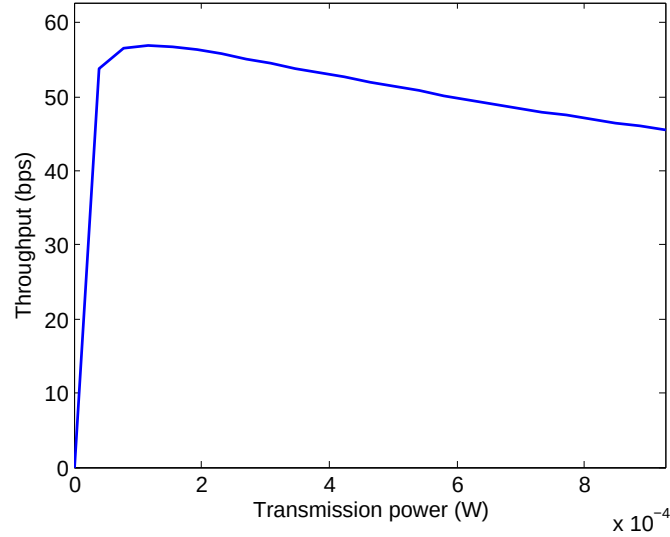


Figure 5.5: Throughput vs. transmission power

There is a trade-off between the choice of transmission time, t_x and transmission power, P_x . If t_x is chosen as a long duration, the amount of transmitted data increases. However, since the overall time slot duration, T , is fixed, increasing t_x causes energy harvesting time, t_h , to be lower. With lower energy at hand, P_x is reduced, which causes the transmission rate to drop. This is shown in Figure 5.5. When P_x is too low, throughput is low. As P_x is increased throughput begins to increase. However,

as P_x increases, t_x must decrease so that the energy causality relation $E_i + P_h t_h \geq E_{cs} + P_x t_x + P_s t_s$ holds. Here, E_{cs} , i.e., the energy spent by CPU and the sensor can be written as

$$E_{cs} = E_{sa} + P_{ca} t_{ca} + P_{cs}(T - t_{ca}) \quad (5.16)$$

where E_{sa} is the energy spent by the sensor to get one reading, P_{ca} and t_{ca} are the power dissipated and time spent by the CPU in active mode, respectively. P_{cs} is the power used by the CPU in sleep mode. Since the CPU is in sleep after taking the reading, the time spent in sleep mode by the CPU is rest of the slot time, i.e., $T - t_{ca}$. Checking (5.14), we see that t_x is a linear factor of throughput and P_x is inside the logarithm. Due to the nature of energy causality and throughput equations, decreasing P_x and increasing t_x causes throughput to increase faster.

We see that without cooperation, throughput up to about 60 bps can be achieved. This means, for a time slot of 120 seconds, about 720 bytes can be sent at each time slot, which should be sufficient for most simple sensing applications.

Next, we try to find a tractable solution for the optimal value of P_x . We first note that $t_x = T - t_s - t_h$, and $E_i + P_h t_h = E_{cs} + P_s t_s + P_x t_x$. Then we place these expressions into (5.14), take the derivative with respect to P_x and equate to zero.

$$\begin{aligned} \frac{d\Gamma}{dP_x} = & \frac{B [P_h - ((P_h + P_s)t_s - E_i + E_{cs})/T] d_x^{-\alpha} \eta_x}{P_n (P_x + P_h) \left(1 + \frac{P_x d_x^{-\alpha}}{P_n}\right) \ln 2} \\ & - \frac{B [P_h - ((P_h + P_s)t_s - E_i + E_{cs})/T] \ln \left(1 + \frac{P_x d_x^{-\alpha}}{P_n}\right)}{(P_x + P_h)^2 \ln 2} = 0 \end{aligned} \quad (5.17)$$

which yields

$$P_x = \left[\frac{\frac{P_h d_x^{-\alpha} \eta_x}{P_n} - 1}{\frac{\eta_x d_x^{-\alpha}}{P_n} L \left(\frac{P_h d_x^{-\alpha} \eta_x}{e P_n} - \frac{1}{e} \right)} - 1 \right] \frac{P_n}{d_x^{-\alpha} \eta_x} \quad (5.18)$$

where L is the Lambert W function, i.e. for any complex number z , the defining function of $L(z)$ is $z = L(z)e^{L(z)}$. We present the details of the derivations of (5.17) and (5.18) in the following.

Throughput can be written as

$$\Gamma = B \log_2 \left(1 + \frac{d_x^{-\alpha} \eta_x}{P_n} P_x \right) \frac{t_x}{T} \quad (5.19)$$

where

$$E_i + P_h t_h = E_{cs} + P_s t_s P_x t_x \quad (5.20)$$

and

$$t_h = T - t_s - t_x \quad (5.21)$$

Therefore, t_x/T can be written as

$$\frac{t_x}{T} = \frac{E_i + P_h T - P_h t_s - P_s t_s - E_{cs}}{T(P_x + P_h)} \quad (5.22)$$

$$= \frac{P_h - [(P_h + P_s)t_s - E_i + E_{cs}]/T}{P_x + P_h} \quad (5.23)$$

Let

$$A = \frac{\eta_x d_x^{-\alpha}}{P_n} \quad (5.24)$$

$$C = P_h - [(P_h + P_s)t_s - E_i + E_{cs}]/T \quad (5.25)$$

$$D = P_h \quad (5.26)$$

$$x = P_x \quad (5.27)$$

so that throughput can be simplified in notation as

$$\Gamma = B \log_2(1 + Ax) \frac{C}{x + D} \quad (5.28)$$

Then

$$\frac{d\Gamma}{dx} = \frac{ABC}{\ln(2)(1 + Ax)(x + D)} - \frac{BC \ln(1 + Ax)}{\ln(2)(x + D)^2} \quad (5.29)$$

which yields (5.17) when values are substituted. Equating to zero and canceling

common terms at each side,

$$\frac{A}{1+Ax} = \frac{\ln(1+Ax)}{x+D} \quad (5.30)$$

$$A(x+D) = (1+Ax) \ln(1+Ax) \quad (5.31)$$

$$Ax + AD - 1 + 1 = (1+Ax) \ln(1+Ax) \quad (5.32)$$

$$(AD-1) + (1+Ax) = (1+Ax) \ln(1+Ax) \quad (5.33)$$

$$\frac{AD-1}{1+Ax} + 1 = \ln(1+Ax) \quad (5.34)$$

$$e^{(AD-1)/(1+Ax)} = \frac{1+Ax}{e} \quad (5.35)$$

$$\frac{AD-1}{1+Ax} e^{\frac{AD-1}{1+Ax}} = \frac{AD-1}{e} \quad (5.36)$$

We use the Lambert W function, defined as $z = L(z)e^{L(z)}$. For our case $L(z) = \frac{AD-1}{1+Ax}$ and $z = \frac{AD-1}{e}$. Then

$$\frac{AD-1}{1+Ax} = L\left(\frac{AD-1}{e}\right) \quad (5.37)$$

$$x = \frac{AD-1}{A L\left(\frac{AD-1}{e}\right)} - \frac{1}{A} \quad (5.38)$$

Substituting values of A and D we obtain (5.18).

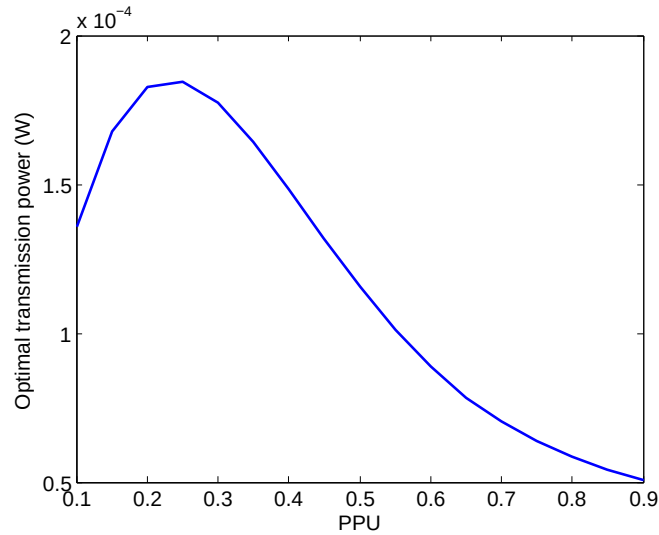


Figure 5.6: Optimal transmit mode power vs PU existence probability

Using (5.18) in (5.14) we obtain the maximum achievable throughput. In Figure 5.6 we depict optimal transmission power for various PU existence probabilities. When PU existence probability, P_{PU} , is too low, the harvested energy is also too low. As P_{PU} increases, harvested energy increases and transmission power also increases. As P_{PU} keeps increasing, it becomes better to reduce P_x and increase t_x . This was depicted in Fig 5.5. Therefore, optimal power reduces as P_{PU} keeps increasing.

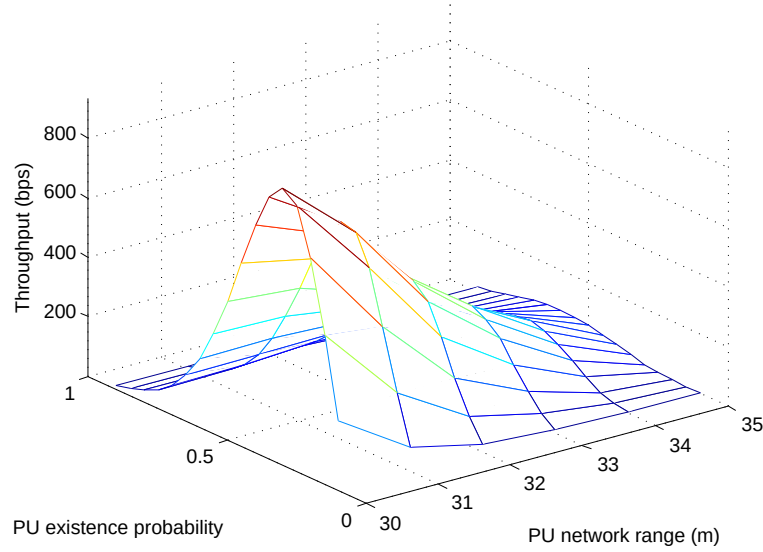


Figure 5.7: Achievable expected throughput for varying harvesting time and PU existence probability

In Figure 5.7, we show the impact of PU existence probability and PU network node density on energy harvesting and thus on throughput. Radius of the network is changed while the number of PUs inside remain the same, i.e. 10 PUs. As the radius increases, the average distance of PUs from the investigated SU node increases. As a result, average harvested power decreases. This causes throughput to decrease. As for the PU existence probability, when this probability is low, harvested energy is low since there aren't many active PUs. As it increases, harvested energy and thus, throughput increases. However, after a certain probability, even though the

harvested energy increases, probability of finding an available channel decreases. Since transmission is halted to the next time slot in such cases, throughput begins to drop.

This suggests that the proximity of PUs is extremely important for EM energy harvesting networks and also, the sweet spot is when the PUs are active about half of the time to enable effective energy harvesting and also, provide opportunity for transmission.

5.4 Analysis of Cooperative Communication

Our aim is the same as the non-cooperative case, i.e., to find the maximum achievable throughput. We focus on a network with two cooperating nodes. Extension to more cooperating nodes is straightforward. We assume there is no change in energy harvesting conditions of the previous section to be able to make a fair comparison. In the spectrum sensing phase the overall detection (Q_d) and false alarm probabilities (Q_f) under OR fusion rule are given as

$$Q_d = 1 - (1 - P_d)^n \quad (5.39)$$

$$Q_f = 1 - (1 - P_f)^n \quad (5.40)$$

where n is the number of cooperating users. Therefore, in this case we have $Q_d \geq \delta$ and $Q_{fa} \leq \beta$ as spectrum sensing requirements.

The required sensing duration for one channel can be obtained by taking similar steps used in derivation of Eqn. (5.9)

$$t_{s1} = \frac{1}{B} \left(\frac{Q^{-1}(\Theta) - (1 + \gamma_{min}) Q^{-1}(\Delta)}{\gamma_{min}} \right)^2 \quad (5.41)$$

where $\Theta = 1 - \sqrt{1 - \beta}$ and $\Delta = 1 - \sqrt{1 - \delta}$ for two node cooperation. In Figure 5.8, we depict the harvested energy and the amount of energy spent in spectrum sensing for various channel bandwidth values. Comparing with Figure 5.3, we see that cooperative case allows use of lower bandwidth, where the break even point has moved from about 9 KHz to 6 KHz. Since in cooperative sensing each individual node has to meet more relaxed sensing requirements, (P_d is always lower than Q_d , etc.),

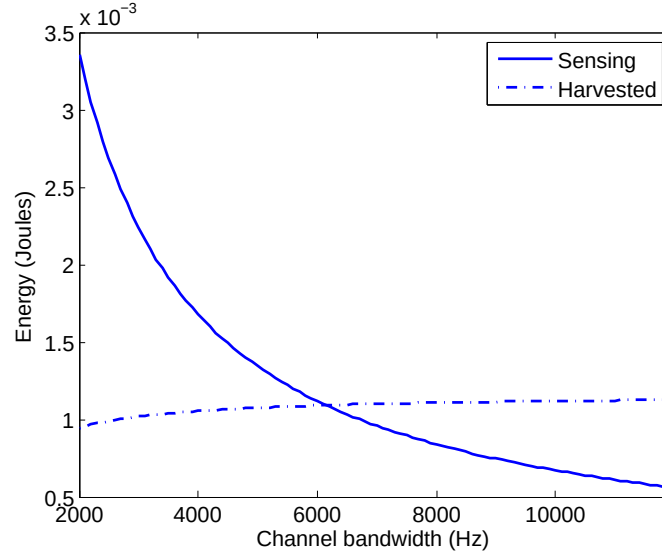


Figure 5.8: Harvested energy and energy spent on sensing for cooperative sensing

number of required samples is lower. This enables a lower minimum bandwidth to be viable.

In cooperative relay-based communication, the destination node receives the signal from both the source and the relay. Two prominent relaying methods are amplify and forward (AF) and decode and forward (DF). For the DF case, we assume that the relay node can successfully decode the data if SNR is above a modulation dependent threshold value [101]. SNR at the destination for these two cases is

$$\gamma_{AF} = \frac{P_x \left(\eta_x d_x^{-\alpha} + \frac{P_x \eta_x^2 d_r^{-2\alpha}}{P_x \eta_x d_x^{-\alpha} + P_n} \right)}{P_n \left(1 + \frac{P_x \eta_x d_r^{-\alpha}}{P_x \eta_x d_x^{-\alpha} + P_n} \right)} \quad (5.42)$$

$$\gamma_{DF} = \frac{P_x (\eta_x d_x^{-\alpha} + \eta_x d_r^{-\alpha})}{P_n} \quad (5.43)$$

Throughput expression for the cooperative case is the same as Eqn. 5.14. However, calculation of $P_x(i, j)$ and $t_x(i, j)$ differ, since the required sensing time is reduced in cooperative sensing. Like the non-cooperative case, there is a trade-off between t_x and P_x . We can simplify the analysis by writing one in terms of the other. Note that

$T = t_h + t_s + t_r + t_x$, where t_r is the receiving duration for the relay and $t_r = t_x$. Also note that $E_i + P_h t_h = E_{cs} + P_s t_s + P_r t_r + P_x t_x$ due to energy causality requirement and $P_r = P_s$ since both are power consumed in receive mode. Using these equations, t_x can be written in terms of P_x and known identities P_h, P_s, T, t_s . Using the SNR expressions (5.42) and (5.43), the maximum expected throughput for AF and DF cases can be written as,

$$\Gamma_{AF} = \frac{1}{B} \log_2 \left(\frac{P_x \left(\eta_x d_x^{-\alpha} + \frac{P_x \eta_x^2 d_r^{-2\alpha}}{P_x \eta_x d_x^{-\alpha} + P_n} \right)}{P_n \left(1 + \frac{P_x \eta_x d_r^{-\alpha}}{P_x \eta_x d_x^{-\alpha} + P_n} \right)} \right) \frac{P_h - (E_{cs} - E_i + (P_h + P_s)t_s)/T}{P_x + 2P_h + P_s} \quad (5.44)$$

$$\Gamma_{DF} = \frac{1}{B} \log_2 \left(\frac{P_x (\eta_x d_x^{-\alpha} + \eta_x d_r^{-\alpha})}{P_n} \right) \frac{P_h - (E_{cs} - E_i + (P_h + P_s)t_s)/T}{P_x + 2P_h + P_s} \quad (5.45)$$

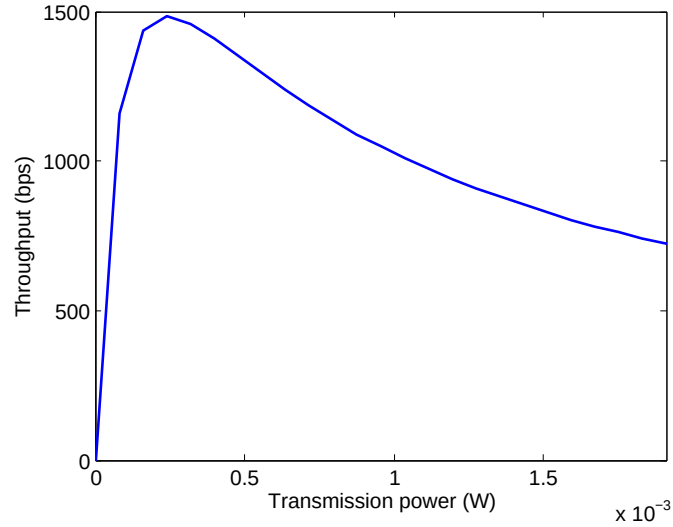


Figure 5.9: Throughput vs. transmission power

Throughput for varying P_x is shown in Fig 5.9. Behavior is the same as the non-cooperative case as expected. Similar to the approach in the non-cooperative case, the achievable expected throughput can be calculated by differentiating (5.44) and (5.45) with respect to P_x , equating to zero to find P_x , then substituting it back into

the equations. Unfortunately, (5.44) is too complex to find a closed form expression for P_x . However, for the DF case, P_x can be found using similar steps in derivation of (5.18) as detailed in the Appendix.

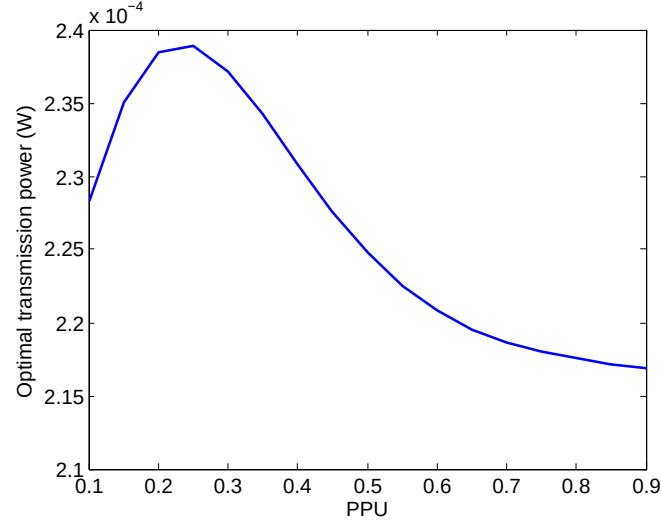


Figure 5.10: Optimal transmit mode power vs PU existence probability for DF

$$P_x = \left[\frac{W(2P_h + P_s) - 1}{WL \left(\frac{W}{e} (2P_h + P_s) - \frac{1}{e} \right)} - 1 \right] \frac{1}{W} \quad (5.46)$$

where $W = \frac{\eta_x(d_{sd}^{-\alpha} + d_{rd}^{-\alpha})}{P_n}$. Here, d_{sd} is the distance between source and destination nodes and d_{rd} is the destination between relay and destination nodes. We plot the optimal transmission power for various spectrum occupancy rates in Figure 5.10. We see that higher transmission power can be used for the cooperative case. The reason is that nodes spend less energy in spectrum sensing and they can use the remaining energy for higher transmission power.

In Figure 5.11, we show how maximum expected throughput changes with PU existence probability and PU network radius. Comparing Figure 5.11 with Figure 5.7, we see that cooperation, increases the throughput. Does this hold for all transmission distances? We expect cooperation to yield poor results when the transmission distance

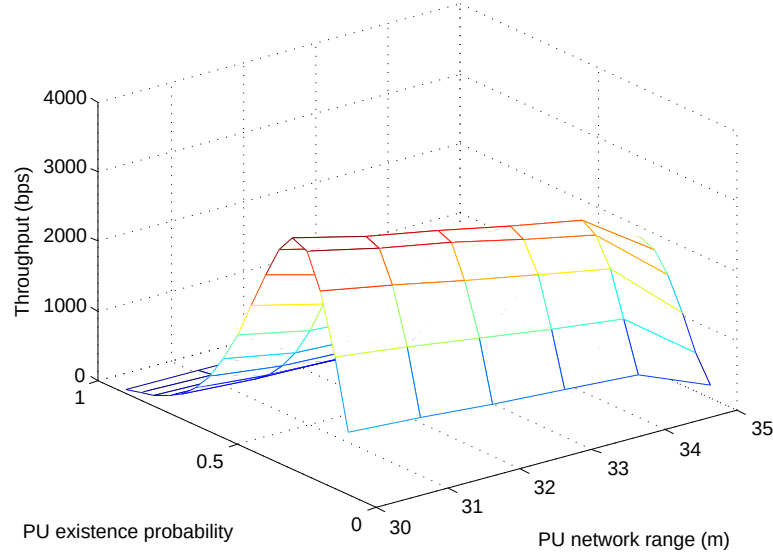


Figure 5.11: Achievable expected throughput for varying harvesting time and PU existence probability for DF

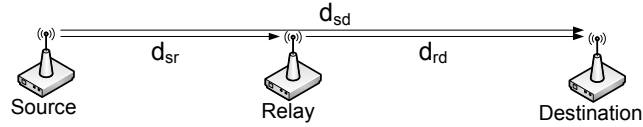


Figure 5.12: Best case node placement for relaying

is low, i.e., when the overhead of cooperation is not worth its benefit. We want to find the conditions under which relaying, together with cooperative spectrum sensing increases the expected achievable throughput. We try to find the cases for which cooperation is not viable even for the best case node placement scenario. By best case node placement, we mean the case where the source, relay and destination are on the same line and relay is between the source and the destination. For the DF case, the best placement is when d_{sr} is such that SNR at the relay is equal to the decoding threshold, where it will be as close to the destination while still being able to decode the data from the source. We depict this in Figure 5.12.

In Figure 5.13, we plot achievable throughput vs transmission distance, using

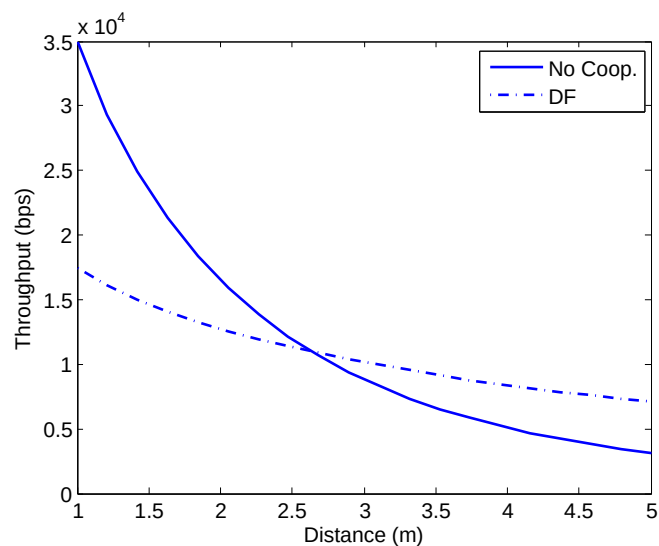


Figure 5.13: Achievable throughput vs transmission distance

optimal P_x values obtained by Eqns (5.18) and (5.46) for the non-cooperative and DF cases, respectively. As seen here, for the typical values given in Table 5.1, cooperation yields worse results only if communication distance is really low, i.e., lower than 2.5 m. This suggests that, unless the SU sensor network is extremely densely deployed, cooperation should be used.

Chapter 6

COGNITIVE RADIO SENSOR NETWORKS IN SMART GRID

Smart grid (SG) is envisioned to be the next generation of electric power systems with increased efficiency, reliability, and safety. With more prevalent use of renewable energy sources which provide irregular power levels, matching the increasing demand for electrical power with the supply is a recent challenge for the power grid. The aging infrastructure necessitates constant monitoring of the grid equipment and facilities. Considering all of these factors, the need for an improved electric network to provide reliable, safe, and economical power delivery becomes apparent [102, 103, 104, 105].

Real-time monitoring of smart grid equipment is essential for detection of failures so that proactive diagnosis and timely response to avoid blackouts and transient faults is possible. Therefore, remote monitoring and control technologies are essential for reliable and efficient power delivery in smart grid [106, 107]. To this end, deployment of a large number of sensors and smart meters in various points of the grid is planned, in order to have detailed, real-time information about the state of devices. The resulting wireless sensor network (WSN) provides two-way communication that enables data relay from nodes to control centers and dissemination of control information from control centers to sensors and actuators.

To be able to provide power for all residential, commercial and industrial zones, the smart grid is deployed in a very large geographical area. The accompanying communication infrastructure has different requirements to meet depending which part of the grid they are on. Consequently, a multi-tier network structure is envisioned. On the consumer side, the Home Area Networks (HANs), Building Area Networks (BANs) and Industrial Area Networks (IANs) facilitate communication

between various smart devices and sensors to provide energy efficient management and demand response [108, 109]. In the rest of this chapter we refer to HANs, BANs and IANs as HANs for brevity. These HANs are connected via Neighborhood Area Networks (NANs) to local access points. Finally, a Wide Area Network (WAN) connects NANs to the control center. Energy flow and network structure of smart grid is depicted in Figure 6.1.

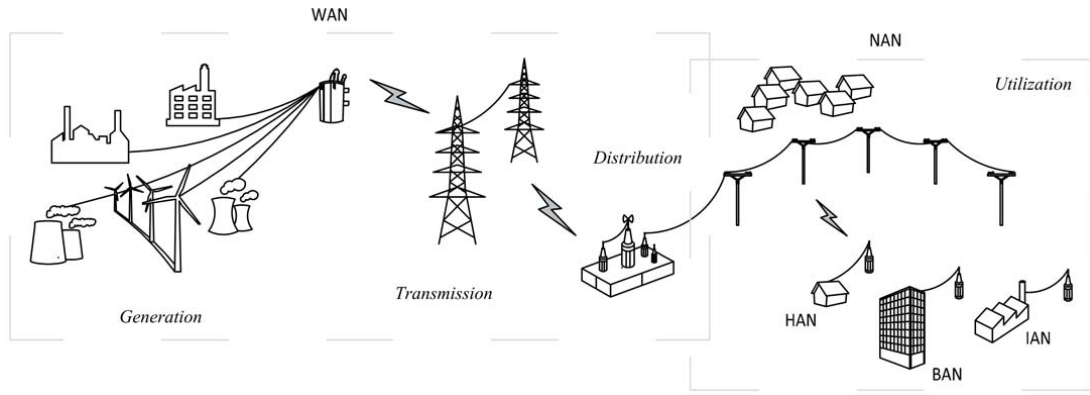


Figure 6.1: Smart grid infrastructure.

There are some serious challenges to overcome in the implementation of this overall smart grid vision [110, 111, 112, 113], such as meeting the stringent reliability, bandwidth and latency requirements, under irregular channel conditions caused by the harsh environmental conditions of the smart grid. One of the most promising solution approaches in overcoming these challenges is to use cognitive radio technology.

A cognitive radio (CR) is a smart device that can sense the spectrum, find vacant bands and change its transmission and reception parameters to use these vacant bands for communication [114], providing opportunistic spectrum access (OSA). The conventional approach to the use of spectrum is on a reservation basis, where certain bands are assigned to licensed users. However, most of these wireless networks are not fully utilized [14]. A network of CR devices can utilize these

licensed bands opportunistically, as secondary users (SUs), where the licensed users, also called the primary users (PUs), have priority over the spectrum band. Cognitive radio sensor network (CRSN) is a recently proposed network paradigm where a distributed network of sensors armed with CR capabilities sense the environment and collaboratively communicate their readings dynamically over available spectrum bands in a multi-hop manner to satisfy application-specific requirements [1].

CRSNs have the capability to provide additional bandwidth for the sensors through OSA. This helps in meeting the high bandwidth requirement in the WANs where the combined data flows of a high number of sensors result in high data rate demand. CRSNs also help with reliability, with their ability to switch to more favorable channels and reduce transmission errors and retransmissions. Furthermore, delay requirements may be met by switching to bands, in which higher transmission distance is possible. This reduces the number of hops, and thus, the delay. In the following section, we take a more detailed look at the reasons why CRSN is appealing for smart grid.

6.1 Applications and Benefits of CRSN in Smart Grid

Sensor nodes have limited energy, memory and processing power. CR operation places additional burden on these nodes with additional operations such as spectrum sensing and spectrum management. However, some of the challenges of communication in SG may not be covered by conventional WSNs. In the following subsection we list these challenges.

6.1.1 Challenges of CRSN in Smart Grid

The challenges of CRSN in Smart Grid can be listed as follows

- *Bandwidth:* Bandwidth requirements are estimated in the 10-100 kb/s range per device in the home or office building [116]. This adds up to large numbers

for NANs and WANs. One of the biggest challenges is to meet this bandwidth demand

- *Varying QoS requirements:* Smart grid applications may have very different QoS requirements in terms of reliability, throughput and delay [165]. Communication methods must be flexible to cover a variety of QoS specifications
- *Crowded ISM bands:* Smart grid meters in a HAN usually operate in the 2.4 GHz license-free ISM frequency band. However, there are already several types of radio systems operating in these bands such as ZigBee, Bluetooth, and Wi-Fi. Interference with these systems should be handled
- *Overlay M2M networks:* Communication infrastructure of smart grid is one example of M2M network. M2M is a recently emerging paradigm and is expected to be applied to many application areas for autonomous monitoring and control. These M2M networks will occasionally operate in the same location with the smart grid and use the same spectrum. Co-existence of these networks must be enabled
- *Scalability:* In the near future, network traffic for smart grid related to monitoring and control is expected to surge to tens of thousands terabytes [118]. This suggests that the communication infrastructure of smart grid cannot be static and has to be adaptable to make room for expansions
- *Noisy environment:* The electromagnetic interference may cause degradations in certain channels. The noise may be about 15 dBm higher compared to background noise, found in outdoor environments [106]
- *Reliability and delay:* Communicating sensor data in real-time and in a reliable manner has high importance in SG. A conventional WSN is configured to communicate in a certain way, and fails when even one assumption in its configuration is no longer valid. It is highly possible to have channel

degradations, networks outages and high interference from neighbor WSNs. Therefore, WSNs with their static communication schemes may not be able to meet the reliability and delay requirements

- *Crowded cellular spectrum:* One approach for wireless access in WAN is using cellular networks. However, it is an expansive solution. Furthermore, existing cellular network is not reliable. Control messages may not meet delay requirements during peak network congestion, causing failure of critical systems. In addition, cellular networks may not be available in some rural areas [119, 120]

CRSNs can exploit the temporally unused spectrum, i.e., spectrum holes. A spectrum hole can be defined as any opportunity by which a CR equipped node can communicate without causing degradation to PU communication. This can be done in two ways. In the first approach, a CRSN node can migrate to another frequency band each time a PU arrives. This is called the interweave approach. Alternatively, a CRSN node can alter its transmission power so that the interference it causes on the PU receiver is below a certain tolerable threshold. This is called the underlay approach. With the ability to access the spectrum in such an opportunistic manner, CR equipped nodes have some advantages over conventional wireless sensor nodes. These advantages can be used to meet these challenges. There are also certain disadvantages due to additional functionality required by the CR. In the following section we discuss these advantages and disadvantages.

6.1.2 Advantages and Disadvantages of CRSN in Smart Grid

We lay out the advantages and disadvantages of CRSN in SG in Table 6.1

Below, we explain how the advantages of CRSN help in covering the challenges mentioned above:

- *Additional Bandwidth:* CR can provide additional bandwidth due to its ability to utilize licensed PU bands opportunistically such as the TV whitespaces, i.e.

Table 6.1: Advantages and disadvantages of CRSN in SG

Advantages	Disadvantages
Additional bandwidth	Increased cost for sensors
Ability to use the best channel	Increased delay due to CR operations
Spectrum dimension in routing	Increased energy consumption for CR operations
Avoid interference in unlicensed bands	Best effort service
Possibility for overlay sensor networks	
Scalable	
Ability to mitigate environmental effects	

abandoned television channels due to the termination of analog TV

- *Choose the best channel:* CR has the capability to sense the channels and gather statistical data. A CR can also learn the PU spectrum access patterns. This provides a chance to match QoS of connections with channel characteristics
- *Spectrum as added dimension to routing:* Spectrum agility provided by CR introduces the dimension of spectrum to routing. Packets can be routed by changing bands along the way to optimize efficiency
- *CR in unlicensed bands:* CR offers alternative bands when ISM bands are too crowded. Alternatively, spectrum sensing feature of a CR can be used to avoid interference with other networks treating them as PUs, while still utilizing these bands
- *Overlay network operation:* Other M2M networks mostly face the same challenges with the smart grid communication network. CR is also a promising solution for them. Thus, it is viable to assume that multiple CRSNs may exist in the same locality. Co-existence of these networks may be handled either by devising methods that enable them to cooperate in CR operations or treat other M2M networks as PUs and use its spectrum management ability to coexist with these networks without interference

- *Scalability support:* Due to their ability to operate in a wide range of frequencies, the amount of spectrum offered by CRSNs can increase, albeit with additional energy and delay cost of spectrum sensing in additional bands
- *Minimization of environmental effects:* SG is a harsh environment for simple sensor nodes. Node outages and electromagnetic interference from the SG equipment has adverse effects on the overall network performance. CR enabled sensor nodes are capable of reconfiguring themselves autonomously without hardware modifications. With the ability of dynamic and opportunistic access to spectrum, sensor nodes can mitigate these effects while minimizing energy consumption

The disadvantages can be explained as below:

- *Increased cost for sensors:* CR capable transceiver, possibly a software defined radio, costs more than a conventional wireless sensor transceiver
- *Increased delay due to CR operations:* Spectrum sensing, spectrum decision, spectrum management and spectrum handoff functionalities may incur additional delay. However, in certain cases, e.g. routing from different bands, switching to a channel where longer transmission distance is possible, etc., CRSN may make up for this delay and may even yield less delay
- *Increased energy consumption for CR operations:* CR operations mentioned above also cause additional energy consumption. A promising solution to cover the additional consumption may be utilizing energy harvesting
- *Best effort service:* Since CRSN operate on an opportunistic manner, there is no guarantee to the level of service in terms of bandwidth, delay, etc. it can provide. However, we should also note that, conventional wireless sensors may also have interference problems in the ISM bands that they operate. Therefore, meeting certain level of service for conventional nodes is also not guaranteed

6.2 Implementation of CRSN in Smart Grid

Each CRSN node provides means for dynamic access to the spectrum. These sensors are composed of a sensing unit, a power unit which possibly has means for energy harvesting, a software defined radio based transceiver with adjustable parameters, and a controlling unit with memory and the processor. The node structure of a CRSN sensor is depicted in Figure 6.2. A line fault sensor, capable of harvesting energy from the power line is shown. The processor commands various units and information flow is to and from the memory unit. Energy harvester and the battery unit supply the required power to all other units. A CR capable transceiver is used to transmit sensing data.

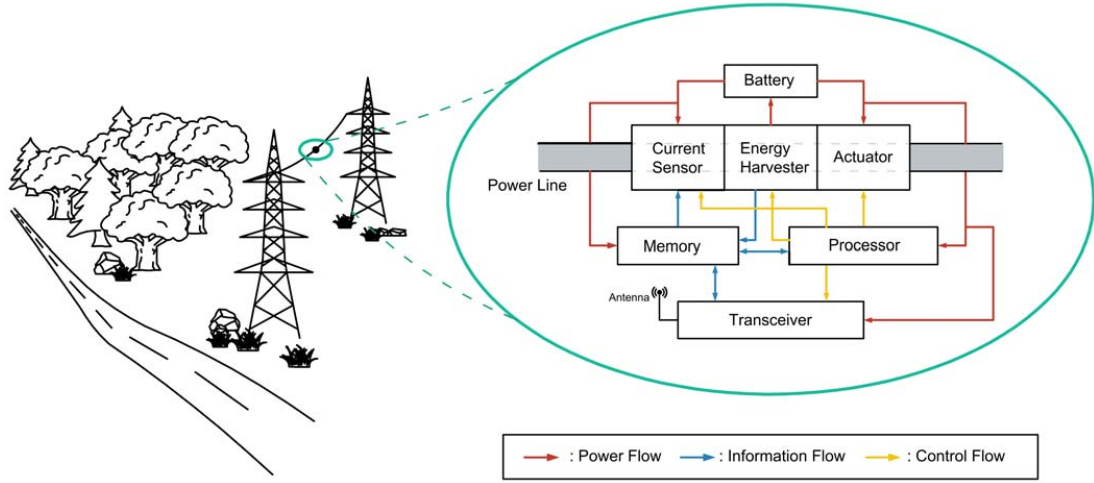


Figure 6.2: Smart grid CRSN node structure.

CRSNs provide several features to meet the challenges for WSNs, mentioned above. However, there are also some challenges in realization of CRSNs in the SG. In the following, we investigate these challenges from the point of view of spectrum management functionalities, i.e., spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility.

6.2.1 Spectrum Sensing

Spectrum sensing schemes must consider the constraints of the nodes. Since a huge number of sensors must be deployed to cover the whole grid, these sensors must be low-cost devices. This means, their processing power, memory and energy are limited. Therefore, solutions that require complex calculations may not be feasible for spectrum sensing. Furthermore, assumptions such as multiple radios on a node may not be feasible due to the cost constraint.

Coordination among the sensors before sensing is mandatory. Bands on which spectrum sensing is performed must be declared “silent” channels and other sensors must not use these channels. Otherwise spectrum sensing results will not be accurate.

There are various approaches to spectrum sensing such as cyclostationary detection, matched filter detection, waveform-based detection, eigenvalue-based detection and energy detection [121]. Generally, more complex methods yield better spectrum sensing performance. However, as stated above, CRSN nodes may not be able to use these complex solutions. On the other hand, high spectrum sensing performance is essential for PU protection. Therefore, to obtain satisfactory spectrum sensing results, cooperative spectrum sensing is essential.

Cooperation increases sensing performance, however, this increase is not linear, and has diminishing returns and has an upper bound [122]. Thus, smart choice of cooperating sensors is an important issue. A cooperative spectrum sensing method in which sensors with high sensing data correlation are censored is proposed in [3]. In Figure 6.3, we depict a possible CRSN deployment. Sensors close to each other “see” the spectrum similarly. Therefore, their spectrum sensing data will be highly correlated. Therefore, when using cooperative spectrum sensing, it is sufficient for the deciding node to get results from one of these nodes. Sensors with a larger distance between them have low correlations in their sensing data and present a different “view” of the spectrum. Obtaining this data from this low correlation node is more valuable for spectrum decision.

Another censoring scheme which considers remaining battery power is given in

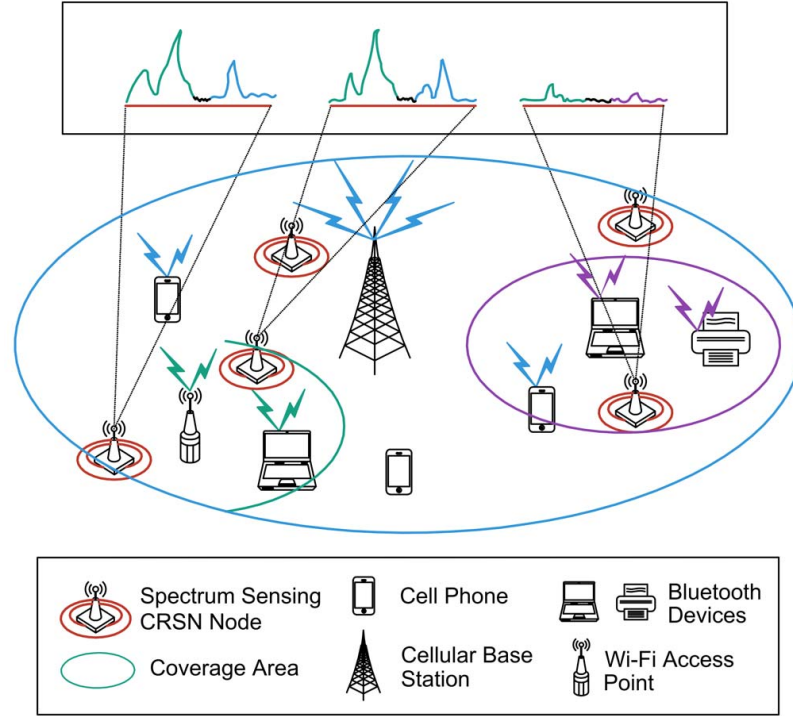


Figure 6.3: Spectrum, as seen by the sensing CRSN nodes.

[123]. In [124], a spectrum decision scheme that enables the coexistence of heterogeneous networks and devices is introduced. An analysis of sensing-performance trade-off is given in [168], which considers the energy cost of by spectrum sensing along with the control performance degradation incurred by imperfect communications.

6.2.2 Spectrum Decision

Once spectrum sensing is performed and available channels are identified, the decision on which channel to use must be made. This decision may be made by a central entity, or it may be made by the sensors in a distributed fashion. Centralized solutions can find optimal solutions since they have all of the sensing data. However, the overhead in passing all sensing results to a central unit may be prohibitive when the number

of sensors is large and/or multi-hop transmission is required to reach the central entity. It may also cause too much delay. Distributed solutions do not have these disadvantages since in this approach nodes only share their spectrum sensing data with their immediate neighbors. This approach may not find the optimal solution. However, the suboptimal utilization can still be close to global optimum [126].

Regardless of whether a centralized or distributed approach is chosen, sensors need to exchange some control information to coordinate spectrum decision, so that different sensors may use different channels to increase spectrum utilization efficiency. A control channel is generally used for this purpose. However, a control channel that is common to all of the sensors in SG is impossible. Therefore, novel mechanisms to handle control data dissemination in CRSNs for SG are needed.

6.2.3 Spectrum Decision

CRSN nodes must vacate the channel they are communicating on as soon as possible upon PU arrival. Moving the ongoing communication to another channel may also be necessary when channel conditions deteriorate due to interference from switch on devices, etc. This functionality is called spectrum handoff. On the one hand, this spectrum mobility enables continuation/improvement of communication; on the other hand, it causes additional delay since new available spectrum channels must be found. Furthermore, sensors in a CRSN have limited memory and caching requirements during handoff may be too high for these constrained devices, if an alternative channel cannot be quickly found. In [127], a spectrum handoff scheme that does not require a common control channel is introduced. Analysis of spectrum handoff is presented in [128, 129]. Further studies that expand such analysis on various parts of smart grid, such as generation, transmission and distribution are needed.

6.3 CRSN Communication Layers

It is worth investigating each communication layer separately. Some properties of CRSNs, such as dense-deployment and event-driven nature have both disadvantages

and exploitable advantages. There are also issues specific to CRSN in SG, such as energy efficiency concerns, harsh environmental conditions and variable link capacity. In this section, we take a detailed look at these issues for each communication layer.

6.3.1 Physical Layer

The OSA property of CRSN requires physical layer parameters such as operating frequency, modulation type, channel coding, transmission power, and spectrum sensing duration to be adjustable. This is a challenge, since CRSN nodes are supposed to be low cost devices.

The physical layer is also responsible for passing various data about channel conditions, such as channel availability, received signal power, etc. to upper layers so that they can be combined to form some statistical information about PU arrival patterns as well as channel conditions and enable spectrum-awareness. Open research issues for physical layer of CRSN can be listed as follows:

- Adaptive modulation and power control mechanisms designed specifically for SG are needed. This is necessary to combat interference from electric grid and other sensors in dense sensor deployment, and to coexist in a heterogeneous sensor network environment
- Methods that exploit statistic data generated by spectrum sensing results and channel conditions in cooperative spectrum sensing, management and handoff are needed
- Non-complex, cooperative spectrum sensing methods that reduce sensing duration of individual sensors are needed

6.3.2 Data Link Layer

Sensor data must be relayed to control stations reliably and in real time. Medium access control constitutes an important first step in achieving this aim. When

providing DSA, silent channels/durations must be determined for reliable spectrum sensing in addition to regular access functionalities.

Since a widely common channel may not be found, broadcasting in CRSN must be investigated. Also multicast, anycast and possibly geocast may be used more in SG CRSNs than in conventional networks. Multicast refers to delivering packets to a group of sensors. Anycast is similar to multicast, except delivery to only one of the nodes in a group is deemed sufficient. Geocast is generally used in vehicular networks but it is also viable in SG, which spans a huge geographical area just like vehicular networks. It is also a multicast paradigm but the node group is referred by their location instead of their network ID. Even though these are routing related problems, medium access for these communication paradigms in a OSA-capable network which prioritizes minimum delay and reliability must be considered.

Duty cycle mechanisms must be integrated with medium access. Interaction of error control mechanisms with duty cycles must be investigated. For example error correction schemes that require retransmissions such as automatic repeat request (ARQ) interact poorly with sleep cycles, causing frequent wake ups. On the other hand, FEC schemes may require too much computation and memory overhead. Thus, data link layer solutions developed for CRSN in SG must jointly consider these issues.

A Cognitive Receiver-Based MAC (CRB-MAC) was proposed in [130] To achieve high energy efficiency, CRB-MAC employs preamble sampling [131] approach to tackle idle listening and support sleep/wakeup modes without synchronization overheads. An access scheme which is based on PU arrival prediction is given in [132]. Two different state estimation cases are addressed. In the first case, the receiver has the acknowledgment of whether the transmitter sends an observation or not where the optimal estimator is standard Kalman Filter. The second one does not have acknowledgment. The problem becomes more complicated since the receiver has to estimate whether the received signal belongs to PU or the transmitting SU sensor.

Open research issues in CRSN for routing layer are stated below

- Coordination of silent intervals to increase performance of spectrum sensing

- Efficient broadcast and multicast methods in a CR environment
- Sleep cycle mechanisms that take retransmissions into account

6.3.3 Network Layer

DSA introduces spectrum as an additional dimension to routing. This provides means to choose the path with the best channel conditions, or the path with least number of hops, by choosing a channel that enables longer transmission distance. In Figure 6.4, we show spectrum-aware routing in CRSN. Figure 6.4 a depicts the network topology, where there are three PUs using three different bands. In Figure 6.4 b we show possible routing paths for a conventional WSN using channel1, channel2 and channel 3. In Figure 6.4 c we show a possible spectrum-aware route, where channel 3 is used in the first hop, channel 2 in the second hop and channel 1 in the last two hops. This is the route with the minimum number of hops and only a CR capable device can take this route when all three PUs are active.

Another alternative is to choose paths with most reliable links. In this context, a reliable link is one in which the PU does not become active frequently. CRSN nodes can keep track of PU activity in each channel. By choosing channels in which PU arrival is less common, the number of handoffs can be minimized. Furthermore, since it is very likely to find such channels available after the first spectrum sensing, the need for additional spectrum sensing is reduced. This results in reduced delay and energy consumption. As seen here, DSA introduces many new objectives to routing.

Research on network layer is limited. A framework that differentiates traffic flows into different priority classes according to their QoS needs and maintains three dimensional service queues attributing delay, bandwidth and reliability of data was proposed in [165]. A routing protocol with focus on price signaling and emergency handling was proposed in [133]. Throughput maximization was considered in [134, 135, 136]. A distributed optimization algorithm that iteratively increases the rates of flows until an overall optimal rate is reached is proposed in [132]. A selective routing scheme which avoids nodes with low battery nodes is given in [124].

Open research issues in CRSN for routing layer are stated below.

- Cognitive network coding and multipath routing methods that increase reliability are needed.
- Methods that jointly consider data fusion and routing may help reduce the excessive sensor traffic and increase energy efficiency.
- Spectrum aware schemes for broad/multi/any/geocast routing are needed. Novel methods to find common channels or map these routing methods to multiple unicast routes efficiently are required.
- Methods specific to CRSN, which use statistical data for channel conditions (e.g. periodically activated interfering nearby devices) or PU arrivals in routing may increase efficiency and reduce delay considerably.

6.3.4 Transport Layer

Transport layer provides end-to-end reliability and congestion control. These tasks are considerably more challenging in CRSNs [137, 138]. Congestion control algorithms must be spectrum aware, and should perform load balancing in a distributed manner. Rate control is also harder due to spatially and temporally varying, high loss links. All of these functionalities must be performed with minimal control packet exchange for high energy efficiency. The RF interference from SG devices adds to these challenges. Open research directions for reliability and congestion control in CRSNs in SG can be listed as follows.

- Energy efficient congestion control algorithms that take SG CRSN into account are needed. For example sensors are densely deployed in some parts of the SG (E.g. HANs) and more sparsely in others (E.g. WANs). However, in HANs, sensors do not do much forwarding. On the other hand, in WANs transmission and distribution lines may be extremely long and sensor data may have to be

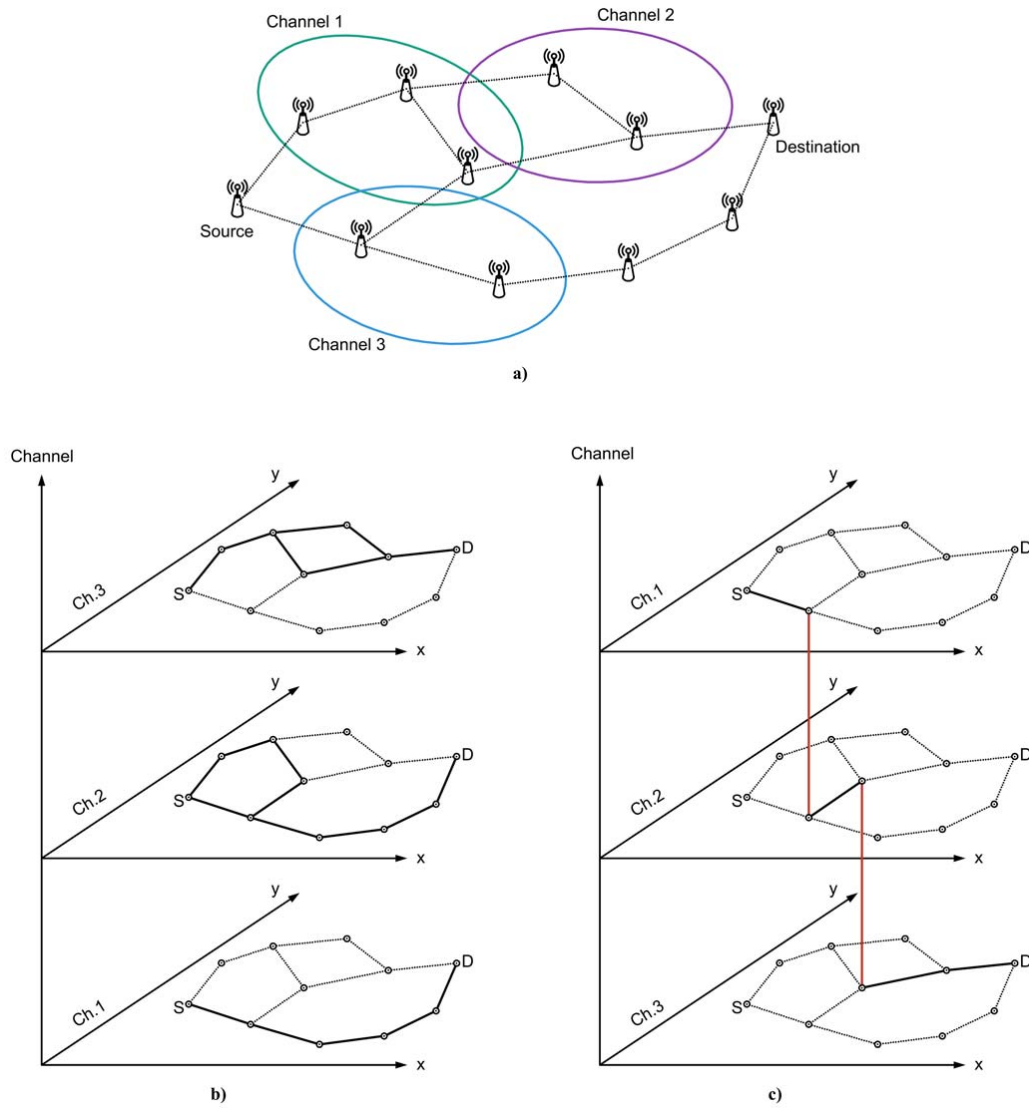


Figure 6.4: Routing in CRSNs.

sent to the control center in a multi-hop fashion. In such cases sensors may have to forward data of many other sensors. Therefore, rate control algorithms must be adaptive to the conditions

- Real-time delivery of sensor data is important. Real-time transport protocols must also maximize reliability

6.4 Multi-Layer Network Structure

SG is deployed over a very large region with different parts having different needs and requirements. Therefore, a hierarchical network structure is deemed suitable for the SG, in which HANs are connected by NANs which are in turn, connected by the backhaul WAN.

6.4.1 WAN

WAN covers a large area and are responsible for reporting the status of critical equipment of distribution system while acting as a bridge for meter data to control centers, and instructions as a response, from control centers to the devices [139]. WAN nodes include sensors/actuators called Intelligent Electronic Devices (IEDs) installed at critical points of distribution grid such as transformers, lightning arrestors, circuit breakers, capacitor banks, junctions, etc. [140]. Responsibilities of WAN may be listed as [139].

- Distribution Automation
- Integration of distributed energy generation and storage options
- Relaying smart meter data from NAN to substation
- Integration of Plug-in Electric Vehicle (PEV) charging pumps

This accumulated data imposes high bandwidth and strict delay requirements. For seamless transmission of data from NANs to the control center, 5 Mbps bandwidth is required [141]. Fiber optic may be the most suitable in terms of providing huge bandwidth and very low latency, i.e., about 5 μ sec per kilometer [142]. However, since WANs span over a huge geographic area, deployment costs may be prohibitive.

With the more prevalent use of renewable energy sources, such as wind and solar energy, new requirements arise. Since the power obtained from these sources may vary considerably, real-time information obtained from these sources is crucial for

electrical energy storage units [143]. Recently, Distributed Energy Resources (DER), small-scale power generation sources located close to where electricity is used (e.g., a home or business) are being increasingly used. To support these sources, WAN has to have a maximum of 100ms data latency [141]. With conventional WSNs, the number of hops may be extensive and prevent meeting the delay requirement. CRSNs can utilize the white spaces in UHF band, allocated to TV broadcasting. These bands enable a much longer transmission distance with same transmission power, which reduces the number of hops.

In [144], a spectrum allocation scheme which tries to match available spectrum to the changing supply of renewable sources is proposed. The idea is that, when these sources are active (e.g. a sunny day for a solar power station, a windy day for a wind power generator, etc.) higher data rate and reliability will be required for these links. Finding spectrum bands that are generally available at these times of the day and reserving these for related renewable source sites will help with meeting the data rate and reliability demands.

WANs monitor, control and manage all the activities during the generation, transmission and distribution of electricity. The spectrum is relatively less crowded, since these operations are generally held on the rural areas. It is reasonable to expect each power plant, dam, etc. to have a large number of sensors in various parts of the facility. Considering the ongoing utilization of renewable energy sources, even if a single sensor per solar panel/wind turbine is used, such areas will also have many sensors. Cognitive radio based approaches are especially promising here, since the amount of data is large but the available spectrum is also plenty.

6.4.2 NAN

Neighborhood area network is an intermediary network which connects multiple HANs to Data Aggregate Unit (DAU). Electricity usage information and any other customer related data in a neighborhood are transmitted to a utility company or a third-party system by NAN for future pricing and/or control operations. NANs can also

be called as Field Area Networks (FANs) when they connect to field devices like advanced metering infrastructure (AMI) or IEDs. A backhaul network is utilized for the connection between NANs/FANs and WANs, and aimed to transport data aggregated from the field between these networks [145].

Smart metering, demand response, distribution automation, electric transportation, load management, prepayment and pricing can be denoted as the main fields where the NANs are applied. The data related to these applications need to be exchanged between numerous customers and substations. Thus, data rate and coverage area metrics which may vary depending on application requirements become crucial for these operations. To convey data for kilometers -up to 10 km with a rate of 0.1-10 Mbps, NANs can be performed over multi-hop capable ZigBee and Wi-Fi mesh networks and/or Power Line Communication (PLC) techniques, as well as individual or collaborative implementation of long distance coverage enabling wired and wireless technologies such as WiMAX, Digital Subscriber Line (DSL), LTE, Cellular and Coaxial Cable [145].

A multi-hop mesh network topology is generally envisioned for NANs. A NAN generally covers a neighborhood. Therefore, spectrum utilization/availability may vary within a NAN. With a conventional WSN using only the ISM bands, it is possible to have bottleneck areas where ISM is widely used. A CRSN can bypass these bottlenecks by using its OSA capability and switching to a licensed band such as TV whitespaces. Since multiple bands can be used with CR capability, the added spectrum may enable new functionality such as surveillance of critical SG equipment.

Transmission efficiency and delay reduction can also be achieved with proper data fusion schemes. Based on gathered information from NANs adaptive, robust electrical power load balancing strategies can be developed [106].

A transmission strategy that classifies data into different priority levels according to their various features is given in [146]. The main idea is that even though aggregated may be large, only a small portion of it is high priority data. The

proposed cognitive solution ensures the most important data is transmitted with a minimum delay under the constraints of the electric-power-system environment and battery power supply.

Another data prioritization solution is given in [147]. The problem is modelled as a weighted network utility maximization (WNUM). Flows are assigned weights according to their QoS requirements and objective of the optimization is set as the weighted sum of these flows.

NANs carry the traffic of multiple HANs. Data for each HAN is a combination of a multitude of sensors. Therefore, meeting the resulting throughput demand on a single band becomes problematic. Spectrum availability may not be as high as in the WAN case since NANs are in urban areas. An alternative is to use 3G or LTE technology. However, having each sensor a subscriber will be too expensive. A promising approach is using online brokers and online auctions. The PU network allocates unused parts of its spectrum for SU use to be handed out using online auctions. With this method, PU network can obtain revenue from its unused resources and CRSN can have opt for these resources when it cannot meet its QoS demands with OSA. An open issue here is cost optimization efforts, generally handled by game theory-based online auctioning techniques.

6.4.3 HAN

HANs are aimed to increase energy efficiency by intelligently regulating energy consumption. They are capable to control, manage, and track the electrical appliances, home-related systems and services. In addition, remote control, security and safety operations, resource usage tracking, lighting management, and healthcare monitoring are some of the major applications conducted in various parts of HANs, i.e., smart homes. A smart home is an application of ubiquitous and/or pervasive computing which is capable to serve user context-aware assistive services with automated and controlled components [148]. These systems can be utilized to overcome energy efficiency problem at the basic level as an extension of smart grids.

An abstract depiction of smart home concept is shown in Figure 6.5.

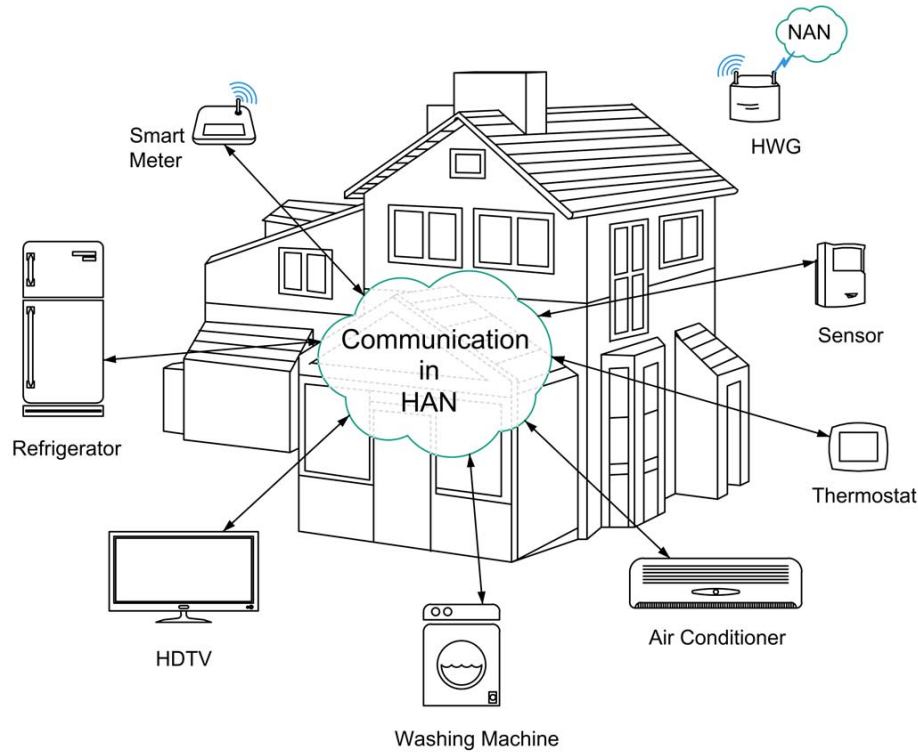


Figure 6.5: Smart home concept.

To consume energy more effectively, demand response, consumption monitoring, and standby power prevention focused gadgets, i.e., smart meters [149], are frequently preferred in home automation applications to inform the user or any other authorized institutions for decision making processes. In addition to smart meters, numerous specialized devices and systems and/or any other related peripherals might be deployed regarding the application requirements to enable and utilize the advanced control architecture of smart houses. As it is noticed, these systems require an exchange and transmission of control and sensory information between all the connected components to realize the previously assigned tasks and ensure the proper system working. To make that possible, a network of collaboratively working devices, i.e., WSNs should be deployed.

Smart homes and WSNs are interdependent systems to regulate the energy utilization, measure the physical environmental conditions, control the usage of electrical appliances and resources, and also monitor a subject's movements, motions and vital signs. Integration of WSNs into the smart home systems leads to the generation of Home Area Networks (HANs) on a larger scale.

HAN ensures ongoing transmission of load information and power data of smart meters from the user side to the utility center, furthermore gives dynamic electricity pricing information in the opposite direction. There are two noteworthy functionalities in HAN: commissioning and control. Commissioning is based on identifying new devices and managing the adaptation of these into the self-organized network. Control is utilized to keep up with the communication link between devices and provides collaboration within the smart grid [150]. With the improvements of advanced sensory structures, flexible and reliable communication technologies, and also enlarging application diversity, WSNs and accordingly HANs are getting more feasible and viable in smart grid applications. Thanks to these advancements, number of controllable devices is increasing excessively each passing day. However, this growth may cause some inevitable problems. For indoor environments, such as homes, buildings, offices, and/or subway stations, mostly ISM band operative wired and wireless communication technologies, like power line communication (PLC), ZigBee, Bluetooth -recently Bluetooth Low Energy (BLE), Wi-Fi and 6LoWPAN are preferred to enable HANs, but this license free and globally available frequency range is becoming inadequate to handle the intensively growing device number. In Table 3, we provide a comparison of these communication technologies.

Ongoing spectrum over-crowdedness on HANs results in channel scarcity, thus affect the proper execution of the needed communication between the system components. In addition, intensive use of 2.4 GHz ISM band by the ZigBee, Bluetooth, Wi-Fi protocols and any other related devices can generate significant interferences to each other, and decrease both the communication quality and the reliability. Development of these systems leads to emerging and promising

technologies for the smart home applications.

It is estimated that the current scarcity on the globally available and license free spectrum will be challenged more with the ongoing increment of the network enabled systems deployment. For example, by 2050, nearly 20% of the world's population will be more than 60 years old, and people in this group of age will confront with health issues and be more inclined to experience effects of long-term chronic illnesses. To accommodate healthcare services and assistive technologies in patients' surroundings [148] to track their vital signs and correspondingly take action in case of emergency and/or when it is needed. However, that will necessitate the inevitable establishment of various control and monitoring mechanisms, actuator systems and communication units.

The other predicted future trend can be stated as the access of 'pay for use' systems into the market. Similar to today's cloud-based electronics, selling price of home appliances is expected to reduce to very low levels in a short run, since the manufacturers and/or dealers will get profit from every use of these goods. To provide proper functionality to this per-use pricing model, it is required to deploy numerous sensors that connect to Internet or any other authenticated local access points for the accurate billing operations. This and the other stated issues which intensively increase the number of spectrum occupying devices will force the limited ISM band to become totally unusable, eventually.

It is obvious to say that, even if the ISM is not a licensed band, cognitive radio operations should be utilized to regulate the usage of spectrum to prevent the expected future failures. Furthermore, today's standardization bodies in the field of WSNs have started to upgrade the communication protocols correspondingly. For example, IEEE has extended its 802.11 standards family with the 802.11af and 802.11ah definitions. IEEE 802.11af, i.e., White-Fi or Super Wi-Fi [151], is also known as a wireless computer networking standard in the 802.11 section, approved in February 2014, that involves Wireless Local Area Network (WLAN) operations in TV white space spectrum in both VHF and UHF bands between the frequencies of

Table 6.2: Comparison of protocols that may be used in a smart home

	Z-Wave	ZigBee	6LoWPAN	Wi-Fi	Bluetooth	BLE
<i>Operating Frequency</i>	868/915 MHz	868/915 MHz, 2.4 GHz	868/915 MHz, 2.4-5 GHz	2.4-5 GHz	2.402-2.482 GHz	2.402-2.482 GHz
<i>Maximum Data Rate</i>	9.6-40 kbps	20/40 kbps, 250 kbps	10-40 kbps, 250kbps	11-54 Mbps	0.7-2.1 Mbps	0.27 Mbps
<i>Nominal Range</i>	30-50 m	10-20 m	10-100 m	10-100 m	15-20 m	10-15 m
<i>Network Size</i>	232	65536	100	32	8	N/A
<i>Applications</i>	Home Automation, Security	Wireless Sensing, Monitoring	Home, Automation, IoT	Monitoring, Internet, Data Network	Wireless, Sensing, Monitoring	Health-care, Beacon, Fitness

54 MHz - 790 MHz.

Transmission on unused TV whitespaces using CR is established by taking measures to protect PUs, for instance, analog TV, digital TV, and wireless microphones [152]. IEEE 802.11ah is another wireless communication protocol, operating in unlicensed bands, which can be referred as a revision of the IEEE 802.11-2007 wireless networking standard. Sub 1 GHz license-exempt bands are used to extend the Wi-Fi network, in contrast with 2.4 GHz and 5 GHz operative conventional Wi-Fi allocations. Another advantage is the lower energy consumption, permitting the formation of large groups of stations or sensors that collaborate to share the signal, supporting the idea of the Internet of Things (IoT).

IEEE is working on a new standard for wireless regional area networks (WRANs), namely IEEE 802.22, which uses white spaces in the TV frequency spectrum [153]. The main idea which lies behind of IEEE 802.22 WRAN is using cognitive radio techniques to permit the sharing of geographically unused spectrum allocated to the TV broadcast service, in order to utilize the broadband access to unreachable/compelling areas like rural and low populating environments. 802.22 can be referred as the first effort conducted worldwide for defining cognitive

radio-based air interface standardization to the opportunistic use of TV bands on a non-interfering basis. These and the other enhancements indicate that cognitive radio necessity will influence the developments of future technologies as well as forming the existing ones. In Table 6.2, we provide a consolidated information on in-home wireless communication technologies. We see that most of these technologies suffer from limited data rate, short communication distances and/or scalability. With the impending spectrum scarcity problem, CR is clearly a very promising alternative to, or at the very least, a complementary access scheme for these technologies.

Chapter 7

OPPORTUNISTIC RELIABILITY FOR SENSOR ACTOR NETWORKS IN SMART GRID

WSNs and WSANs [154] are expected to watch over expensive equipment in smart grid, with sensors monitoring the environment for possible emergency events and communicating with actuators to take proper action when the event occurs. Failure in detection of an emergency event may result in break down of expensive equipment, and in some extreme cases, may even cost lives. Therefore, reliability is considered to be one of the most important issues in smart grid communications. To avoid such losses reliable and timely coordination of sensing results must be addressed.

In smart grid communications, the problem of spectrum scarcity is exacerbated by electromagnetic interference of the devices and harsh environmental conditions. Although CRSNs can be used to mitigate the spectrum scarcity problem, incorporation of CR into distributed sensing requires sharing of spectrum opportunities among CRSN nodes and addressing event specific sensing requirements, while adhering to the inherited collaborative and energy-constrained nature of sensor networks. Furthermore, cognitive radio actor nodes can collect observations of CRSN nodes and cooperate to reach a global estimate, i.e., consensus [156]. Reaching consensus in a decision, i.e., estimation, interval requires efficient and adaptive sharing of spectrum opportunities among cognitive radio sensor and actor nodes, such that desired amount of samples can be collected from sensors with minimum spectrum access and actors can reach a consensus during an estimation interval. In this chapter, we present an analysis of achievable reliability under OSA. We first, lay out the related work in the literature. Then, we list our assumptions and present our analysis.

7.1 Previous Work on Spectrum Sharing in CRSN

Due to limited battery sizes, energy efficiency has been the main consideration for communication algorithm design for CRSN. Energy-efficient channel management is studied in [157]. Residual energy aware channel assignment is investigated in [158]. Energy-efficient spectrum sensing algorithm for CRSN is proposed in [159]. However, these works mainly lack in incorporating collaborative nature of sensor networks, and application specific reliability, i.e., estimation distortion and interval, requirements are disregarded. Furthermore, spectrum sharing problem for cognitive radio networks (CRN) are investigated in [160, 161, 162, 163, 164]. Main drawback of these schemes is missing consideration of detection and monitoring requirements of sensor networks. In our design, we specifically target to exploit collaborative effort of sensor nodes on the same event and achieve reliability opportunistically while reaching consensus among actor nodes in an estimation interval.

Spectrum sharing solutions in other CRN mainly focus on throughput maximization and are proposed to efficiently utilize the scarce spectrum opportunities. In [160], spectrum sharing for multi-hop cognitive radio networks is studied. In [161, 162, 163, 164] spectrum sharing schemes for multiple input multiple output systems have been proposed. The primary reason for their inapplicability in CRSN is their notion of rate maximization. Furthermore, reliable estimation of event features, collaborative nature of CRSN nodes, coordination requirements of CR actor nodes and spectrum efficiency must be addressed while designing spectrum management algorithms for large scale distributed sensing networks. Hence, there is a need for a novel spectrum access mechanism in CRSN that emphasizes on collective reliability, spectrum efficiency and simplicity.

CR based communication in Smart Grid has been investigated in various fronts, such as quality-of-service (QoS) or priority based access schemes [165, 166], network infrastructure proposals [167], investigation of important parameters in CR based network design [168], multimedia communications [169], and green communications [170]. However, reliability is not investigated thoroughly, even though it is one of the

most important requirements.

In this chapter, first, we analyze reliability in event estimation by defining a distortion metric. We characterize required spectrum opportunity to attain desired estimation distortion level while minimum amount of channels are accessed, based on spectrum mobility parameters, i.e., licensed user activity, interference, spectrum sensing and handoff durations, as well as real-time distributed sensing parameters, i.e., observation noise, delay-bound on reaching consensus, and energy consumption limitation per estimation interval. Then, we study required duration for reaching consensus among actor nodes after collection of samples from sensors and generating local estimate based on the interruption probability due to licensed user interference. Two regimes are identified: One in which sufficient spectrum opportunity exists and consensus can be achieved among actor nodes, and one in which actor nodes try to minimize the disagreement as much as they can support, i.e., provide opportunistic consensus, due to limited spectrum availability. The regime of operation depends on the licensed user activity on channels, and the early regime is desirable but achievable only for sparse licensed user existence on the spectrum. It is concluded that in certain environments under sparse spectrum occupancy by licensed users, spectrum access duration of sensor nodes can be adaptively reduced to enable convergence to consensus for actors in an estimation interval. Contribution of this chapter can be outlined as follows

1. *Analysis reliability in event detection*: Local estimation distortion at actor node is modelled with respect to sensing SNR, reporting rate and channel error rate.
2. *Opportunistic Consensus*: A cooperative scheme is proposed, where actor nodes share their local event estimations through opportunistic access of licensed channels to reach a global consensus about the event signal. We show that our scheme increases reliability.
3. *Consensus Convergence*: Impact of interruptions due to licensed user arrivals, mis-detection of licensed users, and wireless channel errors on reaching consensus

is formulated. Prolongation in the consensus convergence time is studied under OSA.

The remainder of the chapter is organized as follows. In Section 7.2, distributed sensing architecture composed of cognitive radio sensor and actor nodes is elaborated. Problem formulation and reliability analysis is presented in Section 7.3. Factors that effect reliability are discussed in Section 7.4. Opportunistic consensus is analyzed in Section 7.5. Simulation results are presented in Section 7.6.

7.2 Network Setup

We assume that the network in question consists of multiple wireless sensor nodes, each equipped with a CR and an actuator node with multiple CR transceivers. These nodes communicate among each other via OSA to perform remote monitoring and actuation tasks. Collected samples s by sensor node m on event signal θ are delivered to the actor node during the reporting interval τ_r over assigned channel c within spectrum access duration τ_a to satisfy reliability requirement D_o of distributed event observations. Reliability measure for estimation of the actor node is defined in terms of distortion D (mean square-error) of the estimated event signal over a τ_a .

Sensor nodes occupy a single CR transceiver with capability of adjusting its operating frequency to any channel c in designated spectrum band by the actor node, i.e., channel set $\mathcal{C}$ of the actor node. Channels are shared between selected sensor nodes participating in event data delivery. Sensor node behavior in a channel c consists of data transmission τ_t , spectrum sensing τ_s and spectrum handoff τ_h periods. We assume each sensor node is assigned to a specific channel for periodic spectrum sensing by the actor node, such that in spectrum sensing intervals τ_s all sensor nodes perform spectrum sensing to detect spectrum holes, i.e., vacant channels. With detection of licensed user, sensor node using that channel performs spectrum handoff and traverses channels provided by actor node to find a spectrum opportunity.

Spectrum handoff duration τ_h includes durations of consecutive channel switching τ_{cs} and spectrum sensing τ_s at the new channel, until a vacant channel is found, i.e., duration between the instant where event reporting stopped due to licensed user detection and the instant when communication is resumed in a vacant channel. To achieve desired distortion level D_o in an estimation interval τ_e , sensors are assigned to channels by the actor node, such that they complete their transmission in spectrum access interval τ_a . Since τ_e includes τ_a as well as delays due to cognitive cycle functionality durations, we have $\tau_e > \tau_a$.

Channels assigned by the actor node, i.e., $c \in \mathcal{C}$, are taken to be homogeneous in terms of licensed user activity and interference. Energy constraints Ω for sensor nodes limit the energy that can be spent for event reporting in an estimation interval. These constraints are taken to be non-equal due to heterogeneous event arrivals in the field and remaining energy of sensor nodes. This energy variation brings limitation to event reporting duration τ_r of sensor nodes, and hence, causes heterogeneities for number of samples reported by each sensor.

7.3 Reliable Distributed Sensing

In this section, we lay out the problem formulation and present initial arguments of our analysis on reliability. We define a so called distortion metric D , which is the mean squared error (MSE) of our estimation of the event signal. We show how reliability depends on spectrum utilization of PUs as well as channel conditions.

Sensor nodes receive the event signal with varying power levels due to certain factors such as their distance from the event, device imperfections and noise. Furthermore, each sensor node has different amount of energy left in their battery. It is also possible that the sensor nodes utilize energy harvesting, in which case, the amount of energy harvested per unit time may vary from sensor to sensor. As a result, the amount of energy that can be consumed during the reporting of events Ω_e , differ among the sensors.

There are also external influences on sensor event data reports such as varying

wireless channel conditions, changes in PU channel utilization patterns, etc. Our aim is to incorporate all of these effects into a single metric that serves as a good indicator for reliability in event estimation.

We assume that the event signal at time t , i.e., $\theta(t)$, is received at sensor node m , with dispersion loss $\gamma(t)$ and added noise $\eta(t)$ as

$$s_m(t) = \gamma_m(t) \cdot \theta(t) + \eta_m(t) \quad (7.1)$$

For estimation of event signal from received samples from sensor nodes, actors use the best linear unbiased estimator (BLUE) [177] for local estimation. This allows us to make no assumptions on sensing noise distribution as long as noise power ξ^2 is known. Therefore, we do not assume any specific distribution for sensed signal and noise. Each sensor sends measured signal $s_m(t)$ to the actor node, where θ is estimated from the received version of $s_m(t)$.

We take both $\theta_m(t)$ and $\eta_m(t)$ are i.i.d. over time. We also assume that $\theta_m(t)$, and $\eta_m(t)$ have zero mean with power σ_θ^2 and ξ_m^2 , respectively. Sensors communicate with actor via opportunistic spectrum access. Actor generates an estimate of the event at the end of each event estimation interval. Under independence over time and space assumption, indices are ignored for all variables. This delay bounded distributed sensing scheme can also be seen as real-time, since it put timeliness constraint on event reports. Received sample vector by the actor at the end of each event estimation interval τ_e , i.e., $\mathbf{r}$, is combination of sensing noise and sensed signal as $\mathbf{r} = \boldsymbol{\gamma} \cdot \boldsymbol{\theta} + \boldsymbol{\eta}$, where $\mathbf{r} = [r_1, \dots, r_{M_s}]^T$, $\boldsymbol{\gamma} = [\gamma_1, \dots, \gamma_{M_s}]^T$, and $\boldsymbol{\eta} = [\eta_1, \dots, \eta_{M_s}]^T$, where M_s is the number of sensor nodes selected by actor node. Estimate of event signal using BLUE is formulated as follows [177]

$$\hat{\theta} = [\boldsymbol{\gamma}^T \mathbf{R}_s^{-1} \boldsymbol{\gamma}]^{-1} \boldsymbol{\gamma}^T \mathbf{R}_s^{-1} \mathbf{r} \quad (7.2)$$

Sample covariance matrix $\mathbf{R}_s$ for received samples at actor is a M_s dimensional rectangular diagonal matrix whose diagonal entries are ξ_m^2 , and other entries are 0. We define a distortion metric $\tilde{D}$, as the the mean square error for BLUE can be

determined as [177]

$$\begin{aligned}\tilde{D} &= E \left[(\hat{\theta} - \theta)^2 \right] = [\boldsymbol{\gamma}^T \mathbf{R}_s^{-1} \boldsymbol{\gamma}]^{-1} \\ &= \sum_{m=1}^{M_s} \left(\frac{\gamma_m^2}{\xi_m^2} \right)^{-1}\end{aligned}\tag{7.3}$$

Taking into account the fact that number of samples provided by each sensor ζ_m , will be different due to various factors such as spectrum handoff and packet errors, we define a corresponding distortion metric D as follows:

$$D = \sum_{m=1}^{M_s} \left(\zeta_m \frac{\gamma_m^2}{\xi_m^2} \right)^{-1}\tag{7.4}$$

Naturally, ζ_m depends on factors such as packet error rate $e_m^{(p)}$, and number of encountered spectrum handoffs. The number of packets that are correctly received by the actor can be expressed as

$$\zeta_m = r_m^{(p)}(1 - e_m^{(p)})\tag{7.5}$$

where, $r_m^{(p)}$ is the amount of packets that node m was able to send within a reporting interval, while avoiding the PU by performing spectrum handoff whenever necessary. In the following section, we analyze the effects of these factors on ζ_m , and consequently on distortion.

7.4 Analysis of Factors that Effect Reliability

In this section, we present an analysis of factors that effect reliability, such as spectrum handoff and packet errors.

7.4.1 Impact of Spectrum Mobility

Incorporation of cognitive radio capability into sensor and actor nodes enables reporting of event data over licensed bands to mitigate crowded spectrum problem. However, intermittent communications due to opportunistic spectrum access and interruptions due to licensed user interference must be addressed. To this end,

actual spectrum access time of sensors, based on spectrum sensing and spectrum handoff functionalities is found.

Here, $r_m^{(p)}$, i.e., the experienced number of packets sent by node m while utilizing licensed spectrum bands opportunistically is obtained. First, we derive the mean data communication duration $E\{\tau_{\text{data}}\}$ before licensed user arrival in channels $\mathcal{C}$ assigned by the actor node. Under exponential inter-arrival and inter-departure durations assumption for PU traffic [171, 172, 173, 174], average data communication duration $E\{\tau_{\text{data}}\}$, i.e., average duration from starting communication in channel $\mathcal{C}$ until a licensed user is detected is found as

$$E\{\tau_{\text{data}}\} = E\{I\}\tau_t \quad (7.6)$$

where $E\{I\}$ is the mean number of $(\tau_s + \tau_t)$ durations before licensed user arrives at a channel in $\mathcal{C}$. To calculate $E\{I\}$, we define the probability of having i intervals without licensed user arrival at the accessed channel as

$$\Pr[I = i] = (P_{\text{hole}})^{i-1}(1 - P_{\text{hole}}) \quad (7.7)$$

where P_{hole} is vacancy probability of a channel in $\mathcal{C}$. Mean of I can be found as

$$E\{I\} = \sum_{i=1}^{\infty} i \cdot \Pr[I = i] = \frac{1}{1 - P_{\text{hole}}}. \quad (7.8)$$

To find the mean of spectrum handoff duration $E\{\tau_h\}$, i.e., the mean of total channel switching and spectrum sensing durations until data transmission can be started in a vacant channel, we define probability of finding a vacant channel via l consecutive handoffs $\Pr[L = l]$ as

$$\Pr[L = l] = P_{\text{hole}}(1 - P_{\text{hole}})^{l-1} \quad (7.9)$$

where we assume licensed user arrivals at different channels of $\mathcal{C}$ are independent from each other.

When a licensed user communication is detected at any of accessed channels sensor nodes accessing that channel traverses channels provided by the actor to find a vacant

channel, where licensed user detected channel corresponds to $c = 0$. Time spent while performing l consecutive handoffs can be found as

$$\tau_h(l) = l \cdot (\tau_{cs} + \tau_s) \quad (7.10)$$

where τ_{cs} is channel switching time when moving between channels. As a result, $E\{\tau_h\}$ can be obtained as

$$\begin{aligned} E\{\tau_h\} &= \sum_{l=1}^{\infty} \tau_h(l) \Pr[L = l] \\ &= \sum_{l=1}^{\infty} l \cdot (\tau_{cs} + \tau_s) P_{\text{hole}} (1 - P_{\text{hole}})^{l-1} \\ &= (\tau_{cs} + \tau_s) \frac{1}{P_{\text{hole}}} \end{aligned} \quad (7.11)$$

To find the number of packets sent by sensor node m , i.e., $r_m^{(p)}$, we use the fact that the total time spent by a node in spectrum sensing, data transmission and spectrum handoff must not exceed the reporting period τ_r . With this restriction, we can find the expected number of handoffs experienced by sensor m , i.e., h_m . We require

$$E\{I\}(\tau_s + \tau_t) + h_m(E\{\tau_h\} + E\{I\}(\tau_s + \tau_t)) \leq \tau_r \quad (7.12)$$

Therefore, we need the maximum value of h_m that satisfies

$$h_m \leq \frac{\tau_r - E\{I\}(\tau_s + \tau_t)}{E\{\tau_h\} + E\{I\}(\tau_s + \tau_t)} \quad (7.13)$$

If we define such h_m as h_m^* ,

$$r_m^{(p)} = \frac{h_m^* E\{\tau_{data}\} \nu_m}{8l_p} \quad (7.14)$$

where l_p is the packet size in bytes and ν_m is the transmission rate in bits/sec. Instantaneous throughput can be defined as $T = r_m^{(p)} / \tau_r$

7.4.2 Packet Error Rate

Each sensor communicates with the actor node over orthogonal channels that experience independent shadowing and zero-mean AWGN. We use the log-normal

channel for received power calculations, which is experimentally shown as the accurate model for low power communication in sensor networks [175]. In this model, the received power at a receiver at distance d from a transmitter is given by

$$P_r(d) = P_t - \text{PL}(d_0) - 10\eta \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma, \quad (7.15)$$

where P_t is the transmit power in dBm, $\text{PL}(d_0)$ is the path loss at the reference distance d_0 in dB, η is the path loss exponent, and X_σ is the shadow fading component with $X_\sigma \sim \mathcal{N}(0, \sigma)$. We denote the communication SNR at the actor with and without licensed user interference as Ψ_w , and Ψ_l , respectively. SNR at the receiver without licensed user interference Ψ_w is given by $\Psi_w = P_r(d) - P_n$ in dB, where P_n is the communication noise power in dBm. On the other hand, signal to interference plus noise ratio (SINR) at the receiver due to licensed user activity is given by $\Psi_l = P_r(d) - P_n - P_l^{(k)}$ in dB, where $P_l^{(k)}$ is the interference caused by licensed user activity at actor node k . To obtain bit error rate P_b to use in analytical derivations, the non-coherent frequency shift keying (FSK) modulation scheme is selected. The bit error rate of this scheme is given by [176]

$$P_b = \frac{1}{2} \exp(-(E_b/N_0)/2), \quad E_b/N_0 = \Psi \frac{B_N}{R} \quad (7.16)$$

where B_N is the noise bandwidth, and R is the data rate. Finally, packet error rate (P_p) for packet length l_p becomes

$$P_p = 1 - (1 - P_b)^{l_p} \quad (7.17)$$

To determine average packet error rate $e_m^{(p)}$ incorporating licensed user interference due to opportunistic spectrum access, we propose an error model based on false-alarm P_f and detection P_d probabilities, and licensed user state transition, i.e., birth β and death α rates. False-alarm, i.e., detection of licensed user communication when licensed user is actually not communicating, probability is represented by P_f and detection probability when licensed user is communicating P_d . Licensed user activity modelled using two state discrete Markov chain model with ON and OFF states [171, 172, 173, 174]. Licensed user being active ($1 - P_{\text{hole}}$) and being inactive P_{hole}

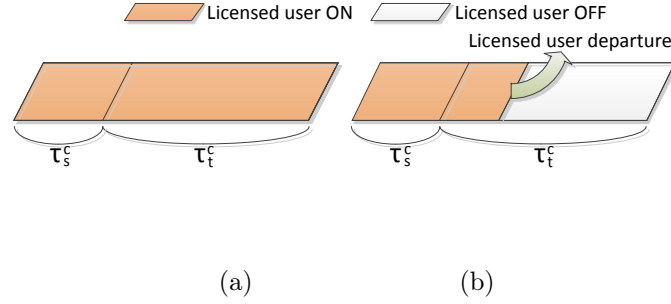


Figure 7.1: Licensed user interference patterns when mis-detection occurs, no state change in (a) and state transition occurs in (b).

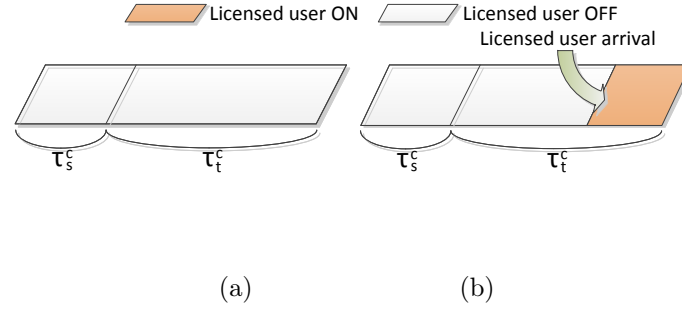


Figure 7.2: Licensed user interference patterns when licensed user is initially OFF while *spectrum sensing*, no state change in (a) and state transition occurs in (b).

probabilities are equal to $\beta/(\beta + \alpha)$ and $\alpha/(\beta + \alpha)$, respectively. Before finding $e_m^{(p)}$, we describe two different cases in which licensed user interference occurs as follows

1. Although licensed user is active, it may not be detected, i.e., mis-detection can occur, with probability $(1 - P_{\text{hole}})(1 - P_d)$. In this case, nodes continue to communicate, though there is ongoing licensed user communication. Hence, they get exposed to licensed user interference, which is illustrated in Figure 7.1.
2. A spectrum band can be identified as vacant and employed by sensor nodes

with probability $P_{\text{hole}}(1 - P_f)$. However, licensed users may start communication during the nodes' transmission period. Thereby, until the next spectrum sensing period, sensor nodes are unaware of the licensed user presence and continue to communicate under licensed user interference, which is illustrated in Figure 7.2.

Licensed user may change its state during τ_t , or it can keep its state along whole τ_t duration. Having τ_t is relatively small with respect to average active and inactive durations of licensed user, e.g., $1/\alpha$ and $1/\beta$, respectively, is a more realistic assumption than having large τ_t that is longer than licensed user transmission duration. Thus, we assume τ_t is smaller than both $1/\alpha$ and $1/\beta$.

Interference due to mis-detection exhibits two different patterns according to τ_t as in Figure 7.1 (a) and (b). It can be through whole τ_t period as in Figure 7.1 (a) or licensed user state may change to inactive from active as in Figure 7.1 (b). The probability that the licensed user is transmitting during the entire τ_t can be obtained as $e^{-\alpha\tau_t}$, and the probability that licensed user goes inactive state from active during τ_t can be found as $1 - e^{-\alpha\tau_t}$. If the licensed user state does not change during the τ_t , the licensed user interference persists over the entire transmission period and in which error rate is P_p^l . However, if state transition between active and inactive states occurs during τ_t , average error rate converges to $(1 - P_{\text{hole}})P_p^l + P_{\text{hole}}P_p^w$. Thus, average packet error rate for the mis-detection case P_p^1 can be expressed as

$$P_p^1 = (1 - P_d) \frac{\beta}{\alpha + \beta} \cdot \left((1 - e^{-\alpha\tau_t}) \frac{\beta P_p^l + \alpha P_p^w}{\alpha + \beta} + e^{-\alpha\tau_t} P_p^l \right) \quad (7.18)$$

Similarly, if licensed user is inactive and there is no false-alarm, interference only happens when licensed user state transition occurs during τ_t , as illustrated in Figure 7.2 (b). Average packet error rate converges to again approximately to $(1 - P_{\text{hole}})P_p^l +$

$P_{\text{hole}}P_p^w$ with probability $1 - e^{-\beta\tau_t}$. Average packet error rate in this case P_p^2 becomes

$$P_p^2 = (1 - P_f) \frac{\alpha}{\alpha + \beta} \cdot \left((1 - e^{-\beta\tau_t}) \frac{\beta P_p^l + \alpha P_p^w}{\alpha + \beta} + e^{-\beta\tau_t} P_p^w \right) \quad (7.19)$$

Then, to find overall packet error rate $e_m^{(p)}$ in opportunistic spectrum access incorporating licensed user interference, we add and normalize P_p^1 and P_p^2 as

$$e_m^{(p)} = \frac{P_p^1 + P_p^2}{\frac{\beta(1-P_d) + \alpha(1-P_f)}{\alpha + \beta}} \quad (7.20)$$

7.4.3 Spectrum Access Duration and Sensor Scheduling Order

The analysis presented in the previous sections provides us with the following expression for distortion metric

$$\begin{aligned} D &= \sum_{m=1}^{M_s} \left(\zeta_m \frac{\gamma_m^2}{\xi_m^2} \right)^{-1} \\ &= \sum_{m=1}^{M_s} \left((1 - e_m^{(p)}) r_m^{(p)} \frac{\gamma_m^2}{\xi_m^2} \right)^{-1} \\ &= \sigma_\theta^2 \sum_{m=1}^{M_s} ((1 - e_m^{(p)}) r_m^{(p)} \Lambda_m)^{-1} \\ &= \frac{\sigma_\theta^2}{8l_p E\{\tau_{\text{data}}\}} \sum_{m=1}^{M_s} (h_m^* \nu_m (1 - e_m^{(p)}) \Lambda_m)^{-1} \end{aligned} \quad (7.21)$$

Minimum number of sensor nodes satisfying distortion constraint can be reached via ordering sensors in the descending sensing SNR (Λ_m) order, i.e., $m = 1$ is the largest SNR sensor node, and using in (7.3) with maximum allowed $\tau_r^{(m)}$ until distortion constraint is satisfied. According to this formulation, instead of using all sensors, only the right group of sensor nodes can be determined and still the distortion threshold D_0 can be achieved.

In this section, we analyze the contribution of data carried at each channel to distortion. The event observation distortion at an actor node is discretized into contribution of each channel D_c , i.e., total distortion is expressed as the addition of

samples belonging to different channels, addressing the reduction in the reported samples over a channel by the spectrum access duration τ_a during estimation interval τ_e . Sensor nodes can move among spectrum holes via spectrum handoff as a licensed user arrives at current accessed channel. However, sensor nodes' communication is interrupted by periodic spectrum sensing as well as spectrum handoff triggered by licensed user arrival. Therefore, effect of opportunistic spectrum availability on event sensing reliability is investigated analytically according to proposed distributed sensing distortion model.

To this end, we define $\mathcal{M}^{(c)}$ as the source sensors of the actor assigned to c th channel for sharing during τ_a . D for proposed distributed sensing scheme can be expressed as

$$D = \left(\sum_c D_c^{-1} \right)^{-1} \quad (7.22)$$

where D_c is the distortion resulted by observations of sensors at channel c . It is dependent on the accessible duration τ_a of a channel assigned by the actor during an estimation interval and required reporting duration of sensors $\tau_r^{(m)}$ sharing the same channel. τ_a s are independent and identically distributed (i.i.d.) random variables with mean μ representing data communication duration in an estimation interval for channels of the actor node. D_c is the distortion achieved when spectrum access duration τ_a in an estimation interval is allowing ω th sensor starting from $m = 1$ to share that channel for event reporting, and it can be expressed as

$$D_c = \left[\sum_{m=1}^{\omega-1} D_m^{-1} + D_{\omega}^{-1} \left(\frac{\tau_a - \sum_{m=1}^{\omega-1} \tau_r^{(m)}}{\tau_r^{(\omega)}} \right) \right]^{-1}, \quad (7.23)$$

for $\sum_{m=1}^{\omega-1} \tau_r^{(m)} \leq \tau_a \leq \sum_{m=1}^{\omega} \tau_r^{(m)}, m \in \mathcal{M}, \omega \in \mathcal{M}$

where ω is the last sensor node that was reporting using the channel c at the instant of licensed user arrival, and D_m is distortion solely depending on samples from sensor

m , which can be obtained using formulation in Section 7.4.3 as

$$\frac{\sigma_\theta^2}{8l_p E\{\tau_{data}\}} (h_m^* \nu_m (1 - e_m^{(p)}) \Lambda_m)^{-1} \quad (7.24)$$

Furthermore, it is deduced that D_c is equal to $(\sum_{m=1}^{|\mathcal{M}^{(c)}|} D_m^{-1})^{-1}$ for $\tau_a \geq \sum_{m=1}^{|\mathcal{M}^{(c)}|} \tau_r^{(m)}$. When $\tau_a \geq \sum_{m=1}^{|\mathcal{M}^{(c)}|} \tau_r^{(m)}$, sensors assigned to channel c are able to find an opportunity to completely transmit their observations to actor during the estimation interval, and desired D_c will be achieved. However, when $\tau_a \leq \mu$, reporting of sensors assigned to a channel are limited by spectrum access duration ($\tau_a \leq \sum_{m=1}^{|\mathcal{M}^{(c)}|} \tau_r^{(m)}$), and contribution to total estimation distortion D_c is calculated using (7.23) via replacing τ_a with its realization. Latest reporting sensor ω at accessed channels can be determined via $\sum_{m=1}^{\omega-1} \tau_r^{(m)} \leq \tau_a \leq \sum_{m=1}^{\omega} \tau_r^{(m)}$, and its unfinished reporting duration can be found as $\tau_a - \sum_{m=1}^{\omega-1} \tau_r^{(m)}$.

Each channel's contribution to distortion of total estimation at actor varies based on sensing SNR Λ_m of assigned sensors to a channel. Therefore, another important issue is the scheduling order of source nodes assigned to same channel. Addressing the interruptions due to opportunistic communication, and hence, random τ_a duration in an estimation interval τ_e , scheduling spectrum access of source nodes with respect to their observation SNR Λ_m in descending order, i.e., highest SNR having node ($m = 1$) accesses first at designated channel, is found favourable.

7.5 Opportunistic Consensus

In this section, based on the previous analysis, we propose a consensus scheme to increase reliability of event estimation. We assume a case where there are multiple actor nodes, each with its own set of sensors. Each sensor-actor group of nodes operate as described in previous sections. However, after actor nodes make a local estimation of the event signal, they communicate their local estimate with other actors to mitigate disagreement and reach a global agreed state. We, first, present an overview of used consensus model, and then, investigate consensus convergence duration with respect

to different algebraic connectivity of actor network for various licensed user arrival β and interference P_l values.

While reaching a consensus is trivial for small scale actor networks, for a large scale actor network computing the global estimate Θ based on local estimates $\hat{\theta}_k$ requires multiple iterations and packet exchanges among actors. Inter-actor communication is subject to licensed user interference. This can either be in the form of licensed user arrival during transmission or mis-detection of licensed user presence during spectrum sensing period. In case of transmission errors, iteration is stopped and this failed step is repeated via automatic repeat request. The exchange of information among actors is performed via a slotted and collision-free medium access control scheme. Consensus convergence time τ_c is determined as the multiplication of number of required iterations Υ to reach consensus and iteration duration τ_i , i.e., $\tau_c = \Upsilon \cdot \tau_i$.

7.5.1 Overview of Consensus Model

We use a cognitive radio actor network composed of K actor nodes. Actor k can communicate with actor l if l is a neighbor of k on a graph $G = (V, E)$, where V denotes the set of vertices, i.e., actor nodes, and $E \subseteq V \times V$ denotes set of the edges between vertices, i.e., links between actor nodes. The *adjacency* matrix $\mathbf{A}$ of the graph G is composed of binary-valued entries $a_{k,l}$ that indicates existence of a link between actor k and l . Value of $a_{k,l}$ is equal to 1 if actor k and l are connected, and $a_{k,l} = 0$ if there is no link between actor k and l . We assume the links E are bidirectional, and hence, the graph G is undirected. Furthermore, $\mathbf{A}$ is a symmetric matrix with 0 diagonal entries, and since $\sum_{k \neq l} a_{k,l} = \sum_{l \neq k} a_{l,k}$, the undirected graph G is called balanced. The *degree* matrix $\mathbf{D}$ of G is a diagonal matrix with entries $d_{k,k} = |\mathcal{N}_k|$ and zero off-diagonal elements, where $|\mathcal{N}_k| = \sum_{k \neq l} a_{k,l}$ is the number of nodes in the neighborhood set $\mathcal{N}_k$ of actor k . Let $\mathbf{L}$ be the *Laplacian* matrix of the graph G , which is defined as $\mathbf{L} := \mathbf{D} - \mathbf{A}$. Entries $l_{k,l}$ of $\mathbf{L}$ are as

$$l_{k,l} = l_{l,k} = \begin{cases} |\mathcal{N}_k| & \text{if } k = l \\ -a_{k,l} & \text{if } k \neq l \end{cases} \quad (7.25)$$

Aim of consensus algorithm is to make each actor node to reach a globally optimal estimate $\hat{\theta}^*$ from a set of measurements, i.e., local estimates $\hat{\theta}_k$ of actor nodes in our system model. This is achieved via communication of local estimates among nearby actors without utilization of a fusion center. By definition of $\mathbf{L}$ sum of all columns or rows is equal to $\mathbf{0}$, which implies that $\mathbf{L}$ has an eigenvalue of 0. Accordingly, associated eigenvector is $\mathbf{1}$ since $\mathbf{L}\mathbf{1} = \mathbf{0}$, or $\mathbf{1}^T\mathbf{L} = \mathbf{0}^T$. Therefore, reached final estimate is of the form $\alpha\mathbf{1}$, and consensus value α is equal to average of local estimates of actors. If G is a connected balanced and undirected graph, a consensus is asymptotically reached with

$$\Theta = \sum_k \hat{\Theta}_k(0)/K \quad (7.26)$$

Since minimization of the difference between states of actors is the aim of consensus algorithm, the *disagreement*, i.e., error, function is defined as

$$J(\hat{\Theta}) = \frac{1}{2} \hat{\Theta}^T \mathbf{L} \hat{\Theta} = \frac{1}{4} \sum_{k=1}^K \sum_{l=1}^L a_{k,l} (\hat{\Theta}_k - \hat{\Theta}_l)^2 \quad (7.27)$$

Using steepest descent technique the minimum of $J(\Theta)$ can be achieved in discrete time as

$$\hat{\Theta}_k(t+1) = \hat{\Theta}_k(t) + \vartheta \sum_{l \in \mathcal{N}_k} a_{k,l} (\hat{\Theta}_k(t) - \hat{\Theta}_l(t)) \quad (7.28)$$

where ϑ is the step-size. In matrix form, dynamics of the actor network can be expressed as

$$\hat{\Theta}(t+1) = \mathbf{P} \hat{\Theta}(t) \quad (7.29)$$

where $\mathbf{I}$ is the identity matrix, and $\mathbf{P} = \mathbf{I} - \vartheta \mathbf{L}$. Value of ϑ is selected appropriately to ensure all eigenvalues of $\mathbf{P}$ are less than 1. The consensus algorithm is initialized with local estimates of actor nodes, i.e., $\hat{\Theta}_k(0) = \hat{\theta}_k$.

In the next section, the described inter-actor distributed estimation framework is used for assessing consensus convergence duration under opportunistic spectrum access.

7.5.2 Algebraic Connectivity and Consensus Convergence

While the performance of consensus algorithm is characterized by its convergence rate, i.e., time elapsed to reach consensus, convergence speed is lower bounded by the lowest non-zero eigenvalue of $\mathbf{P}$, i.e., λ_2 , which is also called *algebraic connectivity* of the graph. Consensus is reached exponentially in discrete-time for connected graphs [156] such that

$$\frac{\|\hat{\Theta}(t) - \Theta\|}{\|\hat{\Theta}(0) - \Theta\|} \leq O(e^{-(1-\vartheta\lambda_2(\mathbf{L}))\tau_c}) \quad (7.30)$$

We state the reaching consensus condition as $\frac{\|\theta(t) - \theta^*\|}{\|\theta(0) - \theta^*\|} \leq \varepsilon$. Therefore, the time elapses until convergence τ_c can be defined as the time needed to smallest eigenvalue of the dynamical system can be reduced by a factor $\varepsilon \ll 1$. A step of iteration fails if licensed user arrives or in case of mis-detection during communication of local estimate. Then, a new vacant channel is moved and failed step is repeated there. Failed step is detected after the end of iteration, hence, iteration is re-started. Instead of trying to know when exactly pu arrived during iteration. To mitigate disagreement for a unit amount $1/(1 - P_p) \cdot 1/(1 - \vartheta\lambda_2(\mathbf{L}))$ iterations are needed, and hence, τ_c is found as

$$\tau_c = \frac{1}{1 - P_p} \frac{\log(\varepsilon)}{1 - \vartheta\lambda_2(\mathbf{L})} E\{\tau_i\} \quad (7.31)$$

where τ_i is the time required for a single iteration, i.e., duration in which all actor nodes communicate their local state once with their neighbor actors. We elaborate calculation of mean of τ_i in the following.

7.5.3 Estimation Interval Partitioning For Consensus

Estimation interval must be partitioned adaptively addressing varying spectrum parameters with spectrum mobility. Objective of our scheme is to provide sufficient duration for communication of local states among actor nodes after completion of local estimation. We first describe MAC for inter-actor communication and

formulate mean iteration duration $E\{i\}$. Then, estimation interval partitioning is introduced.

Actor nodes employ a ρ -persistent carrier sense multiple access (CSMA) mechanism for MAC such that they access channel during slot intervals with a probability of ρ if channel is no other actor node is sensed to be transmitting. Expected number of actor nodes that will transmit when channel becomes idle is given by $|\mathcal{N}_k|\rho$. If $|\mathcal{N}_k|\rho > 1$, then a collision is expected to occur. To prevent collisions and resultant retransmissions, ρ should be chosen accordingly, i.e., $\rho < 1/|\mathcal{N}_k|$. For this scheme, successful transmission probability of actor node k can be found as

$$\varsigma_k = \rho(1 - \rho)^{|\mathcal{N}_k|-1} \quad (7.32)$$

Using ς_k , mean number of channel access trials φ_k before gaining access to channel is found as

$$E\{\varphi_k\} = \sum_{l=0}^{\infty} l\varsigma_k(1 - \varsigma_k)^{l-1} \quad (7.33)$$

Finally, mean duration of an iteration can be found as

$$E\{\tau_i\} = \sum_{k=1}^K \tau_{\text{slot}} E\{\varphi_k\} \quad (7.34)$$

where τ_{slot} is the channel access duration of an actor node while broadcasting its local state to neighbor actors. Found $E\{\tau_i\}$ is incorporated into (7.31), to find τ_c .

Spectrum access duration for sensor nodes is reduced to allow convergence of consensus algorithm. To this end, although, higher available spectrum access τ_a duration is possible, τ_a is reduced at the expense of increased number of required channels during local estimation. Reduced spectrum access duration τ_a^* is determined as

$$\tau_a^* = \min_k \{\mu_k\} - \tau_c \quad (7.35)$$

where $\tau_a^* \geq \max_m \tau_r^{(m)}$. Using developed scheme, α and β values are found, and T_k values are determined and updated according to spectrum opportunities. We now provide performance assessment of our scheme.

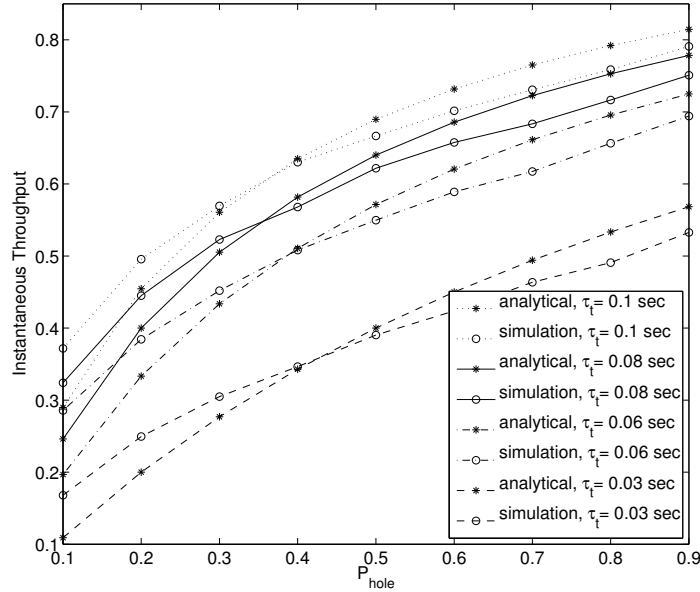


Figure 7.3: Comparison of calculated and achieved instantaneous throughput due to opportunistic spectrum access for $\tau_t = 0.1, \tau_t = 0.08, \tau_t = 0.06, \tau_t = 0.03$ sec.

7.6 Performance Evaluation

In this section, we provide simulation results related to the provided analysis and the proposed consensus scheme.

7.6.1 Instantaneous Throughput

Performance of proposed instantaneous throughput determination model is shown in Figure 7.3. Analytically calculated instantaneous throughput is shown to be closely following achieved one in simulations. τ_s and τ_{cs} is set to 0.02 and 0.005 sec, respectively. P_{hole} is varied from 0.1 to 0.9. Calculated instantaneous throughputs for $\tau_t = 0.1, 0.08, 0.06$, and 0.03 sec overshoot the achieved ones after a critical value of P_{hole} , e.g., after $P_{\text{hole}} = 0.3$ calculated instantaneous throughput exceeds the achieved one for $\tau_t = 0.08$ sec., and similar relationship between simulated and

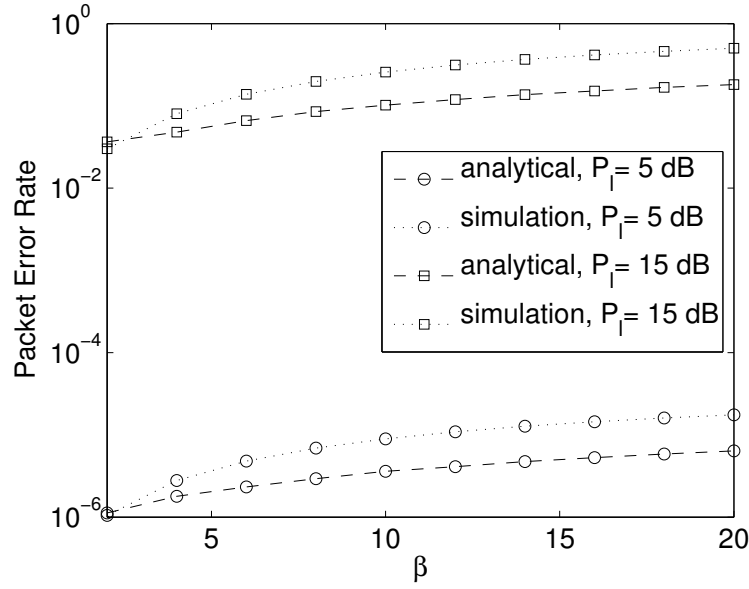


Figure 7.4: Comparison of analytically calculated packet error rate and simulation results with respect to licensed user arrival rate β for SNR values under licensed user interference of $P_l = 5$ and 15 dB.

analytic results is observed for other τ_t values, as well. Therefore, in our design of consensus algorithm, we introduce safety factor κ to reduce calculated throughput by a little amount to compensate for possible overshoots.

We use developed framework to evaluate instantaneous throughput T_k for channels $\mathcal{C}_k$ of actor node k due to opportunistic spectrum access and calculate the mean of the spectrum access duration μ_k in an event estimation interval for sensor nodes connected to actor node k , i.e., $m \in \mathcal{M}_k$, as $\mu_k = T_k \tau_e$.

7.6.2 Error Rate

Performance of proposed analytical packet error rate calculation scheme is presented in Figure 7.4. For received power calculations, transmission power P_t is set to -5 dBm, noise power P_n is set to -90 dBm, path loss exponent η is set to 3, shadowing standard deviance σ is set to 3.8, distance is taken to be 5 m, reference distance d_0 is taken to

be 1 m, reference path loss $PL(d_0)$ is taken as -40 dB, and B_N/R ratio is taken to be unity. Value of τ_t is taken to be 0.05 sec, P_d is equal to 0.9, P_f is equal to 0.1, and α is equal to 10. Simulations are repeated 1000 times and results are averaged. It is shown in Figure 7.4, the analytic formulation follows the simulation values closely. While packet error rate is in the order of 10^{-5} when the licensed user interference P_l is 5 dB, packet error rate becomes in the order of 10^{-2} when P_l increases to 15 dB.

7.6.3 Consensus Convergence Duration

Numerical results are provided to elaborate the consensus convergence duration with respect to algebraic connectivity $\lambda_2(\mathbf{L})$ and available spectrum opportunity in terms of licensed user interference and channels errors. The prolongation of consensus convergence duration with respect to various algebraic connectivity of actor graph G , i.e., from 1 to 20, is discussed. Value of ε is set to -40 dB. Value of $E\{\tau_i\}$ is set to 0.05 sec. To investigate effect of spectrum mobility, effect of licensed user interference P_l is assessed for 5 and 10 dB, and effect of birth rate of licensed user β is assessed for 10 and 20.

For consensus convergence duration τ_c , it has been shown in Figure 7.5 that as the algebraic connectivity λ_2 increases, effect of spectrum mobility, i.e., P_l and β , decreases. Effect of increasing λ_2 becomes marginal after a certain point, e.g., τ_c reduces to its half value when λ_2 increases from 1 to 2, however, when λ_2 is increased from 9 to 10, this increase does not imply any significant reduction of τ_c . For $P_l = 5$ dB, τ_c follows the same pattern for $\beta = 10$ and 20. It is deduced that for low licensed user interference, β value does not effect the τ_c . However, for $P_l = 10$ dB, experienced τ_c increases with β . Sufficient time opportunity to reach consensus among actor nodes should be provided to reach consensus before end of the estimation interval. Therefore, we incorporate analytically formulated consensus duration to limit spectrum access duration for local estimation of actors, i.e., τ_a .

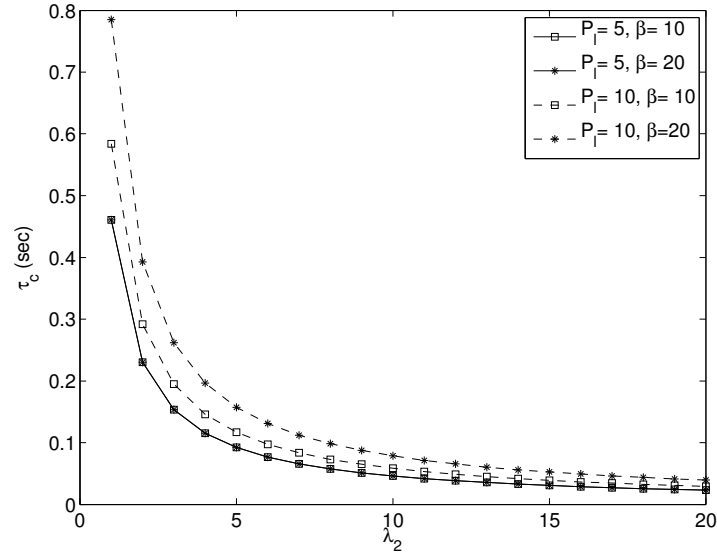


Figure 7.5: Consensus duration with respect to algebraic connectivity for various P_l and β values.

7.6.4 Adaptive Spectrum Sharing for Consensus

In this section, we present simulation results on the performance of proposed sensing framework. In Figure 7.6, consensus reaching performance is presented with respect to algebraic connectivity for different T_k values. P_l is set to 15 dB. It is shown that for different λ_2 values, consensus is reached irrespective of algebraic connectivity. Our scheme achieves higher consensus reaching rate performance with high instantaneous throughput values, i.e., consensus reaching rate decreases with decreasing $\min\{T_k\} =$ from 0.6 to 0.2. Reducing spectrum access duration of sensor nodes in local estimation, provides this performance gain in channels having high licensed user activity spectrum bands. Proposed estimation interval partitioning scheme strictly reduces spectrum access interval in accordance with sparse spectrum availability and high licensed user interference. Reduction of local estimation duration is benefited in high licensed user interference scenarios, and for low instantaneous throughput case, higher duration for

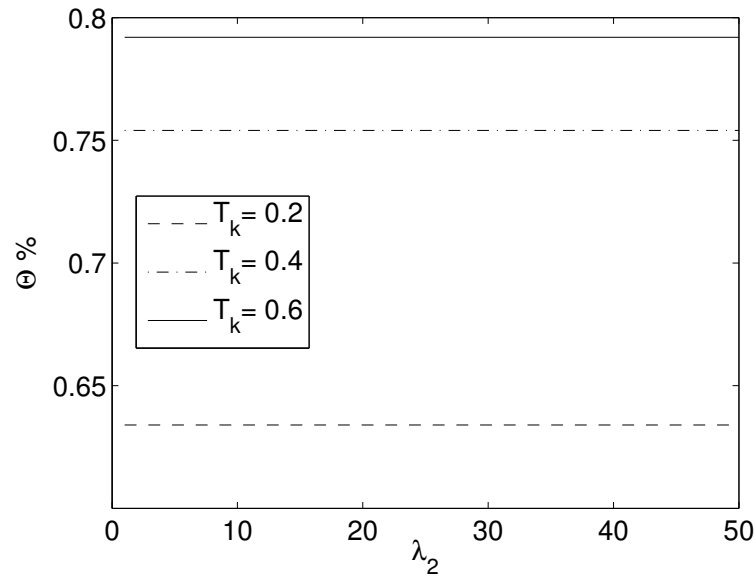


Figure 7.6: Consensus reaching rate of actor nodes.

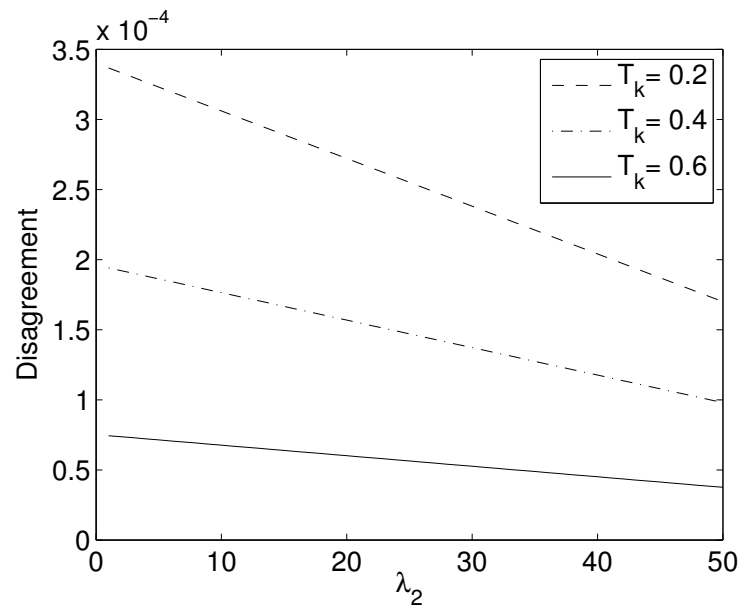


Figure 7.7: Consensus disagreement of actor nodes.

consensus convergence is left.

In Figure 7.7, disagreement among actors at the end of estimation interval is presented. With increasing algebraic connectivity λ_2 , left duration for consensus decreases. Therefore, higher number of incomplete consensus phases yields higher disagreement than desired disagreement ε , which is set to 10^{-4} . Since the predicted τ_c decreases with increased λ_2 , spectrum access interval for local estimation increases, as well. Due to randomness in licensed user activity, this reduction in τ_c results in increase of disagreement among actor nodes. However, as it is shown in Figure 7.7, disagreement is still very close to and in the order of the objective value.

Chapter 8

ADAPTIVE AND COGNITIVE COMMUNICATION ARCHITECTURE FOR NEXT-GENERATION PPDR SYSTEMS

When responding to emergency situations, the quality and sustainability of the communication have great impact on the performance of the first responders. Recent natural catastrophes (e.g. Hurricane Katrina) and terrorist activities (e.g. London metro bombings) revealed that even the most recent TETRA/TETRAPOL systems have inadequacies.

The current PPDR networks provide feature-rich voice centric services but they offer a very limited range of data services for imaging, video, and data files. Recently, Tetra Release 2, Tetra Enhanced Data Services (TEDS) was introduced. Though some efforts have been devoted to upgrade the existing standards with wideband data capabilities, the development towards an enhanced mobile broadband solution for public safety lags far behind the commercial mobile broadband wireless networks [178]. Moreover, today's immediate missing requirement is interoperability, not only between different services, but also within the same service if different systems are in operation between regions [179]. Furthermore, TETRA/TETRAPOL networks have a cell-based central structure and failure in a base station leads to large coverage loss and possibly network partitioning.

To address these inadequacies there has been an increasing amount of work in the literature on network resilience and PPDR networks. Our aim in this chapter is two-fold. We first, classify and examine the previous work in the literature, discussing open research venues for each sub topic. Then we focus on research related to data retrieval during and after an emergency and introduce a novel,

multi-tier, cognitive communication architecture for adaptive and sustainable wireless communication required in PPDR operations.

So far, the existing works on communication in PPDR systems have only partially addressed the problem of providing uninterrupted/sustainable communication. Some propose a dedicated network for public safety operation such as TETRA/TETRAPOL, while others rely on the existing commercial networks [180]. Although some cognitive radio (CR) architectures [181] are also proposed to countermeasure the failure of the existing networks, all these efforts are made in a non-collaborative manner and there is a need to intelligently integrate them and address different issues in a focused way.

8.1 Previous Work on PPDR networks

One of the greatest problems in current networks is the lack of resilience. The research on network resilience can broadly be divided into two as research aiming pre and post emergency.

8.1.1 Research on Pre-disaster Improvements

Most of the research in the literature on network resilience and specifically on PPDR networks may be included among improvements that can be made before the emergency. These mainly include

- resilience analysis
- resilient network design
 - resilient backhaul network design
 - resilient access network design
- developing resilient network layers, or modifying existing network layers to introduce resilience

Resilience Analysis

Resilience analysis research includes finding meaningful metrics to analyze networks in terms of failure types, and developing algorithms that can generate resilient network topologies. Moreover, conventional performance metrics are not suitable for mission-critical networks [182]. With these metrics, high probability events dominate their effect on the performance measures. However, in mission-critical networks, certain events with rare occurrences may have dramatic importance. For example, if link sustainability is taken as an important metric, resulting design may prioritize finding channels that retain desirable conditions. However, in case of a terrorist attack, an adaptive jammer that looks for good channels to jam may render these solutions highly ineffective.

European Network and Information Security Agency (ENISA) issued a report on resilience metrics [183]. The report does not propose new metrics but rather, lays out an overview of previous work on the subject. It is pointed out that measuring the effectiveness of current resilience policies is challenging, and the discipline is still in its early stages.

No consensus is developed on the identification of metrics and standards for measuring resilience. United Nations Development Programme (UNDP) has recently conducted a survey over the resilience measures taken across the world [184]. The report indicates that resilience has various elements (e.g. well-being, vulnerability, etc.), levels (e.g. inputs, impacts, etc.), dimensions (e.g. technical, economical, etc.). Furthermore, measurements may be tailored to context (e.g. Country Disaster Resilience Index for coastal communities). The conclusion of the report is that the resilience metrics and measurements should cover as many of these elements, dimensions, etc. as possible.

Resilient Network Design

Resilient network design research has mostly been on backhaul networks. Standards such as IEEE 802.17 on 1 (RPR) address resilience directly. Amendments to

existing standards, such as IEEE 802.3ah (Ethernet Passive Optical Networks) and recommendations, such as ITU-T G.984 (gigabit passive optical networks) help in developing backhaul networks that remain operational in case of power shortages. These approaches take advantage of ability to function without electrically powered switching components.

Research on this front mostly focuses on ring or mesh topologies that introduce redundancy to obtain fault tolerance [185]. New approaches that use recently emerging network types are needed. For example, vehicle to roadside (V2R) communication is a recent hot topic. In case of backhaul network failures, these networks may be utilized. However, they are generally designed in a linear fashion and lack redundancy, thus, fault tolerance. Also, handover algorithms for V2R are straightforward due to the simple structure of the network structure. Introducing resilience to such recently developing networks either in form of network design (e.g. mesh V2R networks) or algorithm design (e.g. resilient handover algorithms) to exploit them in case of an emergency scenario is an open research area.

Software Defined Networking (SDN) is a new paradigm that simplifies network management by decoupling the decision making system on traffic forwarding (control plane) from the actual underlying system that does the forwarding (data plane). Due to this abstraction, SDN provides a very convenient means for traffic management in case of a disaster [186]. There is minimal amount of work in the literature on using SDN to design disaster resilient backhaul networks. Algorithms that can rapidly adapt to new conditions in case of component failures and configuration changes, which may occur frequently after a disaster, are needed. Analysis and efficient methods that consider mapping of virtual resources to physical components are also among the open research issues.

When a disaster strikes, wired backhaul networks may fail due to wire cuts. Wireless backhaul networks provide a promising alternative. Generally, directional antennas are used in wireless backhaul networks to meet the high performance required. Since the number of directional antennas per unit is limited, node degree

is limited. However, to increase resilience and introduce fault tolerance, high node degree is desired. New research efforts that address the trade-off between node degree, network performance and cost are needed. Another open issue is designing resilient wireless backhaul networks based on the results of these trade-off analyses.

Compared to the research on resilience of backhaul networks, the effort on designing resilient access networks is limited. Access networks may provide invaluable data for first responder units after the disaster. Consider an example case where an operational wireless access point (AP) in a collapsed building can communicate with a wearable health monitoring device in the wireless personal area network (WPAN) of a patient. By accessing the AP, first responder units may gather vital data for their rescue operations.

There are many open research venues on this topic. To name a few, methods that make use of PLC are needed. Recently, PLC is being considered as a part of home digital networks [187]. With proper design, a PLC network with components that have backup batteries, may still be partly operational after a disaster, even in case of occasional power line cuts. Another important alternative is designing resilient femto/picocell HANs. Resilient network designs that make use of these new and emerging access networks are needed

Resilient Network Layers

Algorithms that are developed for various network levels, such as routing algorithms, congestion control algorithms, and network coding algorithms must be reconsidered to increase traffic flow resilience in case of component failures. Most of the research on this topic is on developing countermeasures for malicious attacks [188]. However, outages due to disaster cases are different. There is limited amount of work in the literature such as [189], where a cognitive routing protocol that takes QoS into account is proposed. OSA provided by CR may prove to be of great value for establishing communications in case of a disaster. Research on this front is very limited. Routing algorithms that consider spectrum availability, sensing algorithms that can search,

identify and communicate with operational access network devices, algorithms that consider directional transmission with spectrum availability are some of the open research areas on this topic.

8.1.2 Research on Post-disaster Improvements

Research on work that must be performed after the disaster mainly consist of means of data retrieval from the emergency area and forwarding this data to first responder units and their command and control centers. These can be broadly categorized as

- through-the-wall inspection
- operational device identification
- resilient data fusion and routing

Through-the-wall Detection

Firefighters and first responders use through-the-wall detection technologies to locate people in collapsed or burning buildings. The most dominant research area is ultra wide band (UWB) [190]. However, since UWB uses a very large bandwidth, its impact on wireless communication in the event area must be analysed. It was reported that even though interference from a single UWB device has negligible effect on narrowband (NB) devices, if the NB receiver is closer to the UWB transmitter than to the NB transmitter, this may cause very low Signal to Interference Ratio (SIR) and cause performance degradation in the NB link [191].

Operational Device Identification

Another important issue is to identify operational devices inside the event area. These devices can provide invaluable information to first responder units. They may be under collapsed concrete or in distant locations that first responders cannot move into due to the nature of the disaster (e.g. radiation, fire, etc.). To increase the chance

of identifying and communicating with operational access network devices intelligent means of using directional antennas and fast sensing algorithms that can scan the spectrum bands of these devices are essential. There has been some work on direction of arrival (DoA) estimation to increase the performance of directional antennas [192]. However, algorithms that coordinate scanning of bands in conjunction with DoA to discover operational devices are needed, considering that these operational devices may use a variety of access technologies (IEEE 802.15, GSM, 3G, etc.).

Radiation pattern of directional antennas differ with frequency. Methods that use CR capabilities with directional wireless communication can increase performance. These methods should also consider fading since fading varies with the communicating frequency. Therefore, more resilient and efficient communication may be possible with novel algorithms that take into account all of the aforementioned factors

Resilient Data Fusion and Routing

When the operational wireless devices are found using the means mentioned above, algorithms to retrieve data efficiently and rapidly is essential. Cognitive Radio Sensor Networks are a relatively recent paradigm [1], which can be very useful in a PPDR network architecture. A Cognitive Radio Network can also be used to restore functionality to partially destroyed networks by providing connectivity through alternative bands as proposed in [193]. Such novel resilient data delivery and data aggregation algorithms, restorative routing algorithms that consider spectrum availability must be developed.

We present a summary of the open research issues in Table 8.1, for each research area. One of the overlooked capabilities in PPDR architecture is the capability to extract data from the event area, either from still functional devices in the area or from devices deployed by the first responder units, after the event. In the following section, we present a new adaptive and cognitive PPDR architecture that has the features and structure to cover this shortcoming.

Table 8.1: Categorization of studies on PPDR

Category	Research Area	Open Issue
Pre-Disaster Improvements	Resilience	Metrics suitable for mission critical networks
	Analysis	Resilience analysis for mission-critical networks
	Resilient Network Design	Resilient network architectures for both backhaul and access,networks
		Introducing resilience to emerging network (E.g. V2R, HAN)
		Resilient traffic forwarding algorithms (SDN)
		Resilient network & source coding
		Resilience when mapping virtual resources to physical components
		Resilient network structures for wireless backhaul networks
	Resilient Network Layers	Spectrum-awareness and OSA capability for existing devices
		Modifications to network layers for traffic flow resilience
Post-Disaster Improvements	Through-the-Wall Inspection	UWB for through-the-wall vision
		Inspection of interference of UWB on NB devices
	Operational Device ID	Detection algorithms for operational wireless devices in event,areas
	Resilient Data Fusion and,Routing	Combined use of directional antennas and OSA
		Resilient data fusion
		Spectrum as an additional dimension in routing via OSA

8.2 Adaptive and Cognitive Communication Architecture for PPDR

Post-disaster improvements have attracted less interest from the research community, compared to pre-disaster improvements. The limited existing effort is generally focused on one aspect such as the ICT infrastructure for PPDR vehicles and satellite communication. In this section, we lay out a broader proposal for a new PPDR network architecture that aims gathering data from the event area in case of an emergency and forwards this crucial information to command units. First, we list the challenges that must be overcome by such architecture.

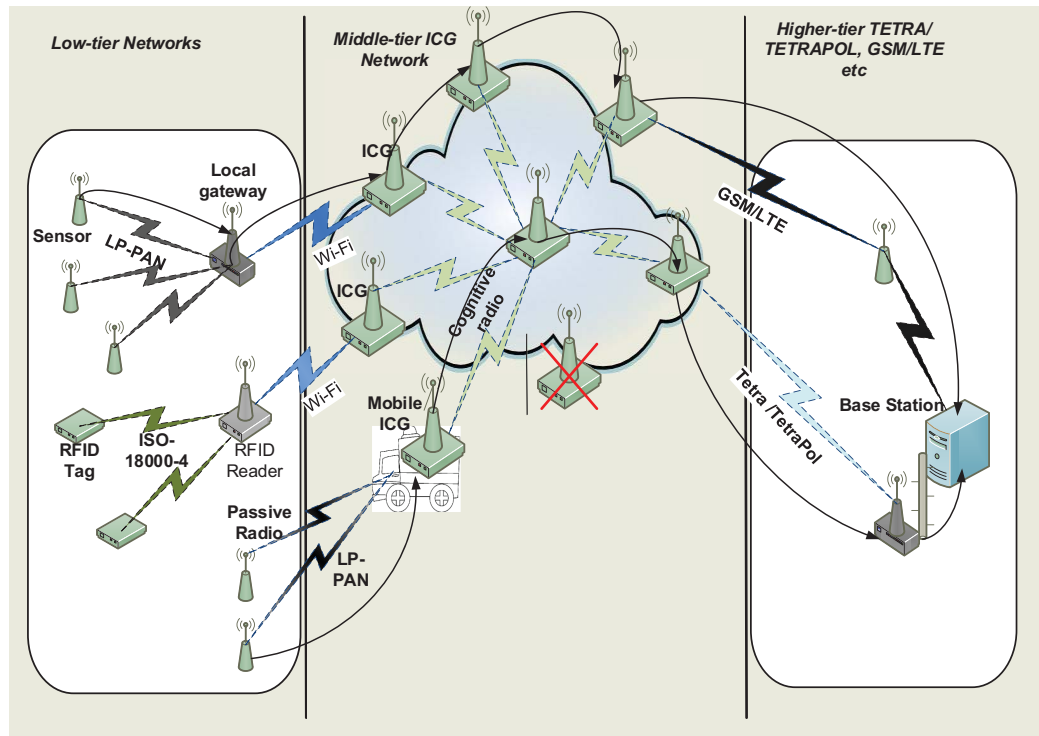


Figure 8.1: Proposed architecture for future PPDR Infrastructure

8.2.1 Challenges

Challenges for a cognitive network tailored for PPDR can be listed as follows:

- **Spectrum Usage:** The fundamental challenge in PPDR systems is to specify the part of spectrum for exclusive use of PPDR communication. However, with new applications such as real-time video from drones, and through-the-wall imaging, the demand for bandwidth in future first responder networks will be exceptionally high and exclusive access to the spectrum may not be sufficient, since only a limited amount of bandwidth can be spared for any one service
- **Interoperability:** In disaster scenarios, various national and international organizations perform rescue operations to cover the large incident region. This requires interoperability of the devices and equipment.
- **Self-organization:** In order to help emergency personnel to concentrate on the tasks, incident area network should be deployed quickly, with little human maintenance. Therefore, devices must be capable of self-organizing into a network.
- **Reliability:** Reliability is required for data to be consistently and continuously transported to the central command station or the data collection points. Also, first responders' connections amongst themselves and the command center should be reliable.
- **Scalability:** It refers to the ability of a system to support large number of parameters without impacting the performance. These parameters include number of nodes, traffic load and mobility aspects. Limited processing and storage capacities of the radio devices are also a concern.

8.2.2 Proposed Network Architecture

We propose a novel multi-tier cognitive communication architecture that can overcome these challenges. The required resilience and adaptation are provided with the concept of Intelligent Cognitive Gateways (ICGs). An ICG is a gateway with multiple interfaces to interact with both various low level devices such as sensor

nodes, RFID readers, Wi-Fi routers, etc., and high level devices such as commercial and backbone network devices. ICGs provide means for OSA through their cognitive radio interface. They can be manufactured in various forms such as mobile ICGs, and ICG with the capability of passive communications. The details of the three-tiered architecture as shown in Figure 8.1 are as follows.

Low Tier Application Network

Low tier consists of WSN nodes composed of any kind of sensing devices, remote health monitoring, telemetry and voice phones. The low tier elements are usually low power devices with short range communication capabilities.

The potential applications commonly realized in PPDR system deploy a variety of lower-tier devices used for day-to-day operations, as well as on-scene mobile devices. For example, a remote healthcare monitoring application can deploy ECG, asthma (Nanotube Asthma Sensor), swine flu, and diabetes sensors (Glucose sensor etc.) at low tier. Several of these low tier elements are organized in one unit and can form network nucleus interfacing to middle tier by one gateway/port only.

An example of the network nucleus could be the RFID reader fetching information from large number of tags. Thus, low tier network is analogous to the WSN that builds ad hoc auto configuring architecture based on short-range transmission network. Data collected by these devices are sent to a nearby ICG directly or via multi-hop routing through neighboring nodes. Therefore, ICG integrates the most widely used low power wireless interfaces such as IEEE 802.15.4. Additionally, battery-less devices may also be used. These devices do not communicate actively. They have a passive radio interface which can modulate reflected waves. This enables the capability for mobile ICGs to move into the event area and fetch information from these passive sensing devices by sending radio waves to them.

Middle Tier Application Network

ICGs form the middle-tier of the architecture and enhance the existing PPDR infrastructure. They provide close-in connectivity to lower-tier devices in order to access backhaul network. These ICG nodes are not only deployed for day-to-day routine operations of the evolving PPDR applications, but also allow self-configured ad hoc extension to the infrastructure in incident areas. ICGs are equipped with intelligent cognitive radio capability that can tune into any of the communication bands of the lower tier devices, recognize and authenticate nodes and provide communication interface to/from application networks. Each ICG forms a cluster with its lower tier surrounding devices.

Established standards for CR, such as IEEE 802.22 and IEEE 802.11af have certain problems when used in a first responder network. 802.22 is a centralized approach that relies on a base station. Basing the whole architecture on a BS that may not be operational is a problem. On the other hand, 802.11af requires connection to a geolocation database (GDB) to query available bands. Such connection may not be available in an event area. However, first responders may keep copies of these databases and bring them along to be used in the emergency area. Therefore, IEEE 802.11af is better suited for our architecture.

High Tier Application Network

The third tier is formed by the existing radio networks used for surveillance or monitoring such as TETRA and TETRAPOL or commercial GSM/LTE network, satellite network, or even Wi-Fi hot spots as shown in Figure 8.1. For backhaul access, ICGs forward data through other ICGs until a contact with one of these backhaul networks can be established and then exploit these existing infrastructure.

The deployment of ICGs mainly includes the establishment of static ICG sites to provide the coverage in all the possible regions where the PPDR organizations potentially operate.

According to the capacity requirements, the deployment also ensures that the

ICG network has sufficient connectivity with the backhaul networks connecting to PPDR remote stations. Moreover, the self-configuration property of the communication protocols developed for ICG network allow the mobile ICGs to join the network spontaneously to overcome the possible failures of existing nodes or extending the coverage area within no time. Thus, the ICG network aims to enhance the existing infrastructure of public (TETRA), commercial (LTE), and satellite networks. Moreover, ICGs also facilitate PPDR applications by supporting multiple fixed spectrum interfaces in addition to OSA for ubiquitous communication. Furthermore, the ability to self-configure and adaptively change communication parameters provides robustness and sustainability, which is much needed in disaster relief scenarios.

8.2.3 PPDR Communication Framework

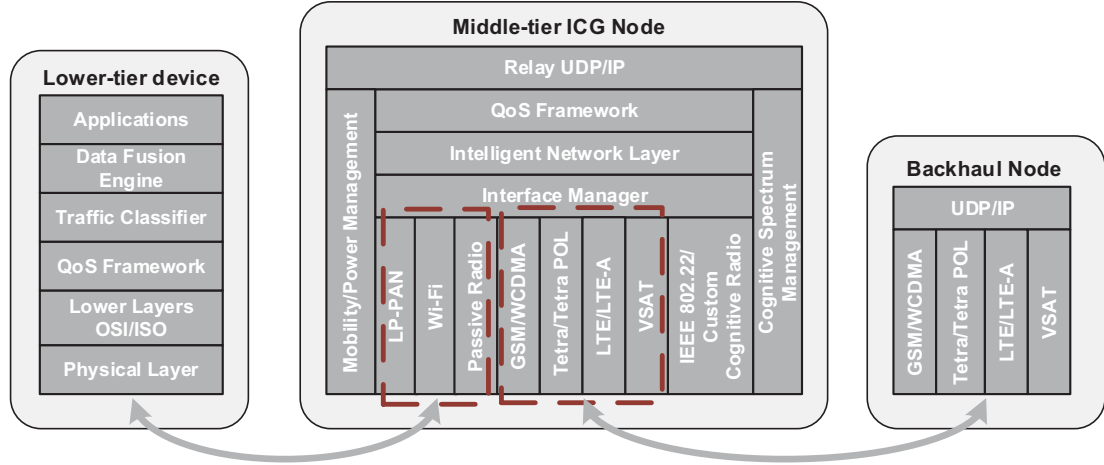


Figure 8.2: Communication protocol stack of the architecture

Figure 8.2 demonstrates the system level approach for designing communication protocols at different tiers of the proposed PPDR architecture. Data from different applications running on PPDR network is classified using traffic classifier layer according to the priority of the application or a particular scenario to achieve minimum time of delivery of event from the network layer, where event has been

detected to decision point. Early warning system is based on micro-fusion of data supplied by local sensing element and traffic classifier output. A QoS framework based on the communication requirements of PPDR data maps the classified traffic to different traffic queues for transmission and ensures that the required QoS is provided to each traffic class.

Network layer and other lower layers of ISO/OSI provide addressing mechanism, error correction, and link layer functionality, and are responsible to route data to a base-station using appropriate ICGs. SDN can be used here. However, SDN has centralized approach [194], whereas ICG network has ad-hoc structure. Moreover, such centralized approaches have single point of failure problem. Therefore, SDN is more suitable for a higher layer, and may especially prove valuable for interoperability, by controlling and coordinating the flows of different first responder units.

Middle tier forming PPDR infrastructure is built by the deployment of a number of ICGs in pre-disaster arrangement as well as the on-scene deployment of ICGs. These ICGs implement self-configuration protocol to enable flexible and resilient PPDR architecture. They also implement ad hoc routing protocol to dynamically determine the route according to the availability of the infrastructure. Essentially they are relay nodes, which forward application data from lower tier to application base-station. Since the proposed architecture is an enhancement to the existing PPDR infrastructure, it integrates existing commercial and public wireless network into our architecture by adding an interface to ICG. Therefore, it enables to exploit the pre-installed communication infrastructure using UDP or TCP/IP protocol for accessing the application base-station. While communication between the ICGs is performed over cognitive radio interface, this makes the ICG middle tier network spectrum efficient and resilient. Its functions are divided into the following layers:

- Relay layer acts as a relay and builds the data to an IP packet for transmission to higher tier
- QoS framework implements the services that include mapping the lower tier

QoS functions to higher tier QoS functions, prioritizing interfaces, etc.

- Intelligent Network layer performs the task of finding route and appropriate interface to send data to base station. This may involve coordination with other ICGs.
- Interface manager maintains and monitors the status of each interface and acts as a single access point to higher layer. It also shields all the underlying interfaces' complexity to simplify the design of higher layers

8.3 Comparison of Architectures

In this section, we aim to present a comparison of the proposed architecture with other PPDR architectures in the literature. We investigate six criteria that we believe is important for future PPDR networks.

1. Interoperability indicates that the architecture supports multiple network interfaces of various first responder units.
2. Expansion is the ability to increase coverage on demand.
3. Anti-jamming is required for terrorist attacks.
4. Recovery is the capability to cover for failed units in the architecture.
5. Deployment indicates whether the architecture is infrastructure-based or ad-hoc.
6. Broadband capability is the finally criterion we are interested in

We present comparison of our architecture with four other architectures, the TETRA Enhanced Data Services (TEDS), LTE-based solution proposed in [178], Satellite-based architecture in [180] and cognitive radio capable solution in [181].

Table 8.2: Comparison of existing work with our architecture

	Our Architecture	TEDS	LTE-based	Satellite based [180]	CR based [181]
Interoperability	Yes (multi-interface)	No (only TETRA R2)	Only LTE devices	Wi-Fi & Satellite Bands	No
Expansion	Yes (due to mobile ad hoc ICG nodes)	Limited	Not possible	Yes	Yes
Anti-jamming	Cognitive spectrum provides more resilience against jamming or attack	Fixed spectrum, Jammed bands cannot be restored	Fixed spectrum, Jammed bands cannot be restored	Fixed spectrum, Jammed bands cannot be restored	Yes
Recovery	Easy recovery in disaster (multi-hop and mesh connectivity)	Might be unavailable in disaster	Might be unavailable in disaster	Limited (no multi-hop)	Might be unavailable in disaster
Deployment	Infrastructure /Adhoc	Infrastructure	Infrastructure	Infrastructure /Ad hoc	Infrastructure /Ad hoc
Broadband	Yes	Wideband (upto 450kbps)	Yes	Yes	No (Only voice)

As summarized by Table 8.2, our solution covers the widest range of features. The new TETRA network architecture has problems mainly due to its strict infrastructure based architecture. It lacks important capabilities such as data forwarding and dynamic spectrum access. Furthermore, despite the improvements, it still has insufficient bandwidth for future PPDR networks which have high bandwidth demands (e.g., for real-time video). LTE-based approach suffers from similar inadequacies except for bandwidth. The architecture proposed in [180] offers some flexibility by use of mobile access points. However, it cannot offer anti-jamming since it does not have CR capability, and only offers limited recovery since it does not support multi-hop communication. The CR-based solution does not support data links and like the others, does not have interoperability support.

To highlight the capabilities of ICG, we analyze a hypothetical case. ICGs are deployed in a building, before disaster. We present a simple analysis of the communication area inside the rubble that can be covered by ICGs. We take the

path loss as 7 dB and 4 dB, for concrete and brick, respectively, for a thickness of 0.1m.

We have evaluated path loss of these materials and found it to be linear in the log scale. These results are in line with those in the literature (e.g. [195]). We assume a receiver sensitivity of -110 dBm, transmitter and receiver antenna gains of 30 dBi. Transmission power of 50 dBm is assumed to be used in emergency situation. This allows for a total attenuation of 190 dB. We realize that this power value is much higher than allowed 2W EIRP in Europe and 4W EIRP in US. However, ICGs will only use this high transmission power mode for emergency rescue operations, for a very short time to collect data from the event area. Therefore, we think this is a reasonable assumption.

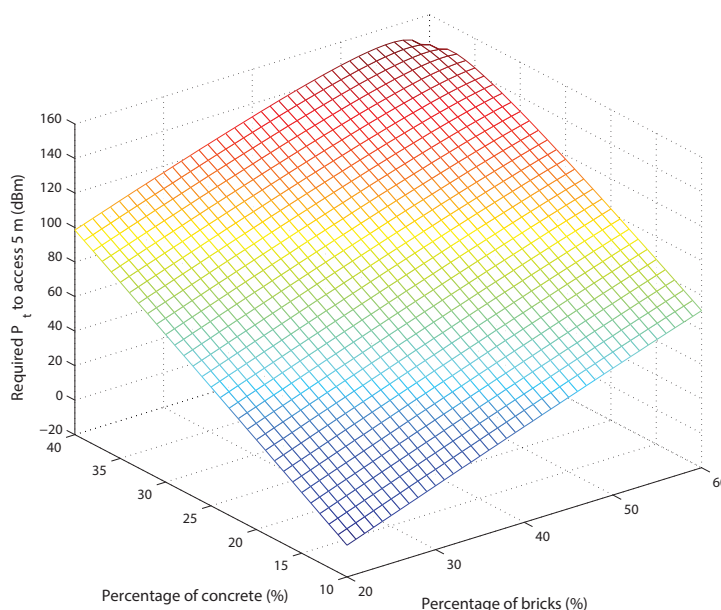


Figure 8.3: Power required to transmit to 5 m for various material percentages

In Figure 8.3, we show the amount of power needed to transmit successfully to a 5 m distance for various percentages of concrete and brick in the rubble. For a high amount of cases, ICGs can transmit data when they are 5 m deep in the rubble

8.4 Simulation Results

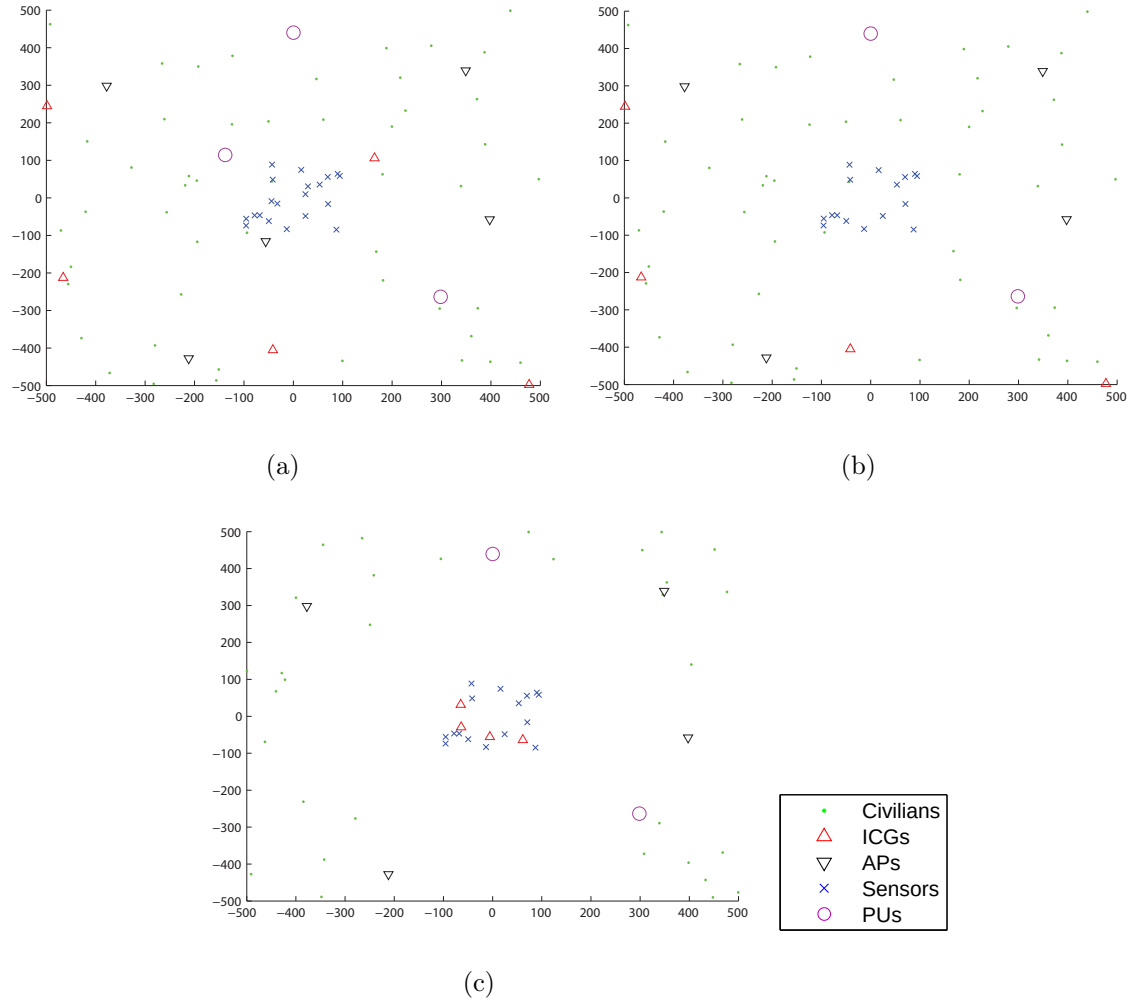


Figure 8.4: Sample positions for simulation elements a) before event b) after event c) at simulation end (200 s)

In this section, we provide the results of the simulations performed to demonstrate the effectiveness of our architecture. We assume a disaster scenario where a certain emergency situation occurs in the middle of the simulation area, taken to be 500 m x 500 m. People, sensors, ICGs, and primary users (PU) are located randomly according to a Poisson Point Process within the area. Since we are only interested in the sensors located in the event area, we focus on sensors within 100 m of the event.

To compare the effectiveness of ICG, we place an equal number of Wi-Fi access points (APs) inside the area. We choose Wi-Fi for comparison, because centralized systems such as cellular has the problem of single-point-of-failure, which is critical for disaster scenarios. We assume a channel bandwidth of 20 MHz for APs, as supported by most IEEE 802.11 variants. We take 6 MHz as channel bandwidth for ICGs (TV whitespaces). Since nowadays most TV users are cable subscribers, the number of TV users that use over-the-air antennas is low. Therefore, we assume three PUs.

After the event, some of the devices are destroyed with probabilities inversely proportional to their distance to the event. Furthermore, people and ICGs start to move. We assume the “gravitational” mobility model proposed in [196], i.e. people move away from the event area with velocities inversely proportional to their distance to the event, and ICGs move towards the event area with velocities proportional to the square of the distance to the event

We compare the throughput of data gathered from the sensors by ICGs and APs, by repeating the same scenario for both cases. We run the simulation 1000 times with different random placements. For each placement, we assume PU existence probabilities (probability of a PU being active), from 0.1 to 0.9.

In Figure 8.4, we show sample random location distributions before the event, right after the event and at simulation end, i.e., 200 seconds after the event, respectively. By comparing these figures, we see that some of the equipment gets destroyed in the event. Also, people have moved away from the event area and ICGs have moved closer by the end of 200 seconds.

We present the throughput obtained by ICGs and APs in Figure 8.5. ICGs provide higher throughput even though their channel bandwidth is considerably lower (6 MHz vs. 20 MHz). As time progresses, people move away from the area, reducing both the number of users served by APs and the interference on APs. Therefore, AP throughput increases with time. However, ICG throughput increases more rapidly, since ICGs can get closer to the sensors and further increase their SINR. The wider deviation on ICG throughput is due to different PU existence probabilities.

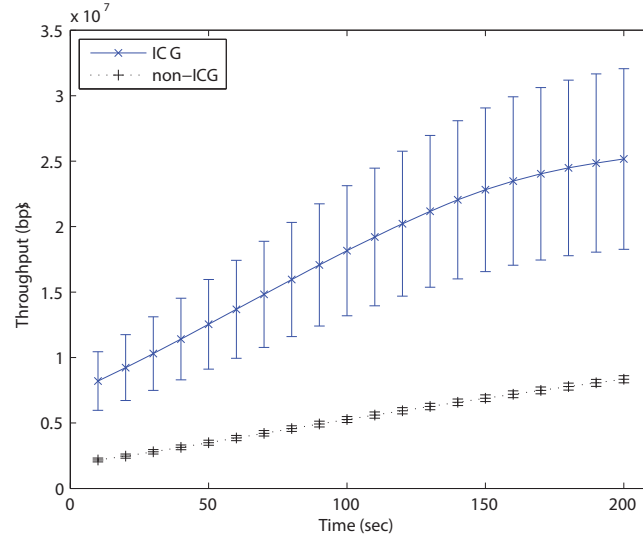


Figure 8.5: Throughput vs time

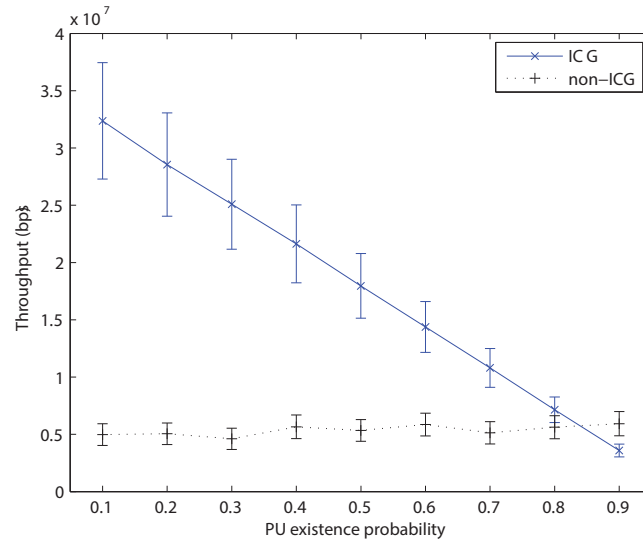


Figure 8.6: Throughput vs PU existence probability

The effect of PU existence probability is presented in Figure 8.6. ICGs perform better up to PU existence probability of 0.85, showing our proposed architecture enables higher throughput for majority of the cases.

Chapter 9

ROUTING IN COGNITIVE VEHICULAR NETWORKS

With the recent interest in providing ubiquitous wireless access, vehicular networks have attracted significant interest from academic community as well as major car manufacturers and governmental bodies [197, 198, 199]. Considering the large number of vehicles on the roads and the ever increasing demand for the wireless spectrum, it is envisioned that in the near future vehicles will have cognitive radio capability to combat the spectrum scarcity problem. The resulting network paradigm called cognitive vehicular network (CVN), has a very dynamic nature due to the high speed of the vehicles which causes channel conditions and spectrum availability to change rapidly.

One of the biggest challenges in in such a dynamic network is routing. The initial research on routing for CVNs was mostly extensions to routing schemes proposed for vehicular ad hoc networks (VANETs), which were themselves modifications to routing schemes designed for mobile ad hoc networks (MANETs). However, there are some significant differences between the two in terms of routing as detailed in the next section.

9.1 Challenges and Exploitable Features of CVN

Routing in CVNs has some specific challenges. These mostly arise from the high speed of vehicles and the specific nature of traffic in CVNs. These challenges can be listed as follows:

- *Channel conditions changes:* These can be divided into two

- *Environmental changes* E.g. shadowing changes due to various buildings while a vehicle is moving in urban areas
 - *Fast fading*: High mobility causes rapid changes in received multipath components of a signal
- *Topology changes*: Vehicles rapidly getting in and moving out of transmission range of each other cause fast changes in neighbor list of a node
- *Node density changes*: Vehicles can go through dense highways, and then move to uncrowded streets. Therefore, total demand for bandwidth and network congestion may change drastically
- *Spectrum availability changes*: Spectrum availability is location dependent. Vehicles may move from crowded commercial regions, where there are lots of PUs, to residential areas with few PUs and abundant available spectrum. Thus, bandwidth availability may be highly erratic
- *Wide range of QoS needs*: QoS requirements change from high reliability and minimum delay for vehicle collision avoidance applications to high bandwidth for in-car multimedia infotainment applications. Reliability is vital for certain applications such as safety messages pertaining to vehicle proximity, road hazards, and other emergencies. Compared to conventional networks, the stakes are much higher since human life is at risk. Therefore, strict adherence to QoS requirements is of utmost importance

While these challenges aggravate the implementation of effective routing mechanisms for CVNs, there are also some features specific to CVNs that can be exploited.

- *Abundant energy*: Since the transceiver is a part of the vehicle, energy consumption is not as much of a concern as it is for conventional hand held devices

- *No size and weight concern:* The radio equipment is part of the vehicle and will not be carried around like handheld wireless devices. Therefore, size and weight are less of a concern
- *Higher cost possible:* Since the CR unit is part of a much bigger cost, i.e., that of the vehicle, adding a small increase to the cost of CR unit by adding more capabilities is viable.

As a result following abilities can be added to CVNs

- *More processing power and memory:* CVNs can use more sophisticated spectrum sensing, spectrum management and cooperation schemes compared to conventional CRNs
- *Multiple radios:* Solutions that involve multiple transceiver units are viable. E.g., one for common control channel (CCC) monitoring, one for spectrum sensing and another for data transmission
- *Higher transmission power:* Transmission range can be increased or concurrent transmission from different transceivers can be made where appropriate
- *Predictable mobility patterns:* In VN, moving patterns are more predictable since vehicles have to move on roads. By obtaining data on the layout of roads, more accurate mobility prediction algorithms may be utilized
- *Precise location information:* Future vehicles will be equipped with Global Positioning System (GPS) devices, which introduce features such as
 - Location information is available at all times
 - Synchronization is easier due to very accurate GPS clock

In the following sections, we investigate the existing routing schemes for CVNs, as well as some earlier solutions developed for MANETs and VANETS that have been

inspirations for the mentioned CVN routing solutions. We conduct our investigation according to various categorizations as shown in Fig 9.1 and provide an extensive review of the literature.

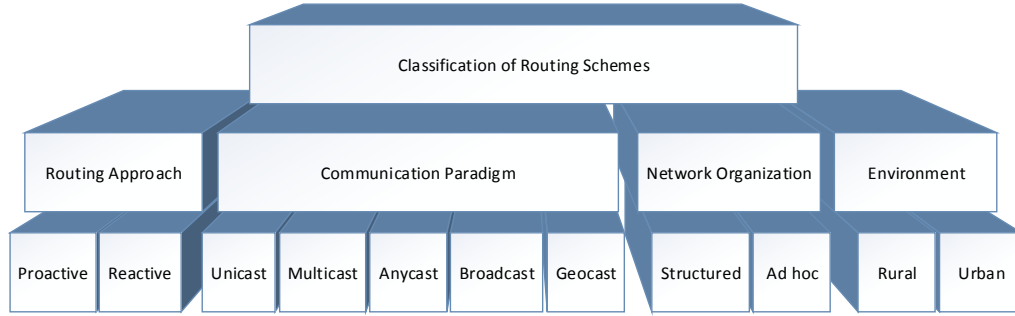


Figure 9.1: Classification of routing schemes.

9.2 Approaches to Routing in CVN

There are two main routing approaches. Proactive routing schemes [218, 219, 220, 223] update their routing tables with periodic messages regardless of whether there is a routing request or not. Reactive routing schemes [221, 222, 223] try to find routes when a routing request arrives.

9.2.1 Proactive

The advantage of proactive routing is that packets can be routed immediately since the routing tables are up-to-date all the time. The disadvantage is that since CVNs are highly dynamic, the frequency of route update messages must be considerably higher than conventional MANETs. Since these messages are sent regardless of network load or available bandwidth, the overhead may be excessive.

As the number of nodes gets higher, routing tables become harder to maintain, especially if the networks has a highly varying topology as in CVNs. This scaling

problem makes pure use of proactive schemes unfit for CVNs, since they ultimately aim to connect a vast number of vehicles over huge geographical distances.

On the other hand, if the number of nodes is not high, optimal routing decisions may be made since all of the required information about links is maintained in the routing tables [212]. This suggests a hierarchical routing model, where proactive mechanisms are used in a higher layer only to connect predetermined special nodes, e.g. roadside units (RSUs), to send packets to a certain region. Once the packet reaches the related region, reactive methods may be utilized. This idea was used in [223] for CVNs.

In terms of spectrum availability, in proactive schemes nodes perform spectrum sensing periodically and maintain a spectrum availability map. Most of the studies that determine routes by optimizing a certain metric inherently assume a proactive scheme [211, 213, 215, 224]. There are also proposal to modify routing protocols developed for MANETs for CVNs [220].

9.2.2 *Reactive*

Reactive routing schemes do not have the high overhead problem of proactive schemes. However, they are slower to respond to route requests, since the route is determined after the request by probing the nodes generally by flooding or similar types of messaging.

Reactive schemes are mostly used in ad hoc networks, where forwarding decisions are made by individual nodes as the packet moves towards the destination. Spectrum sensing is performed just before packet forwarding. This introduces certain delay to routing, and the most optimal route may not be chosen since global information is not available. However, the spectrum availability information and neighbor node list is current and the message overhead is kept to a minimum.

Generally, local optimization is made to minimize or maximize a certain metric at each hop instead of a global optimization [216]. Most used metrics are Expected Transmission Time (ETT), Expected Transmission Count (ETX), delay [214] and link

stability [201]. In CVNs, network topology changes rapidly both due to high speed of the vehicles and due to changes in spectrum availability. Choosing next hops by trying to maximize may lead to the choice of channels which are used very frequently by the PU. Even if the data rate at that channel is high, PU arrival is also more likely. Upon PU arrival, a lot of time will be wasted on finding another available channel and negotiating spectrum assignment, which reduces the overall throughput. Therefore, link stability is a concern that is specific to VNs and more so to CVNs.

9.3 Communication Paradigm

Communication paradigm may be unicast, multicast, anycast, or broadcast. Unicast routing is from a single source to a single destination. It is generally used in vehicle infotainment and Internet access. Most of the research is on unicast routing [201, 214, 215, 220]. Multicast routing originates from a single source to a number of destinations. This is generally used when an application need to send messages to multiple users [225, 226, 227]. In anycast routing, the aim is to reach any one of the nodes in a certain group [228]. The difference between multicast and anycast is that in multicast the message is routed to all of the nodes in the group, while in anycast it is sufficient if only one of the nodes in the group receive the message. Broadcast is used to send messages to all of the nodes in the vicinity.

For VNs, there is another type of routing, called geocast. Geocast is actually a special form of multicast or anycast, where the destination group is identified by their location. Geocast is used to send warning messages to vehicles in a certain area (e.g. in case of an accident) or to gather information from them [229, 230, 231]. The communication paradigms are shown in Figure 9.2.

Multicast, anycast, broadcast and geocast are particularly hard for CVNs, since common spectrum availability is harder to find for a group of nodes instead of a pair of nodes. To the best of our knowledge, there is still no research on any of these routing paradigms for CVN.

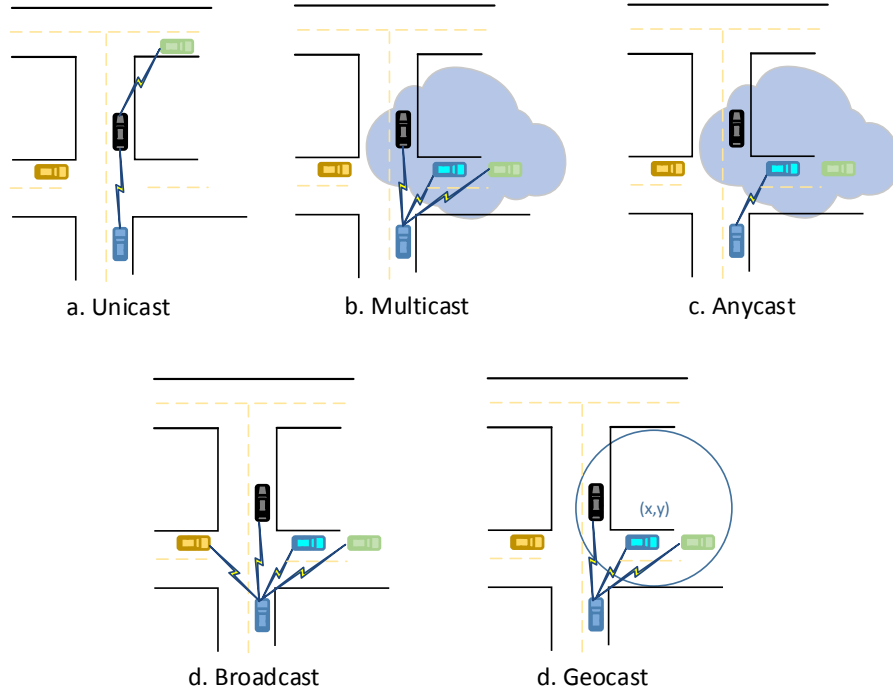


Figure 9.2: Communication paradigms.

9.4 Network Organization

Routing in CVNs may be broadly divided into two based on network organization: Structured and ad hoc. Structured CVNs usually have RSUs to control the communication. Routing schemes developed for structured CVNs generally employ a centralized approach where each RSU controls a certain area, collects information and routing demands from vehicles and disseminate channel allocation and routing decisions. On the other hand, in ad hoc vehicular networks there are no predetermined elements in the network structure. The whole network generally only consists of vehicles and there are no infrastructural elements to help with routing. These two possible network organizations are shown in Figure 9.3.

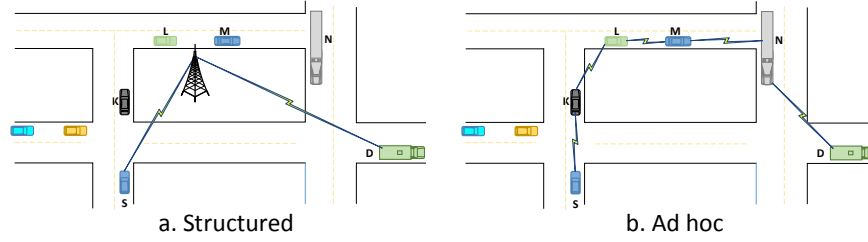


Figure 9.3: Network organization.

9.4.1 Structured

Structured CVNs are formed using RSUs. Generally RSUs maintain or have access to spectrum availability map as well as location information of all vehicles inside their domain. In a sense they are the base stations (BSs) of the CVN. They either directly determine routing decisions [211], or help vehicles by answering their queries [212, 213].

An alternative method of using cognitive radio is to find active networks and utilize them. In [214] a cognitive communication device for CVNs is proposed. The device is capable of using various types of networks such as satellite, GSM, Wi-Fi through its multiple interfaces. A structured network architecture with RSUs and vehicles using this device is envisioned in which RSUs manage their respective sites the whole network is coordinated by a Services Access and Management Server (SAMS). Nodes that have access to networks with limited coverage (UHF,VHF, 802.11) run modified versions of well-known proactive routing protocol OLSR, called GPS enabled Optimized Linked State Routing Protocol for Multiple Interfaces (GOLSR-MI) while nodes that have access to global networks such as General Packet Radio Service (GPRS), Wireless Local Loop (WLL) and satellite uses the modified version of reactive routing protocol Ad hoc On-Demand Distance Vector (AODV), called AODV for Multiple Interfaces (AODV-MI).

9.4.2 *Ad hoc*

Ad hoc vehicular networks generally only consist of vehicles. Forwarding decisions are made individually at each hop. Most of the proposed solutions are geo-location based and assume that the locations of the destination and the neighbor vehicles are known. Since there is no coordinating entity, generally multiple radios per vehicle are assumed [201, 214, 215]. One of the radios is used for coordination between the neighbor vehicles, while other(s) are used for data exchange.

Routing schemes for ad hoc network structures cannot yield optimal solutions since global optimization is not possible. On the other hand, due to highly dynamic nature of CVNs the large control message overhead that is inevitable in centralized solutions is avoided.

The relay nodes can be chosen according to a number of considerations such as delay [214], path stability [201, 215] and expected transmission count which is the average number of transmissions required to deliver a packet across a link [216].

9.5 *Routing Based on the Environment*

Solution approach may change considerably depending on the conditions of the area vehicles are in. There is a huge difference in the amount of available bandwidth between rural and urban areas. The traffic density may be higher than urban areas in highways, but the spectrum availability may be similar. Therefore, solutions developed assuming one type of environment may not be applicable to another. Even though research is more focused on routing in urban environment, there are also a few studies that target urban areas and highways for CVNs.

9.5.1 *Rural Areas and Highways*

Rural areas are characterized by lower vehicle density, higher spectrum availability, lower number of obstructions (i.e. lack of high buildings) and generally lower vehicle speeds. Therefore, it is generally more suitable to adopt routing schemes form

MANET. However, in VNs in rural areas may be partitioned due to frequent losses of line-of-sight (LOS) to neighbor vehicles because of the curved roads and absence or low number of RSUs. Thus, in addition to spectrum awareness, specific modifications to adopted routing schemes are needed.

Greedy Perimeter Stateless Routing (GPSR) [200], and the routing scheme proposed in [201] were designed to address the issues of open environments for traditional VNs. GPSR works in two stages. This two-step approach is adopted by many of the later routing schemes, including those designed for CVNs. In the first stage, a greedy algorithm forwards packets to the nodes nearest to the target. As the packets get to the nearest connected node but it does not have direct connection to the destination stage two is operation is executed. In this stage, perimeter forwarding is used and packets are forwarded according to right hand rule to select the next route. This last stage is called the “recovery stage”. We present detailed explanation when discussing types of routing in Section 7. There are also routing schemes that are more suitable for highways such as dynamic gradient-based routing (DGR) [202].

None of these schemes have spectrum awareness. However, they are solid approaches that can form the basis for cognitive routing for VNs in rural environments. One of the rare solutions for routing in rural CVNs is presented in [201], where routes are established by trying to maximize the expected duration of the link. Since both spectrum availability and network topology are highly dynamic, considering the lifetime of links in the route may considerably improve the communication performance.

9.5.2 Urban

Most of the research in routing for VNs is concentrated on urban environments. The main difference compared to routing in rural areas is the consideration of vehicle traffic on alternative roads. Some of the solutions find paths through fixed “anchor points” in the topology that help with routing [203, 204], while others discuss the

advantages of dynamic selection of these anchor points [205, 206]. Some make use of static RSUs [207] and others argue busses and/or taxis operating in the city as mobile RSUs increases performance [208, 209].

One of the possible methods to identify spectrum availability in urban areas where shadowing degrades spectrum sensing performance is to use spectrum availability maps. These maps are either issued by an authority or formed cooperatively by gathering the spectrum sensing results of nodes in the locality. Using this idea, spectrum-map-empowered opportunistic routing (SMOR) was proposed in [217]. Authors introduce two algorithms. One for regular size networks and one for large scale networks where only local spectrum availability information is not sufficient to determine end-to-end routes. However, these algorithms do not address the problems caused by high speeds of vehicles in VNs.

Another problem specific to urban areas is related to GPS. Most of the routing protocols for VNs use geo-location based routing. Furthermore, spectrum maps also use location data, mostly obtained from GPS. Therefore, performance of most routing methods depends on the accuracy of GPS data. However, GPS connectivity may be problematic in streets surrounded by high buildings. These locations are called urban canyons. In [210], authors report that GPS signal strength may fall way below minimum in such scenarios. Even if an accurate spectrum availability map exists, routing will be adversely affected if location information is faulty or non-existent. Further research is needed in this area.

9.6 Types of Routing

Communication in CVNs is generally multi-hop. Routing schemes can be classified according to the methods they employ in choosing their next-hop. The employed methods can be greedy routing, delay tolerant routing, cluster-based routing or QoS-based routing. Below we investigate each of these methods.

9.6.1 Greedy Routing

The most common routing method is greedy routing, where the next hop is chosen to be the node that is closest to the destination [200, 220]. This reduces the number of hops and thus, theoretically the overall delay. Generally, the availability of GPS is assumed. In such cases, since the coordinates of both the destination and the neighbor nodes are known, the neighbor closest to the destination node can be determined. However, it is possible to have scenarios where none of the neighbors are closer to the destination than the current forwarding nodes. This is depicted in Figure 9.4. Node S wants to forward packets to the destination node D. However, none of its neighbors are located closer to D. By purely greedy forwarding, it is not possible to route the packets to the destination. However, there is a path through vehicles K, L and M to the destination. In such cases, where greedy algorithms fail certain recovery algorithms are proposed. The simplest recovery mechanism is flooding. However, while it is effective, it is highly inefficient. In [200], face routing is used for recovery. In face routing the so-called right-hand rule is invoked, where if a closer node to the destination cannot be found, the algorithm walks around the faces of a planar graph, which are progressively closer to the destination vertex. This enables packets to be routed through vehicles K, L, M and N to D in Figure 9.4. A survey on recovery methods can be found in [232].

9.6.2 Cluster-based Routing

Aside from the need for recovery mechanisms, another problem of greedy algorithms is that in choosing the next hop closest to destination, they generally opt for the furthest node in their communication range. With high vehicle speeds, it is possible that these next hop vehicles go out of transmission range before the communication ends. Furthermore, due to the high distance, the channel between these nodes is not likely to have the highest data rate.

The routing takes place in two phases. In the first phase, cluster members send their packets to the cluster head. This is called inter-cluster communication. In the

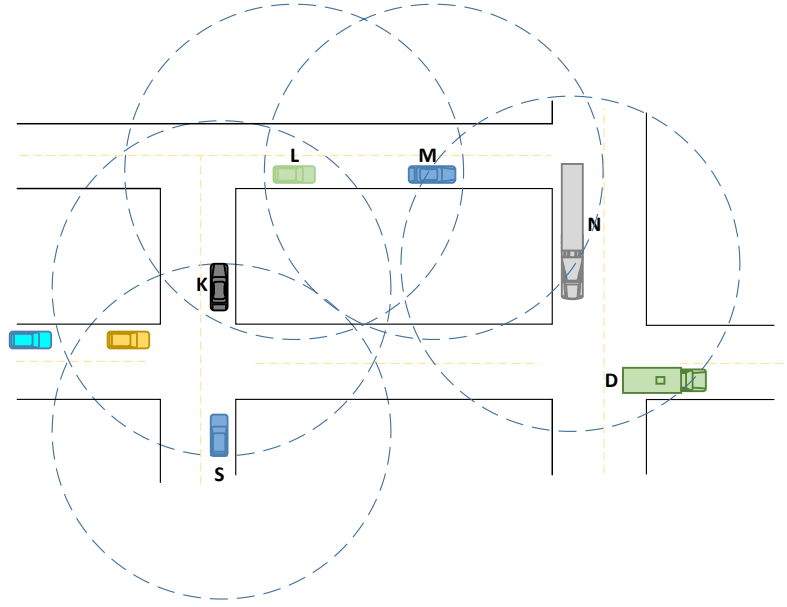


Figure 9.4: Greedy routing.

second phase, cluster head forwards the packets to other related cluster heads [224, 237]. Cluster head selection algorithms take into consideration parameters such as vehicle speed, number of neighbors, distance between neighbors, etc. In CVNs spectrum availability should also be taken into account. Nodes that have more available channels common with their neighbors are better candidates for cluster heads. On the other hand, unlike in MANETs, energy state of the nodes is not an issue in VNs.

Cluster-based routing is especially useful while disseminating security related information to vehicles within certain vicinity. In [238], vehicles are organized in zones, called peer spaces, according to their common interests. The number of peers inside a peer space is limited since there is no advantage for a peer to maintain knowledge for many others. This helps with reducing the overhead inside a peer space.

Cluster-based formations are also suitable for cooperative spectrum sensing. While

cooperation increases spectrum sensing performance, the gain reduces as the number of cooperating nodes increase. The delay incurred by exchanging spectrum sensing data and negotiating among the cooperating nodes also increase with the number of nodes. Therefore, cluster-based methods, with limited number of nodes in each cluster tend to yield good results. Furthermore, coordination of spectrum sensing and routing is needed to obtain “silent” channel on which spectrum can reliable be sensed. Cluster-based mechanisms also help with such coordination. However, the amount of research on this area is limited [224, 237].

9.6.3 Delay Tolerant Routing (DTR)

In VNs network partitioning is a common occurrence since links may frequently be broken due to high vehicle velocity. Delay tolerant routing or opportunistic routing is used in such cases, where a node passes the packets to another node that travels in the direction of the destination. The intermediate node stores and carries the packets as it moves towards the destination and relays the packets once it gets into the communication range of the destination or the partition of the network that is connected to the destination.

In DTR, information is generally transmitted in as bundles of multiple packets. These “bundles” contain all relevant information such as protocol data, authentication data, etc. that is required for the completion of a transaction in one go [233, 234]. This helps avoiding several round trips to exchange protocol messages and/or authentication.

DTR can be used both in ad hoc and structured networks. In ad hoc networks vehicles are the only means to “carry” the messages. In structured networks, RSUs may be used to store the bundle until a vehicle moving towards the destination arrives.

Since the network is not fully connected when a DTR scheme is used, delivery of the bundle is not guaranteed. Therefore, some schemes used multiple copies of the bundle [235].

A survey of routing protocols for vehicular delay tolerant networks can be found

in [236]. However none of the investigated solutions are for CVNs. DTR in CVN is an open research area.

9.6.4 QoS-based Routing

CVN applications have a wide range of quality of service (QoS) requirements. Safety related applications such as vehicle collision avoidance have very low, strict minimum delay and reliability requirements, while in-car multimedia infotainment applications have high bandwidth requirements. Since human lives are at stake, strict adherence to QoS requirements is of utmost importance.

Link stability is one of the most important QoS factors. Aside from the essential reliability issues, it affects both data transmission rate and delay incurred by routing [201]. The scheme proposed in [239] uses vehicle position, speed and trajectory information to estimate quality factors of a route. These factors are used to form a metric called Expected Disconnection Degree (EDD) which is an estimation of probability that determines the breakability of route during given time period.

In [240], a cross-layer routing scheme is proposed, where path selection and routing decision are made according to different QoS requirements. Analysis of end-to-end reliability and total power consumption are provided. The multi-interface cognitive device proposed in [223] takes QoS requirements into consideration to prioritize the interfaces accordingly, though the exact mechanism is not explained in detail.

9.7 Security Issues

Malicious attacks related to routing either take advantage of the algorithmic properties of the routing protocols or advertise fake locations to their neighbor nodes. CVNs are especially challenging for secure routing algorithm design. One of the reasons for this is that due to mobility, an attacker may move into coverage of its victim, change its routing table with false advertisements and then move away before detection. In an environment where, legitimate nodes also move in and out of coverage range very frequently, such malicious information may be hard to detect

[241].

With regard to geo-location based routing schemes, a malicious node may advertise fake locations for both itself and for other nodes. These attacks are difficult to mitigate. These may be countered to a degree with the predictability of vehicle movement in VNs.

VNs, especially in rural areas, have a single dimensional structure, i.e. the road that the vehicles travel. As the distance between nodes in a single dimensional structure increase, the probability of end-to-end connectivity decreases [242]. This makes an attacker easier to partition the network.

On the other hand, attacks that aim to deplete node battery are not effective in VNs. Also, nodes in VNs have higher memory and computation power and therefore, they are capable of supporting complex authentication mechanisms.

Chapter 10

CONCLUSIONS

Cognitive radio increases spectrum utilization and communication quality with opportunistic spectrum access capability and adaptability to the channel conditions. These salient features can also be exploited in resource-constrained sensor networks and can also be used in various communication systems such as PPDR networks and vehicular networks. In this thesis, we investigated the viability of CR in various networks. The following areas have been investigated

- Cognitive radio sensor networks
- Cooperative coarse spectrum sensing for CRSN
- Cooperative fine spectrum sensing for CRSN
- Throughput maximization in EM energy harvesting CRNs
- CRSN in smart grid
- Reliability under OSA for cognitive sensor-actor networks in smart grid
- CR-based network architecture for PPDR networks
- Routing in CVNs

In the following sections we list our contribution for each topic.

10.1 Cognitive Radio Sensor Networks

Under this topic, we investigate cognitive radio sensor networks; a new sensor networking paradigm formed by adopting cognitive radio capabilities in wireless sensor networks. We discuss advantages and limitations of CRSN and explored the applicability of the existing networking solutions for cognitive radio and sensor networks in CRSN along with their shortcomings. Even though cognitive radio and wireless sensor networks have individually been studied extensively, there exist significant challenges for the realization of CRSN. We anticipate that our work will provide better understanding of the potentials for CRSN and motivate research community to further explore this promising paradigm.

10.2 Cooperative Coarse Spectrum Sensing for CRSN

We present CC4C, a coarse spectrum sensing scheme to be used in a two-stage spectrum sensing method for CRSN. CC4C matches our proposal on fine sensing for CRSN, i.e. CCS perfectly to form a two-stage sensing scheme, since both methods make use of correlations of environmental readings of the sensor nodes and once they are calculated for one, they can be used by the other one. Simulation results show that CC4C is considerably more energy efficient compared to the other schemes. Comparing delay incurred by spectrum sensing, we see that CC4C yields the best results in the low SNR region, where delivering sensing requirements is the hardest.

10.3 Cooperative Fine Spectrum Sensing for CRSN

An energy-efficient, cooperative fine spectrum sensing scheme for CRSN, CSS, is presented. Energy efficiency is obtained by using the correlations of sensing data to reduce the number of nodes that participate in the sensing. Since rest of the nodes can switch to sleep mode, significant amount of energy conservation is obtained. With the reduced number of nodes that have to share their results, the latency incurred by spectrum sensing is also reduced. We have performed extensive simulations to

compare the accuracy (i.e. ROC curves), the energy consumption and sensing delay of the proposed solution with various other cases. Simulation results verify that CSS has better detection performance, imposes less energy consumption and less delay.

10.4 Throughput Maximization in EM Energy Harvesting CRNs

We present an analysis of expected maximum throughput in cognitive EM energy harvesting wireless networks. Instead of assuming the exact or statistical energy harvesting profile knowledge, we derive the expected harvested energy by investigating a common wireless network topology where PUs, from which the EM energy is harvested are located according to a PPP process. Overall, our results indicate that EM energy harvesting is feasible for a cognitive wireless sensor network if it can tolerate high sleep cycles. It is worth noting that the maximum throughput depends on the PU existence probability. Therefore, our scheme could be improved by a learning algorithm which can keep track of PU activities. Another method is to use cooperation in spectrum sensing and relaying in data transmission, since this reduces the power required by each node. We examine the cooperative case and provide the solution for maximum expected achievable throughput for decode and forward type relaying. Then, we point out the fact that cooperation may not always be the better solution, and we investigate the condition under which cooperation yields higher expected throughput.

10.5 CRSN in Smart Grid

We discuss utilization of CRSN in SG. We point out additional burdens that come with cognitive operation and examined reasons which make CRSN promising despite its additional costs. We analyzed various functionalities that provide spectrum awareness and detailed each communication layer from the view of a CRSN node. We provided relevant work in the literature in related parts of the text and listed open research issues. Future directions to enable CRSN in SG can be listed as efforts to include opportunistic spectrum access to ongoing standardization efforts on communication in

SG, regulations that enable online auctioning mechanisms, and cost-benefit analysis of adding cognitive radio capability to sensor nodes.

10.6 Reliability under OSA for Cognitive Sensor-Actor Networks in Smart Grid

Reliable spectrum access and reaching consensus with cognitive radio sensor and actor nodes is discussed. A consensus scheme is proposed to increase reliability by enabling consensus convergence of actor nodes with minimum spectrum access. Effects of licensed user in terms of both interruption and interference are modeled, and implications on design and performance are highlighted. Proposed scheme is shown to be satisfying consensus convergence requirements, especially in dense licensed user activity and high interference scenarios which can be encountered in various portions of the Smart Grid.

10.7 CR-based Network Architecture for PPDR Networks

Under this topic, we introduce an adaptable and resilient architecture that enables sustainable communication and timely gathering of crucial event data and its delivery to the responder units at the site as well as the command and control centers that are off-site. We lay out communication requirements and challenges that should be addressed by the next-generation PPDR network architecture and explained how the proposed solution fulfills these requirements.

10.8 Routing in CVNs

We examine the conditions specific to vehicular networks and lay out the challenges for routing in CVNs. We further list some properties of VNs that can be exploited such as multiple transceivers, abundant energy, more memory and better processors, enabling more complex algorithms. We investigate the state-of-the-art in routing for VNs and then CVNs. We point out open research issues.

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