

Energy Efficient User Association and Handover in 5G Heterogeneous Cloud Radio Access Networks

by

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**Energy Efficient User Association and Handover
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To my mother Maide and my brother Özgür

ABSTRACT

5G wireless networks are expected provide data rate improvement, low-latency, ultra-reliable and energy-efficient communication. Heterogeneous Cloud Radio Access Network (HCRAN) has been proposed to meet the aforementioned goals in 5G through the combination of Macro Base Stations (MBS)s, which operate at LTE cellular frequencies, and Small Base Stations (SBS)s, which operate at mmWave frequencies, with cloud infrastructures. For the provision of high data rates in 5G HCRANs, dense deployment of SBSs is necessary because high bandwidth available in millimeter wave spectrum enables to meet the data rate demands. On the other hand, for ultra-reliable and low-latency communication, special techniques are used to overcome high pathloss since mmWave signals are very susceptible to physical blockage. However, dense deployment of SBSs leads to a rise in power consumption and carbon emission, whereas techniques proposed for ultra-reliable and low-latency communication cause increase in signaling overhead and decrease in achievable rate and latency performances. This, in result, drives research efforts to find more energy efficient and reliable user association approaches. To that end, this thesis mainly focuses on the development of novel energy efficient user association methods and a handover algorithm in 5G HCRANs. First, based on the realistic power consumption model proposed for 5G, an energy-efficient user association approach is proposed in Uplink/Downlink Decoupled HCRANs and improvements of the proposed model in power consumption, delay and fairness have been examined. In addition, to enhance the robustness of mmWave signals to blockages in a mobile scenario, a User-Base Station association method, which is based on multi-connectivity technique, is proposed and the effects of the proposed User-Base Station association method on the power consumption, achievable rate, delay and reliability have been investigated. Last, to

increase achievable rate, latency and reliability performances of Multi-Connectivity based Uplink/Downlink Decoupled HCRANs in case of high mobility, an Energy constrained Handover policy has been proposed to minimize the number of handovers. The supremacy of the proposed algorithms over existing methods are demonstrated by simulations in terms of closeness to the optimal for different networks sizes and various data rate requirements.



ÖZETÇE

5G teknolojisinin kablosuz ağların veri hızını iyileştirmesi, düşük gecikme süreli, ultra güvenilir ve enerji tasarruflu iletişim sağlaması beklenmektedir. Heterojen Bulut Radyo Erişim Ağı, LTE hücreli frekanslarda çalışan makro baz istasyonları ile milimetre dalga frekanslarda çalışan küçük baz istasyonlarının bulut altyapıları ile birleştirilerek, yukarıda belirtilen hedeflere ulaşma amaçlı önerilmiştir. 5G Heterojen Bulut Radyo Erişim Ağlarında yüksek veri hızlarının sağlanması için, küçük baz istasyonlarının yoğun şekilde konumlandırılması gerekmektedir, çünkü milimetre dalga spektrumunda bulunan yüksek bant genişliği veri hızı taleplerini karşılamayı sağlar. Öte yandan, ultra güvenilir ve düşük gecikmeli iletişim için, milimetre dalga sinyalleri fiziksel tıkanmaya karşı çok hassas olduğundan yüksek yol kaybının üstesinden gelmek için özel teknikler kullanılmaktadır. Bununla birlikte, küçük baz istasyonlarının yoğun şekilde konumlandırılması güç tüketiminde ve karbon emisyonunda bir artışa yol açarken, ultra güvenilir ve düşük gecikmeli iletişim için önerilen teknikler, ek yükte artışa ve ulaşılabilir hızda ve gecikme performanslarında azalmaya neden olmaktadır. Sonuç olarak bu, daha verimli ve güvenilir kullanıcı ilişkilendirme yaklaşımları bulmak için araştırma çabalarını teşvik eder. Bu amaçla, bu tez esas olarak 5G Heterojen Bulut Radyo Erişim Ağlarında yeni ve enerji verimli kullanıcı ilişkilendirme yöntemlerinin ve bir aktarım algoritmasının geliştirilmesine odaklanmaktadır. İlk olarak, 5G için önerilen gerçekçi güç tüketimi modeline dayanarak, yukarı bağlantı / aşağı bağlantı ayrılmış Heterojen Bulut Radyo Erişim Ağlarında enerji tasarruflu bir kullanıcı ilişkilendirme yaklaşımı önerilmiş ve önerilen modelin güç tüketimi, gecikme ve adalet alanındaki gelişmeleri incelenmiştir. Ayrıca, bir mobil senaryoda milimetre dalga sinyallerinin tıkanmalara karşı sağlamlığını arttırmak için, çoklu bağlantı tekniğine dayanan bir Kullanıcı-Baz İstasyonu ilişkilendirme yöntemi önerilmiş ve

önerilen Kullanıcı-Baz İstasyonu ilişkilendirme yönteminin güç tüketimi, ulaşılabilir hızı, gecikme ve güvenilirliği araştırılmıştır. Son olarak, yüksek hareketlilik durumunda çoklu bağlantı tabanlı yukarı bağlantı / aşağı bağlantı ayrılmış Heterojen Bulut Radyo Erişim Ağların ulaşılabilir hızı ve gecikme ve güvenilirlik performanslarını arttırmak için, aktarım sayısını en aza indirmeyi amaçlayan enerji kısıtlı bir devir politikası önerilmiştir. Önerilen algoritmaların mevcut yöntemlere göre üstünlüğü, farklı ağ boyutları ve çeşitli veri hızı gereksinimleri için en uygun olana yakınlık açısından simülasyonlarla gösterilmiştir.

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NOMENCLATURE

5G	Fifth-Generation
BBU	Base Band Unit
BBU-Cloud	Base Band Unit Cloud
BH	Backhaul
BILP	Binary Integer Linear Programming Problem
CFLP	Capacitated Facility Location Problem
CKFLP	Capacitated k-facility location problem
CN	counter
CRAN	Cloud Radio Access Network
C-V2X	Cellular Vehicle to Everything
DL	Downlink
ECHO	Energy Constrained Handover
FH	Fronthaul
GAP	Generalized Assignment Problem
HCRAN	Heterogeneous Cloud Radio Access Network
HetNet	Heterogeneous Network
HO	Handover
ITS	Intelligent Transportation Systems
LoS	line-of-sight
LP	Linear Programmings
LPR-R	LP Relaxation-Rounding
LV	Local Value
MBS	Macro Base Station

MC	Multi-connectivity
MCUAA	MC based User Association Algorithm
MIMO	Multiple Input Multiple Output
mmWave	Millimeter wave
MV	Main Value
MLoS	Non-line-of-sight
PMA	Perfect Matching Algorithm
QoE	Quality of Experience
QoS	Quality of Service
RMA	Repeated Matching Algorithm
RRH	Remote Radio Head
RSS	Received Signal Strength
RV	Reference Value
SBS	Small Base Station
SL	Sidelink
SN	Split Number
SNR	Signal-to-Noise-Ratio
SRAA	Selection and Repetition based user Association
SSCFLP	Single Source Capacitated Facility Location Problem
TS-EOS	Two-stage Energy Optimization Scheme
UE	User Equipment
UL	Uplink
V2X	Vehicle to Everything
V-based	Velocity-based
VNS	Variable Neighborhood Search
VR	Vehicular Relay
VUE	Vehicular User

Chapter 1

INTRODUCTION

1.1 5G: Beginning Of A New Era Of Connectivity

The wireless communication is on the brink of a new era that will transform the method of communication. Transformation is going to be based on three use case families; enhanced Mobile Broadband, massive Machine Type Communications, and Ultra-high Reliable and Low Latency Communications and 5G systems is going to be the first realization in this new era of connectivity, where aforementioned use cases will be connected to each other creating a unified system.

5G wireless networks are expected provide data rate improvement, low-latency, ultra-reliable and energy-efficient communication and they are going to be active on the frequency spectrum over 6GHz band, which supports enormous bandwidth at mmWave frequencies. HCRAN has been proposed to meet the aforementioned goals in 5G through the combination of MBSs, which operate at LTE cellular frequencies, and SBSs, which operate at mmWave frequencies, with cloud infrastructures.

HCRANs are designed through the integration of HetNets and CRANs to enable denser network deployments and simultaneously deliver increased energy efficiency. From HetNets, HCRANs inherit tiered deployment of MBS and SBSs. In HetNets, MBS provide coverage and SBSs serve to boost capacity, accomplish desired data demand and improve energy efficiency by offloading users from MBS to SBSs with the aim of reducing dynamic power consumption of MBS. On the other hand, CRAN introduces a centralized processing entity, which computes workloads, accounts for QoS and enables optimized orchestration of the number of users per BS and energy

consumption. In CRANs, BBUs are decoupled from the RRHs. BBUs are gathered into the BBU-Cloud and RRHs and BBUs are connected to each other through FH links. Most of the control plane signaling takes place in the BBU-Cloud for coordinating the inter-tier interference between SBSs and MBS. The control and broadcast functionalities are shifted from SBSs to MBS, which alleviates capacity and time delay constraints on FH links and supports the burst traffic efficiently. The features stated about 5G HCRANs provide a very convenient environment for achieving high capacity, ultra reliable low latency and energy efficient communication.

To provide high data rates, dense deployment of SBSs is necessary because high bandwidth available in millimeter wave spectrum enables to meet the data rate demands. On the other hand, for ultra-reliable and low-latency communication, special techniques are used to overcome high pathloss since mmWave signals are very susceptible to physical blockage. However, dense deployment of SBSs leads to a rise in power consumption and carbon emission, whereas techniques proposed for ultra-reliable and low-latency communication cause increase in signaling overhead and decrease in achievable rate and latency performances.

According to the challenges posed, this thesis mainly focuses on the development of novel energy efficient user association methods and a handover algorithm in 5G HCRANs.

1.2 Contributions of Thesis

The contributions of this thesis on HCRANs can be listed as:

Chapter 2

- We propose an energy-efficient user association approach in UL/DL Decoupled HCRANs with the help of a realistic power consumption model proposed for 5G.
- We analyze the efficiency of the proposed UE-BS association approach with power consumption, delay and fairness metrics.

- We adopt mmWave physical layer characteristics in which we restrict the number of simultaneous transmissions by the number of RF chains.
- We formulate the optimization problem as a SSCFLP. Since SSCFLP is NP Complete, we propose a heuristic algorithm denoted as SRAA to solve the formulated optimization problem. Rather than dealing with all UEs and all BSs in each run as in RMA and PMA, SRAA forms feasible UE-BS pairs with LP Relaxation method and solves matching problems for each feasible UE-BS pairs repeatedly to find minimum power consuming UE-BS pairs.
- We illustrate the superiority of the SRAA to previously proposed solution methods in terms of closeness to the optimal for different network sizes and various data rate requirements via extensive simulations.

Chapter 3

- We provide a comprehensive framework for the minimization of power consumption in MC based UL/DL Decoupled UE Association in 5G HCRAN.
- The investigation of the MC based UL/DL Decoupled UE Association in 5G HCRAN is done with realistic power consumption models, including both signaling overhead and transmissions within the BBU-Cloud, which is key in the analysis of the advantage of the usage of multiple BSs.
- UL/DL decoupled UE-BS association and transmission with effective rate are used to further improve the performance through higher system flexibility.
- We investigated the effects of the proposed UE-BS association method on the power consumption, achievable rate, delay and reliability.
- We formulate the optimization problem as a SSCFLP. Since SSCFLP is NP Complete, it cannot be solved to optimal in polynomial time. Therefore, we propose a heuristic algorithm denoted as MCUAA for the formulated problem.

Instead of turning on/off BSs or assigning user with BSs according to a random binary string as in the previous study, the MCUAA has a primal solution based on LP Relaxation. Moreover, the current solution in the previous study is improved by selecting a pre-defined UE-BS association method, changing the current UE-BS association with respect to pre-defined association method and then applying local search. On the contrary, the LP Relaxation provides input to the following GAP heuristic to solve many-to-many assignment problem.

- We analyze the proposed algorithm and verify its superiority over existing methods by simulations.

Chapter 4

- We provide a holistic framework for the minimization of HO number in HCRANs by using an ECHO execution policy to overcome the limitations of RSS based and velocity based HO policies for the first time in literature.
- The framework incorporates realistic power consumption models encompassing transmissions in the BBU-Cloud and signaling overhead, which are crucial points in analyzing the benefits of MC, UL/DL decoupled user association and transmission with effective rate.
- We constrain the number of simultaneous transmissions by the number of RF chains.
- We formulate the HO problem as a BILP. The problem is proven to be NP-Hard. Since it is NP-Hard, a heuristic algorithm is proposed and is called as ECHO algorithm. Instead of executing HO based on RSS or Velocity, ECHO algorithm executes HO based on checking if the difference of the energy consumption in consecutive time-slots is below a pre-defined power value. Moreover, at each given time-slot, ECHO algorithm forms feasible UE-BS or UE-BS cooperation pairs by LP Relaxation and solves GAP heuristic to assign unassigned UEs with

UE-BS or UE-BS cooperation pairs to find the least power consuming UE-BS association pattern.

- We analyze number of HOs, time complexity and effect of distance and blockage on the HO behavior of the proposed algorithm. We demonstrate the supremacy of the ECHO algorithm over existing methods by simulations in terms of closeness to the optimal for different networks sizes and various data rate requirements via extensive simulations.

Chapter 5

- We provide an efficient heuristic for the optimization problem of the UL/DL decoupled energy efficient VUE association or VUE-VUE association in SL with the aim of minimizing total network power consumption subject to rate, capacity and effect of FH links.
- The distinction of the proposed heuristic algorithm to previously proposed solution methods is demonstrated in terms of closeness to the optimality via extensive simulations.

1.3 Thesis Outline

The rest of thesis is organized as follows:

- **Chapter 2:** HCRAN is a network architecture that combines MBSs and SBSs with cloud infrastructures. The dense deployment of SBSs in HCRAN is needed to provide high data rates to UEs but causes high energy consumption. Unrealistic power models lead to inefficient UE association schemes in terms of energy. In this paper, we study the joint optimization of UL and DL decoupled UE association and switching on/off the SBSs in HCRAN by incorporating a realistic power model with the objective of minimizing the power consumption in HCRAN. The power model encompasses static and the dynamic power consumption of MBS, the static power consumption of SBS, the power consumption

of transmission links to cloud infrastructure and the power consumption of UEs. The problem is transformed into SSCFLP which is NP-Hard. We then propose a heuristic algorithm based on the use of LP relaxation and solving many-to-one assignment problem with GAP heuristics. Extensive simulations demonstrate that the proposed heuristic algorithm performs very close to optimal and achieves significant improvements in minimizing total power consumption compared to coupled UE association algorithm and algorithms utilizing the power consumption models that do not encompass MBS dynamic power consumption and the power consumption of transmission links to cloud infrastructure for various scenarios.

- **Chapter 3:** MC is proposed in 5G to mitigate the deterioration of QoS owing to LoS blockage and lack of communication resources. The main idea of MC is to associate single UE with multiple network layers and multiple radio access technologies, simultaneously. In previous studies, MC is demonstrated to increase capacity, provide high reliability and decrease outage probability. However, for the first time in literature, we incorporate MC into the optimization of the total power consumption in 5G HCRAN. Upon formulation of the problem as a BILP, proving its NP-hardness, a heuristic algorithm is proposed consisting of LP Relaxation and rounding and GAP heuristic, which takes the outputs of the LP Relaxation and rounding as inputs and checks if it further minimizes the power consumption. We analyze power consumption, time complexity and achievable rate of the proposed algorithm and verify its superiority over existing methods by simulations.
- **Chapter 4:** In 5G HCRANs, dense SBSs and MBSs, operating at mmWave and conventional cellular frequencies, respectively, coexist and overlap within a cloud infrastructure to provide uninterrupted coverage and high data rates to mobile UE. However, the small coverage of the SBSs and the hypersensitivity of the RSS to blockages in mmWave frequencies result in high number of HOs.

In previous studies, number of HOs are minimized by using RSS or velocity based handover execution policies, which cause unbalanced UE-BS association and increase overhead of re-association in 5G mmwave Networks. In this chapter, we study the problem of MC based energy constrained UL/DL decoupled UE association with the goal of minimizing the number of HOs in 5G HCRAN, while considering UL/DL decoupled UE-BS association, transmission with effective rate and accurate power consumption model encompassing transmissions in the cloud and signaling overhead. We first formulate the problem as a BILP, which is proven to be NP-Hard. Then we present a heuristic algorithm to solve BILP, that forms feasible UE-BS or UE-BS cooperation pairs by LP Relaxation and solves GAP heuristic to assign unassigned UEs with UE-BS or UE-BS cooperation pairs to find the least power consuming UE-BS association pattern. Extensive simulations demonstrate the supremacy of our proposed algorithm over existing methods in maximizing robustness to distance and blockages and minimizing total number of HOs and time complexity in terms of closeness to the optimal for different networks and various data rate requirements.

- **Chapter 5:** C-V2X communications, which support wireless connectivity between vehicles, road side units and pedestrians in cellular networks, enables VUE to select either VUE-VUE or VUE-Network transmission mode for safe, reliable and energy efficient transmission. In this paper, we propose an energy efficient transmission mode selection algorithm for V2X-enabled communications in cellular networks. We study the joint optimization of UL and DL decoupled VUE association, VUE-VUE association in SL and switching on/off the SBS in a Cloud Network by incorporating a realistic power model with the objective of minimizing the power consumption in the Cloud Network. The power model encompasses static and the dynamic power consumption of MBS, the static power consumption of SBSs, the power consumption of transmission links to cloud infrastructure and the power consumption of VUEs in UL and SL. The problem is transformed into SSCFLP which is NP-Hard. We then propose a

heuristic algorithm based on the use of LP relaxation and solving many-to-one assignment problem with GAP heuristics. Simulation results demonstrate that the proposed heuristic algorithm performs very close to optimal and achieves significant improvements in minimizing total power consumption.



Chapter 2

UPLINK/DOWNLINK DECOUPLED ENERGY EFFICIENT USER ASSOCIATION IN HETEROGENEOUS CLOUD RADIO ACCESS NETWORKS

2.1 Introduction

5G wireless networks are expected to provide 1000-fold data rate improvement and save up to 90 percent of energy consumption compared to the present systems [1]-[3]. HCRANs have been proposed to provide energy saving and rate improvement in 5G through the integration of HetNets and CRANs. From HetNets, HCRANs inherit tiered deployment of MBSs and SBSs. In HetNets, MBSs provide coverage and SBSs overlaid on MBSs serve to boost capacity, accomplish desired data demand and improve energy efficiency by offloading UEs from MBSs to SBSs with the aim of reducing dynamic power consumption of MBS. However, in case of expansion of the network size with dense deployment of BSs, the power consumption of the network increases and association of UEs to BSs of different tiers results in high inter-tier interference between MBS and SBS tiers [4]. On the other hand, CRAN introduces a centralized processing entity, BBU Cloud, which computes workloads, accounts for QoS and enables optimized orchestration of the number of UEs per BS and energy consumption. In CRAN, BBUs are decoupled from the RRHs, BBUs are gathered into the BBU Cloud and RRHs and BBUs are connected to each other through FH links. Nonetheless, the non-ideal FH links with limited capacity and long time delay degrade performances of CRANs [5]. To better manage aforementioned challenges and to ensure a better designed network aiming to support challenging 5G technology requirements [6], HCRAN has been proposed [3, 7]. In HCRAN, CRAN operation

mechanism is incorporated into HetNets and BSs from different tiers are connected to the BBU Cloud via FH links whereas the BBU Cloud is connected to Internet through BH links. Additionally, most of the control plane signaling takes place in the BBU Cloud for coordinating the inter-tier interferences between SBSs and MBSs. The control and broadcast functionalities are shifted from SBSs to MBSs, which alleviates capacity and time delay constraints on FH links and supports the burst traffic efficiently. This configuration allows UEs to communicate via several possible sets of BSs. Such a change in the architecture in the long run may lead to deploying more BSs than the UEs served, which causes high power consumption.

Power saving strategies proposed for HetNets include smart topological designs with the goal of providing better coverage to UEs, improvement of BS hardware design and introduction of dynamic on/off schemes according to UE distribution over time. First, in the context of smart topological designs, utilization of relays between BSs and UEs is proposed with the aim of bringing network closer to UEs [8]. In addition to relays, cell-zooming technique [9], which adjusts the cell size by adjusting the TX power according to UE traffic in the cell, is proposed to provide minimum required QoS for all UEs. Second, the BS hardware is improved by adopting energy efficient power amplifiers [10], or by replacing existing power amplifiers with new efficient devices using digital predistortion or envelope tracking for wide band signals [11].

With controlled planning of turning on/off schemes of SBSs, the total power consumption is minimized while satisfying the QoS constraints of UEs. QoS constraints of UEs include coverage probability [12], that is defined as the probability that a UE is in coverage, and area spectral efficiency [13], which is defined as the sum of the maximum average rates of UEs per unit bandwidth per unit area. Other QoS constraints are outage probability [14], bandwidth limitation of BSs [15] and minimum rate requirement [16]. Nonetheless, the MBSs are assumed to be always active to ensure the coverage and SBSs are turned on/off based on the system load. A potential deficiency of existing strategies is that overall power models for HetNets do not include capacity limit and the dynamic power consumption of MBS. Besides ensuring

coverage, the UE traffic can also be accommodated by the MBS as well as the rest of on SBSs, when any of the SBSs is turned off. Therefore, load dependency and hardware dependency of MBS dynamic power consumption have remarkable impacts on the total power consumption.

Unlike HetNets that consider only dynamic on/off scheme of SBSs, in CRAN, capacity and the power consumption modes of FH links are considered in addition to RRH power consumption. The power consumption for energy efficient UE association in CRAN is modeled by using the power consumption of RRHs and FH links for different modes considering the capacity of FH links [17]- [20]. RRH power consumption and FH link power consumption are assumed to be constant in [17]- [19] or stated as a function of data rate and transmit power of RRHs in [20]. Additionally, sleep mode power consumption of RRHs and FH links are included in [17]- [20], while being ignored in [18]. On the other hand, capacity of FH links is the energy bottleneck of CRANs since the number of on RRHs and FH links is determined according to the capacity of FH links and the UE traffic being carried. FH links are assumed to have sufficiently high capacity in [17] and [19], constant capacity in [18] or stated as the maximum number of UEs that can be supported on each FH link in [20]. However, none of the studies consider the joint effect of capacity limitation in terms of the maximum traffic load that can be carried by the switch in FH link associated with RRH and the power consumption as a function of data rate and power consumed per bit/s by a FH link.

In HCRAN, the challenges arisen out of the integration of HetNets and CRAN are offset by the dynamic resource and power allocation with the aim of maximizing energy efficiency in DL or in UL [4, 21] and investigating the effect of UL and DL power consumption on the capacity [5, 22, 23]. DL HCRAN power consumption model includes the power consumption of SBSs, MBS and FH links in [22] or RRHs and FH links without incorporating the power consumption of MBSs [5] with aim of maximizing energy efficiency subject to rate [22] or inter-tier interference constraints [5]. On the other hand, UL HCRAN power consumption model in [23] encompasses

the UE power consumption aiming to optimize relay selection, network selection and power allocation jointly with the objective of maximizing energy efficiency subject to rate constraints. Nonetheless, none of the studies for energy efficient UE association in HCRAN consider dynamic power consumption of MBS, the power consumption of FH link and capacity of FH link jointly. Also, none of them consider to optimize UL and DL EE performances, jointly.

Since UEs can have different SINR values in UL and DL, UE association to the same BS both in UL and DL may not be energy efficient [24]- [27]. Therefore, load balancing with UL and DL decoupling paves the way for energy efficient UE association by considering UL SIR for improved UE association in UL to SBSs with reduced transmit power in [28], assigning UEs to the UL and DL of different BSs independently based on UL and DL SIR values in [29] or by exploiting unused spectrum to assign a UE to a BS and allocating more than the minimum bandwidth to reduce transmit power of the UE [30]. On the other hand, SIR is not sufficient to decide on the load balancing for decoupled UL/DL scenarios, so UE association should also consider overall load of the cells and cell BH capacity [31], whereas UL and DL UE association should also consider beam-forming design and transmit power of BSs and UEs [32]. However, none of the studies above aim to improve achievable rate with the help of improved UL and DL SNR, considering FH link capacity and reduced transmit power by enabling UEs to connect to different BSs both in UL and DL.

The goal of this chapter is to formulate and propose efficient solution methodology for the optimization problem of the UL/DL decoupled energy efficient UE association with the goal of minimizing UL and DL power consumption in HCRAN while considering the accurate power consumption models, rate, capacity and effect of FH links.

2.2 System Model

2.2.1 HCRAN Architecture

The architecture of HCRAN is shown in Figure 2.1. In our model, MBS provides

C-Plane, carrying control signaling, cell specific reference signals, resource allocation and traffic processing, for the whole architecture. MBS operates at LTE cellular frequencies and is equipped with $N_{RF,M}$ RF chains. Within the coverage of MBS, there are K SBSs containing $N_{RF,S}$ RF chains and operating at mmWave frequencies. SBSs are mainly used to provide high speed data transmission with D-Plane, which carries actual UE traffic and executes traffic processing to satisfy QoS (without C-Plane), in hot spots. Additionally, there are N_b UEs that request connection in the coverage of MBS and are equipped with a single antenna. Each UE can be served by exactly one BS both in UL and DL, therefore UE demand is not splittable. Lastly, dynamic on/off transition of SBSs is analyzed at a certain time instant.

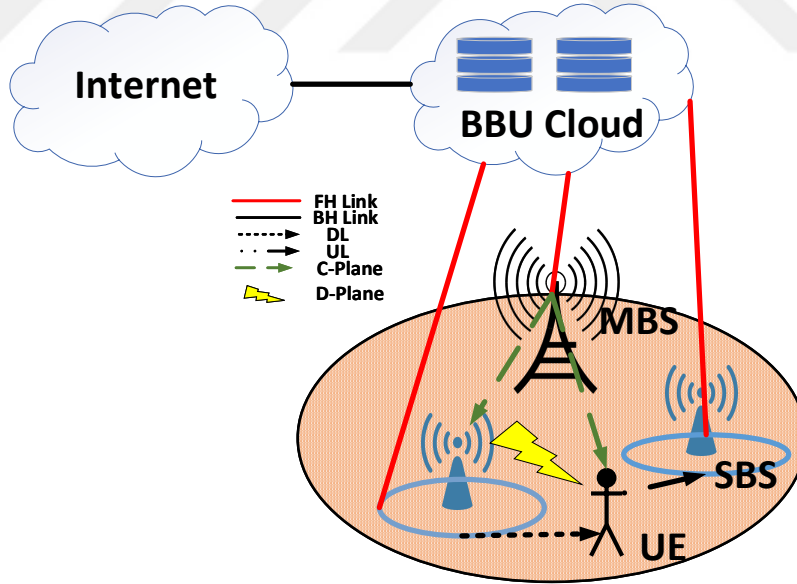


Figure 2.1: HCRAN Architecture

BSs and BBU Cloud are connected through FH links whereas BBU Cloud and Internet is connected through low-latency with sufficiently large capacity BH links. FH links are assumed to be constrained by capacity denoted by C_{fh} .

2.2.2 HCRAN Channel Characteristics

The channel estimation is done based on Channel State Information Reference Signal transmitted from MBS and SBSs [36]. The attenuation levels from MBS and SBS S to UE j are denoted by α_{Mj} and α_{Sj} , respectively. The attenuation levels from UE j to MBS and SBS S in UL are θ_{Mj} and θ_{Sj} , respectively. With the information gathered about attenuation levels, BBU Cloud decides on the least power consuming UE-BS pair both in UL and DL for each BS and UE and establishes a connection [37].

Though directional transmission is utilized, each UE j is exposed to interference power by other BSs, that do not serve UE j . The interference power at UE j in DL, $P_{j,Idl}$, is calculated as in [107]:

$$P_{j,Idl} = \sum_{i'=1, i \neq i'}^{K+1} P_{t,i'} * \alpha_{i'j} \quad (2.1)$$

where i is M or S, $P_{t,M'}$ and $P_{t,S'}$ indicate the transmission power of interfering MBS and SBS S , respectively and $\alpha_{i'j}$ is the DL path loss measured at the UE j based on the DL transmit power of the interfering BSs.

Due to different transmission bandwidths and transmit powers, BSs provide different achievable rates in DL from MBS and SBS S to UE j , denoted by $R_{d,Mj}$ and $R_{d,Sj}$, respectively. The achievable rates in DL are formulated as [67]:

$$R_{d,ij} = B_i * \log \left(1 + \frac{P_{t,i} * \alpha_{ij}}{|N_{RF,i}| * (N_0 * B_i + P_{j,Idl})} \right). \quad (2.2)$$

where i is M or S, B_M and B_S represent the transmission bandwidth for MBS and SBS S , respectively. $P_{t,M}$ and $P_{t,S}$ indicate the transmission power of MBS and SBS S , respectively, N_0 is the power spectral density of the noise and α_{ij} is the DL path

loss measured at the UE based on the DL transmit power of the reference symbols. Maximum number of UEs that can be simultaneously served by SBS S and MBS is less than or equal to the number of RF chains $N_{RF,S}$ and $N_{RF,M}$, respectively, which is motivated by the spatial multiplexing gain of the described multi-UE hybrid precoding system in [33].

The power assignment for the transmission at the UE is performed to overcome γ fraction of the path loss with respect to a reference received power per resource block at 0 dB path loss, P_0 , below P_{max} [40], and equal to:

$$P_{t,UE} = \min\{P_{max}, P_0 + \gamma * \alpha_{ij}\} \quad (2.3)$$

where i is M or S. Though directional transmission is done, each UE j is exposed to interference power. The interference power at UE j in UL, $P_{j,Iul}$, is calculated as in [107]:

$$P_{j,Iul} = \sum_{i'=1, i \neq i'}^{N_b} P_{t,UE} * \theta_{i'j} \quad (2.4)$$

where i is M or S and $\theta_{M'j}$ and $\theta_{S'j}$ is the UL path loss measured at the UE j based on the UL transmit power of the reference symbols for interfering MBS and SBS S, respectively.

The achievable rates in UL $R_{u,Mj}$ and $R_{u,jS}$ are formulated as in [67]:

$$R_{u,ji} = B_i * \log \left(1 + \frac{P_{t,UE} * \theta_{ij}}{N_{0i} * B_i + P_{j,Iul}} \right) \quad (2.5)$$

where i is M or S and, θ_{Mj} and θ_{Sj} is the UL path loss measured at the UE based on the UL transmit power of the reference symbols for MBS and SBS S, respectively. B_M and B_S represent the transmission bandwidth for MBS and SBS S, respectively. N_{0M} and N_{0S} is the power spectral density of the noise at each SBS S and MBS, respectively.

$Q_{d,j}$ and $Q_{u,j}$ are demanded data rate of UE j in UL and DL, respectively.

The channel utilization is defined as the ratio of the demanded data rate to the data rate that can be supported over the channel. The channel utilization from MBS and SBS S to UE j in DL are denoted by $\beta_{d,Mj}$ and $\beta_{d,Sj}$, respectively, and formulated as $\beta_{d,ij} = \frac{Q_{d,j}}{R_{d,ij}}$, where i is M or S as in [41]. On the other hand, the channel utilization from MBS and SBS S to UE j in UL are denoted by $\beta_{u,jM}$ and $\beta_{u,jS}$, respectively, and formulated as $\beta_{u,ji} = \frac{Q_{u,j}}{R_{u,ji}}$ where i is M or S as in [41].

2.2.3 Power Consumption Models of Network Components

MBS power consumption, P_M , includes both the static power consumption P_{Static} and the dynamic power consumption $P_{Dyn,M}$ [42]. P_{Static} consists of the power consumption of rectifier, air conditioner and BH link [44]. $P_{Dyn,M}$ is formulated as $F * P_l$, where $F = \frac{\sum_{j=1}^{N_b} \beta_{d,Mj} + \beta_{u,jM}}{N_{rfM}}$ is the load factor that represents the ratio of the sum of channel utilization of the active UEs both in UL and DL to the total capacity of MBS in terms of RF chains, and P_l consists of the power consumption of power amplifier, the transceiver, the digital signal processing unit.

Each SBS S with coverage range less than 30 meters and output power around 20 dBm is assumed to consume constant power, P_S , across all traffic load since SBS S has a limited service capacity (4 to 16 UEs) and can easily get overloaded. P_S includes power consumed in microprocessor P_{mp} , in FPGA P_{FPGA} , in transceiver $P_{tx,S}$ and in power amplifier $P_{amp,S}$ as in [42]:

$$P_S = P_{mp} + P_{FPGA} + P_{tx,S} + P_{amp,S} \quad (2.6)$$

Due to decoupled UL/DL transmission, the power consumed on FH link in DL is denoted as $P_{d,fhl}$ and is a linear function of the demanded data rate of UE j in DL, $Q_{d,j}$ [46], whereas the power consumed on FH link in UL is denoted as $P_{u,fhl}$ and is a linear function of the demanded data rate of UE j in UL, $Q_{u,j}$.

The power consumption of a UE, $P_{u,j}$, consists of circuit power consumption $P_{circuit}$ and power consumed in the power amplifier P_{amp} , which is formulated as $\frac{P_{t,UE}}{\rho}$ in [47],

where ρ is power amplifier efficiency:

$$P_{u,j} = P_{circuit} + P_{amp} \quad (2.7)$$

The power consumed on FH link is denoted as P_{fhl} and it is a linear function of the demanded data rate of UE j , Q_j [46].

2.3 Problem Formulation

The joint optimization of UE association and switching on/off the SBSs with the objective of minimizing the system power consumption by incorporating the dynamic power consumption of MBS, FH link power consumption and the UE power consumption given the capacity and rate constraints is formulated as follows:

$$\begin{aligned} \min \quad & P_{static} + \sum_{j=1}^{N_b} (\beta_{d,Mj} * P_l * x_{Mj}) + P_{fhl} * \sum_{j=1}^{N_b} Q_{d,j} * x_{Mj} + \sum_{S=1}^K P_S * T_S + \sum_{S=1}^K P_{fhl} * \sum_{j=1}^{N_b} Q_{d,j} * x_{Sj} \\ & + w * \left(P_{fhl} * \sum_{j=1}^{N_b} Q_{u,j} * y_{Mj} \right) + w * \left(P_{fhl} * \left(\sum_{S=1}^K \sum_{j=1}^{N_b} Q_{u,j} * y_{Sj} \right) \right) + w * \left(\sum_{j=1}^{N_b} (\beta_{u,jM} * P_l * y_{Mj}) \right) + \\ & w * \left(\sum_{j=1}^{N_b} (P_{u,j} * \beta_{u,jM} * y_{Mj}) \right) + w * \left(\sum_{j=1}^{N_b} P_{u,j} \sum_{s=1}^K \beta_{u,jS} * y_{Sj} \right) \end{aligned} \quad (2.1-01)$$

$$\text{s.t.} \quad Q_{d,j} * x_{Sj} \leq R_{d,Sj}, \quad j \in \{1, N_b\}, \quad S \in \{1, K\} \quad (2.1-02)$$

$$Q_{d,j} * x_{Mj} \leq R_{d,Mj}, \quad j \in \{1, N_b\} \quad (2.1-03)$$

$$Q_{u,j} * y_{Sj} \leq R_{u,jS}, \quad j \in \{1, N_b\}, \quad S \in \{1, K\} \quad (2.1-04)$$

$$Q_{u,j} * y_{Mj} \leq R_{u,jM}, \quad j \in \{1, N_b\} \quad (2.1-05)$$

$$x_{Mj} + \sum_{S=1}^K x_{Sj} = 1, \quad j \in \{1, N_b\} \quad (2.1-06)$$

$$y_{Mj} + \sum_{S=1}^K y_{Sj} = 1, \quad j \in \{1, N_b\} \quad (2.1-07)$$

$$\sum_{j=1}^{N_b} \beta_{d,Sj} * x_{Sj} + \sum_{j=1}^{N_b} \beta_{u,jS} * y_{Sj} \leq N_{RF,S}, \quad S \in \{1, K\} \quad (2.1-08)$$

$$\sum_{j=1}^{N_b} \beta_{d,Mj} * x_{Mj} + \sum_{j=1}^{N_b} \beta_{u,jM} * y_{Mj} \leq N_{RF,M} \quad (2.1-09)$$

$$\sum_{j=1}^{N_b} Q_{d,j} * x_{Sj} + \sum_{j=1}^{N_b} Q_{u,j} * y_{Sj} \leq C_{fh}, \quad S \in \{1, K\} \quad (2.1-10)$$

$$\sum_{j=1}^{N_b} Q_{d,j} * x_{Mj} + \sum_{j=1}^{N_b} Q_{u,j} * y_{Mj} \leq C_{fh} \quad (2.1-11)$$

$$x_{Sj} \leq T_S, \quad j \in \{1, N_b\}, \quad S \in \{1, K\} \quad (2.1-12)$$

$$\begin{aligned}
 & y_{Sj} \leq T_S, \quad j \in \{1, N_b\}, \quad S \in \{1, K\} \\
 \text{Vs} \quad & T_S, x_{Mj}, x_{Sj}, y_{Mj}, y_{Sj} \in \{0, 1\}, \quad j \in \{1, N_b\}, \quad S \in \{1, K\}
 \end{aligned} \tag{2.1-13}$$

The decision variables of the problem are T_S , which is a binary variable taking value 1 when SBS S turns on and 0 otherwise; x_{Mj} and x_{Sj} , which are binary variables taking values 1 in case of association of UE j to MBS and SBS S in DL, respectively and 0 otherwise, y_{Mj} and y_{Sj} , which are binary variables taking values 1 in case of association of UE j to MBS and SBS S in UL, respectively and 0 otherwise.

Objective function (2.1-01) of the optimization problem is minimization of the total power consumption. It includes the static power consumption of MBS, the dynamic power consumption of MBS in DL, the opening cost of SBS S , FH link power consumption in UL and DL, the dynamic power consumption of MBS in UL, the UE power consumption in case of association with MBS in UL and the UE power consumption in case of association to SBS S . It emphasizes the contribution of the power consumption in UL to the total power consumption. Constraints (2.1-02) and (2.1-03) ensure that the data rate demand of UE j in DL should be less than or equal to the achievable rate from SBS S and MBS to UE j , respectively. Constraints (2.1-04) and (2.1-05) ensure that the data rate demand of UE j in UL should be less than or equal to the achievable rate at SBS S and MBS from UE j , respectively. Constraints (2.1-06) and (2.1-07) assure that UE j can only be assigned to MBS or SBS S in UL and DL, respectively. Moreover, constraints (2.1-08) and (2.1-09) indicate that maximum number of UEs that can be simultaneously served by a BS in UL and DL is less than or equal to the number of RF chains that belongs to SBS, $(N_{RF,S})$, or to MBS, $(N_{RF,M})$, respectively. Constraints (2.1-10) and (2.1-11) imply that the total data being forwarded on the FH link by the assigned UEs both in UL and DL can not exceed the total FH link capacity. Constraints (2.1-12) and (2.1-13) show that SBS S is turned on if there exists an assigned UE in DL or UL.

Theorem 1. *The minimization problem formulated in Section 2.3 is an NP-Complete*

SSCFLP [34], which is a special case of *CFLP*.

Proof. We reduce NP-Complete *SSCFLP* [34] proposed in Section 2.3 to set cover problem [48]. Given a set of j UEs, i BSs, the set cover problem aims to minimize the cost weighted average distance between UE and the nearest of the selected BSs.

First, we assume that the UEs can be served by more than one BS in UL and DL or, which relaxes variables x_{Mj} , y_{Mj} , x_{Sj} , y_{Sj} and T_S to be continuous. In this case, our optimization problem is reduced to *CFLP* [49].

The *CFLP* is NP-Complete as a generalization of the NP-complete set cover problem [48], where $N_{rf,M} = +\infty$, $N_{rf,S} = +\infty$ and $C_{fh} = +\infty$. Therefore, the *SSCFLP* studied in this paper is NP-Complete. $\square$

2.4 Solution Methodology

We propose a polynomial time heuristic algorithm to solve *SSCFLP*. The objective of *SRAA* is to minimize the total power consumption by improving the output of the primal heuristic composed of LP-Relaxation and rounding process with the help of repeated use of two heuristic algorithms, heuristic for modified matching and heuristic for re-allocation of UEs. In previously proposed heuristic algorithms such as *RMA* [34] and *PMA* [35], all UEs as unassigned UEs and all BSs as off BSs are taken as input to heuristic algorithms. In contrast, in *SRAA*, as a result of LP relaxation and rounding, we obtain a set of assigned UE-BS pairs, unassigned UEs and off BSs as the input to the proceeding heuristic algorithms. This reduces the complexity of the algorithm, enables comprehensive and fast search for the minimum and allows the algorithm perform close to optimal.

2.4.1 Selection and Repetition based UE Association Algorithm

The flowchart of the *SRAA* is given in Figure 2.2. The algorithm starts with the initialization of SN, S_{max} , LV, MV and RV. SN counts how many times a UE-BS pair is split into unassigned UEs and turned off BS, S_{max} is the maximum number of

allowed split process, LV is the power consumption value obtained from the heuristic algorithm for modified matching or re-allocation, MV is the power consumption value of the SRAA and RV is the sum of the power consumption value obtained from LP relaxation and rounding and the power consumption value of assigning unassigned UEs to random on BSs.

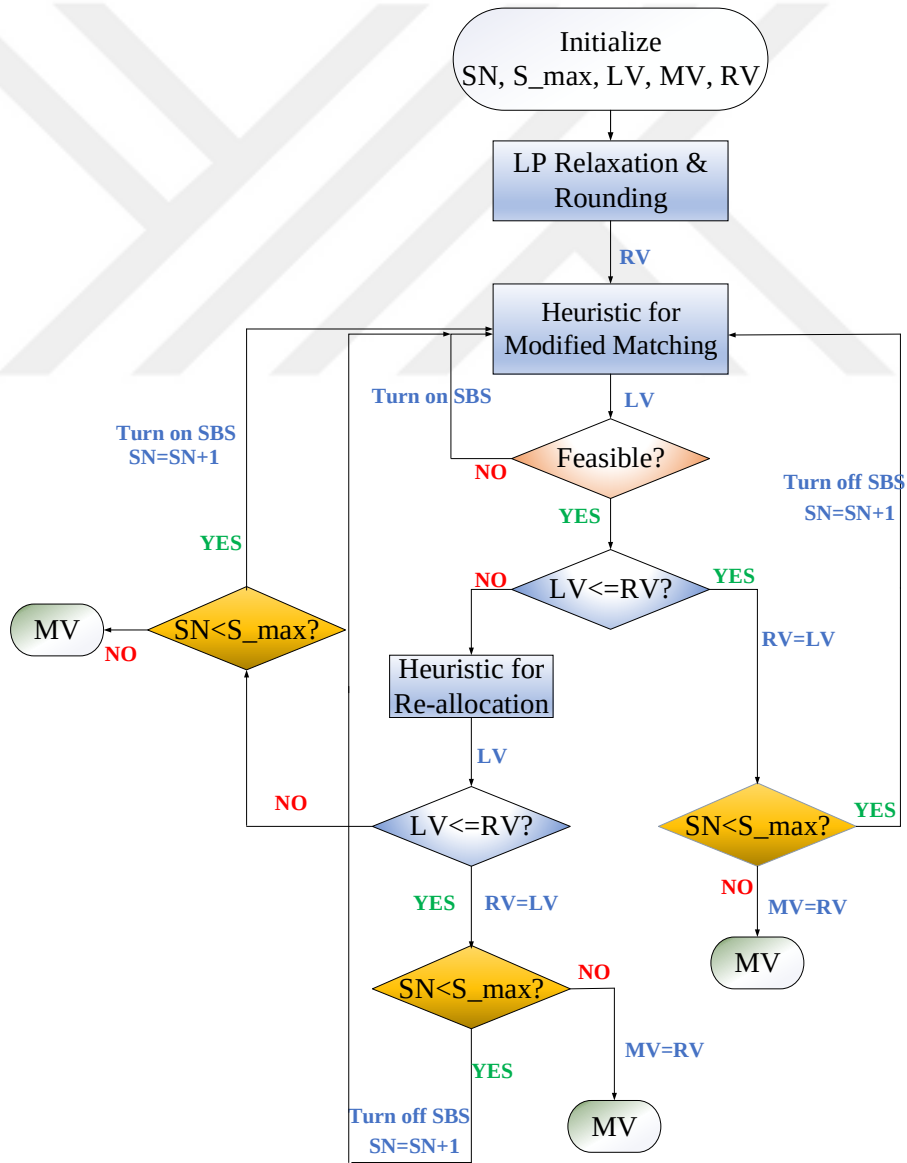


Figure 2.2: General Structure of the SRAA

First, LP Relaxation of the binary integer problem in Equation (2.1-01) is solved, and RV is set to value of LP relaxation and rounding. After rounding process, we obtain a set of assigned UE-BS pairs, unassigned UEs and off BSs. Then, the set is the input to the heuristic for modified matching, where a heuristic for GAP is solved to assign unassigned UEs to on BSs. If the on BSs are not able to provide service to unassigned UEs, then the solution of the heuristic is infeasible, the BS on the top of off BS list, where off BSs are listed in capacity increasing order according to sum of β values in UL and DL of unassigned UEs, where each sum is calculated for each BS and all unassigned UEs present in the network, is turned on and heuristic for modified matching is run again. Otherwise, LV is set to the power consumption of the output of the heuristic for modified matching. If the power consumption value obtained from the heuristic for modified matching is less than RV, then SRAA turns off the BS on top of on BS list, where on BSs are listed in capacity increasing order according to their residual capacities, which are obtained by subtracting the sum of β values of assigned UEs in UL and DL from the total capacity values. The UEs assigned to the turned off BS become unassigned and heuristic for modified matching is run again to check if the power consumption can be further decreased by turning off an on BS as long as SN is less than S_{max} .

If the heuristic for modified matching does not provide decrease in the power consumption, SRAA checks if the UEs of the assigned UE-BS pairs can be re-allocated to further minimize total power consumption by using the heuristic for re-allocation of UEs. If UE re-allocation provides further decrease in total the power consumption, the BS on top of on BS list is turned off, the UEs assigned to the turned off BS become unassigned and heuristic for modified matching is run again to check if the power consumption can be further decreased as long as SN is less than S_{max} . Otherwise, the BS on top of off BS list is turned on and heuristic for modified matching is run again to check if the power consumption can be further decreased as long as SN is less than S_{max} .

The selection process to find the least power consuming BSs out of n BSs consumes

$\mathcal{O}(\log n)$ time, since we divide n BSs into two sets, which contain on BSs and off SBSs and each set is sorted according to capacity values. Instead of checking every BS to find the least power consuming BSs, we simply divide-and-conquer by looking based on where each BS stands in the list with respect to their capacity value and we select the least power consuming out of on BS list. We associate each of m UE with the on BSs, where the association of each UE consumes $\mathcal{O}(m)$ time. Therefore, the complexity of the algorithm is $\mathcal{O}(m \log n)$.

The detailed description of the main functions of the SRAA algorithm is stated as follows:

LP Relaxation & Rounding

LP Relaxation of the binary integer optimization problem in Equation (2.1-01), is solved, rounded and set of assigned UE-BS pairs, unassigned UEs and off BSs is obtained as an output. However, we encounter infeasibility issues related to violation of some constraints of the optimization problem. Detailed explanations on how we overcome infeasibility problems and obtain this set are as follows:

- Values of all decision variables are equal to 0.5. With rounding process, all values are rounded up to 1 revealing each UE is assigned to two BSs. In this case, the constraints (2.1-06) and (2.1-07) are violated. To prevent one UE-multiple BS association, we calculate the power consumption value of association of UE with each BS by setting the corresponding association values to 1 and evaluating the additional contribution in the objective function of the optimization problem (2.1). The BS providing a lower power consumption value is set to 1 while the other is set to 0. However, the input to the following heuristic for modified matching should contain at least one unassigned UE, one on BS and one UE-BS pair. Therefore, the BS on top of on BS list is turned off and the UEs associated with it become unassigned. We gather unassigned UEs and UE-BS pairs as input to heuristic for modified matching.

- Values of all decision variables are less than 0.5 and rounded down to 0 indicating all UEs are unassigned and all BSs are off. However, the input to the following heuristic for modified matching should contain at least one unassigned UE, one on BS and one UE-BS pair. Therefore, the BS on top of off BS list is turned on. We obtain unassigned UEs and an on BS as input to heuristic for modified matching.
- Values of decision variables have such values that after rounding the UE-BS associations are feasible. In this case, the BS on top of on BS list is turned off and the UEs associated with it become unassigned. We get unassigned UEs and UE-BS pairs as input to heuristic for modified matching.

Modified Matching Problem

The Modified Matching Problem aims to minimize the system power consumption by assigning unassigned UEs to UE-BS pairs or on BSs without turning on additional BSs. Unlike the optimization problem 2.1, which takes only unassigned UEs and off SBSs as input, Modified Matching Problem takes unassigned UEs, UE-BS pairs and on BSs as input. Moreover, the capacity constraints at SBS sb , MBS and FH link are updated as $N_{RF, sb} - C_{sb}$, $N_{RF, M} - C_M$, $C_{fh, sb} - N_{sb}$ and $C_{fh, M} - N_M$ respectively where C_{sb} , C_M , N_{sb} and N_M are the capacities allocated to assigned UEs at SBS sb , MBS, FH link of SBS and MBS, respectively. The optimization problem is formulated as:

$$\begin{aligned}
 \min \quad & \sum_{sb=1}^R \sum_{j=1}^P ((Q_{d,j}^t * P_{fhl}) * z_{sb,j} + P_i) + \sum_{sb=1}^R P_S + \sum_{j=1}^P (\beta_{d,Mj} * P_l) * z_{Mj} + P_{static} + \sum_{j=1}^P (P_{fhl} * Q_{d,j}) \\
 & w * \sum_{sb=1}^R \sum_{j=1}^P (P_{u,j} \sum_{sb=1}^R \beta_{u(j,sb)} + (Q_{u,j} * P_{fhl})) * v_{sb,j} + w * \sum_{j=1}^P \left((P_{u,j} + P_l) * \beta_{u,jM} \right) * v_{Mj}
 \end{aligned} \tag{2.2-01}$$

$$\text{s.t.} \quad \sum_{j=1}^P \beta_{d,(sb,j)} * z_{sb,j} + \sum_{j=1}^P \beta_{u,(j,sb)} * v_{sb,j} \leq N_{RF,sb} - C_{sb}, \quad sb \in \{1, R\} \quad (2.2-02)$$

$$\sum_{j=1}^P \beta_{d,Mj} * z_{Mj} + \sum_{j=1}^P \beta_{u,jM} * v_{Mj} \leq N_{RF,M} - C_M \quad (2.2-03)$$

$$\sum_{j=1}^P Q_{d,j} * z_{sb,j} + \sum_{j=1}^P Q_{u,j} * v_{sb,j} \leq C_{fh,sb} - N_{sb}, \quad sb \in \{1, R\} \quad (2.2-04)$$

$$\sum_{j=1}^P Q_{d,j} * z_{Mj} + \sum_{j=1}^P Q_{u,j} * v_{Mj} \leq C_{fh,M} - N_M, \quad (2.2-05)$$

$$z_{Mj} + \sum_{sb=1}^R z_{sb,j} = 1, \quad j \in \{1, P\} \quad (2.2-06)$$

$$v_{Mj} + \sum_{sb=1}^R v_{sb,j} = 1, \quad j \in \{1, P\} \quad (2.2-07)$$

$$\forall s \quad z_{sb,j}, v_{sb,j}, z_{Mj}, v_{Mj} \in \{0, 1\}, \quad j \in \{1, P\}, \quad sb \in \{1, R\}$$

where R is the number of on SBSs and P is the number of unassigned UEs. The decision variables of the problem are $z_{sb,j}$ and $v_{sb,j}$, which are binary variables taking values 1, when an on SBS sb and an unassigned UE j gets associated with each other in UL and DL, respectively and 0 otherwise; z_{Mj} and v_{Mj} , which are binary variables taking values 1 when MBS and an unassigned UE j gets associated with each other in UL and DL, respectively and 0 otherwise.

Different from the binary integer optimization problem with the objective function, Equation (2.1-01), objective function Equation (2.2-01) aims to minimize the power consumption by including the power consumption of UE-BS pairs, on BSs and association of unassigned UEs to on BSs or UE-BS pairs. Additionally, unlike the capacity constraints in Equations (2.1-08), (2.1-09) and (2.1-10), capacity constraints in Equations (2.2-02), (2.2-03), (2.2-04) and (2.2-05) provide less capacity due to capacity reserved for assigned UEs at SBS sb , MBS and FH link of SBS sb and MBS, respectively.

The optimization problem in Section 2.4.1 has the form GAP. GAP is NP-Hard

and due to its NP-Hard nature, it cannot be solved to optimality in polynomial time [50]. We utilize the heuristic algorithm, which aims to find a subset of UEs that has a feasible association with a BS and assigns all UEs with BSs, such that the power consumption is minimized, to solve the problem [51]. First of all, sum of β_d and β_u values are calculated for each UE-SBS and UE-MBS pair, stored in a capacity matrix. Similarly, the power consumption values of UE-SBS and UE-MBS pairs are calculated and stored in a profit function matrix, where columns represent BSs and rows represent UEs. Then, a BS is turned on randomly and the UEs, whose sum of β_d and β_u values do not exceed the capacity limit of corresponding BS are selected to get associated with the on BS. Accordingly, profit function matrix is decomposed into two sub-matrices. In the first sub-matrix, the rows of the selected UEs are assigned to the power consumption value of the selected UE-BS pair, the unselected UE-on SBS row-column pairs save their values and unselected UEs-off BSs row-column pairs are assigned to zero. The second sub-matrix is formed by subtracting the first sub-matrix from the profit function matrix. The columns, which are all composed of zeros, are eliminated and the matrix becomes the new profit function matrix. This decomposition and elimination processes continue until there is one column, which is all composed of zeros. The UEs associated with BSs are recorded and not allowed to re-associate in ongoing decomposition and elimination processes. The solution is the sum of the minimum power consumption values of each pair and a valid association of UE-BS pair.

Heuristic for re-allocation of UE-BS pairs

Heuristic for re-allocation of UE-BS pairs takes the outputs of the modified matching heuristic, which are UE-BS pairs and the total power consumption value, as inputs and checks if re-allocation of UE-BS pairs further minimizes the total power consumption.

The heuristic algorithm proceeds as follows: β values of UEs for each on BS are calculated. First, the BS on the top of on BS list is selected and the UEs associated with the selected BS are exchanged with the UEs associated with the remaining BSs

in the on BS list one by one. In each exchange process, the capacity requirement is checked and corresponding power consumption is saved. The power consumption value of the heuristic is updated with the minimum power consumption value obtained in whole exchange process for a UE and UE-BS allocation is updated with UE-BS association, which provides the minimum power consumption. Then, this exchange process is repeated for all on BSs in on BS list and their associated UEs without changing the association of previously exchanged UEs.

We present an example to clarify the process with Figure 2.3. First, MV, LV, RV and SN are set to zero and S_{max} is set to 2. DL transmission is represented with straight line whereas UL transmission is represented with dashed line. On BSs and off BSs are listed in capacity increasing order according to their residual capacity values. Then, by using the output of the LP relaxation and rounding in Section 2.4.1, network is formed as in Figure 2.3-1, with three UE-BS pairs (green circles-red triangles), two unassigned UEs (black triangles). RV is updated with the solution of the LP relaxation of the binary integer optimization problem and rounding.

We run heuristic for modified matching. We assume that capacity of on BSs in Figure 2.3-1 is not sufficient to provide connection to UEs. Therefore the association between unassigned UEs and UE-BS pairs is infeasible. In this case LV does not change, we turn on SBS 3, which is on top of off BS. Heuristic for modified matching is run again, unassigned UEs get associated with on SBS 3, the association is feasible and LV is set to the power consumption value of UE-BS association in Figure 2.3-2. Next, we assume that LV is less than RV. RV is set to LV, SN is less than 2, SBS 1 is turned off to check if less number of on BSs can provide service to UEs and appended to the end of off BS list. The UEs assigned with SBS 1 become unassigned and SN becomes 1 in Figure 2.3-3. Heuristic for modified matching is run again, the association is assumed to be infeasible, LV does not change and SBS 4 is turned on. The unassigned UEs get associated with SBS 4 and LV is set to the power consumption value of UE-BS association in Figure 2.3-4. We assume that LV is greater than RV, therefore RV does not change. Heuristic for re-allocation is run, LV is set to the

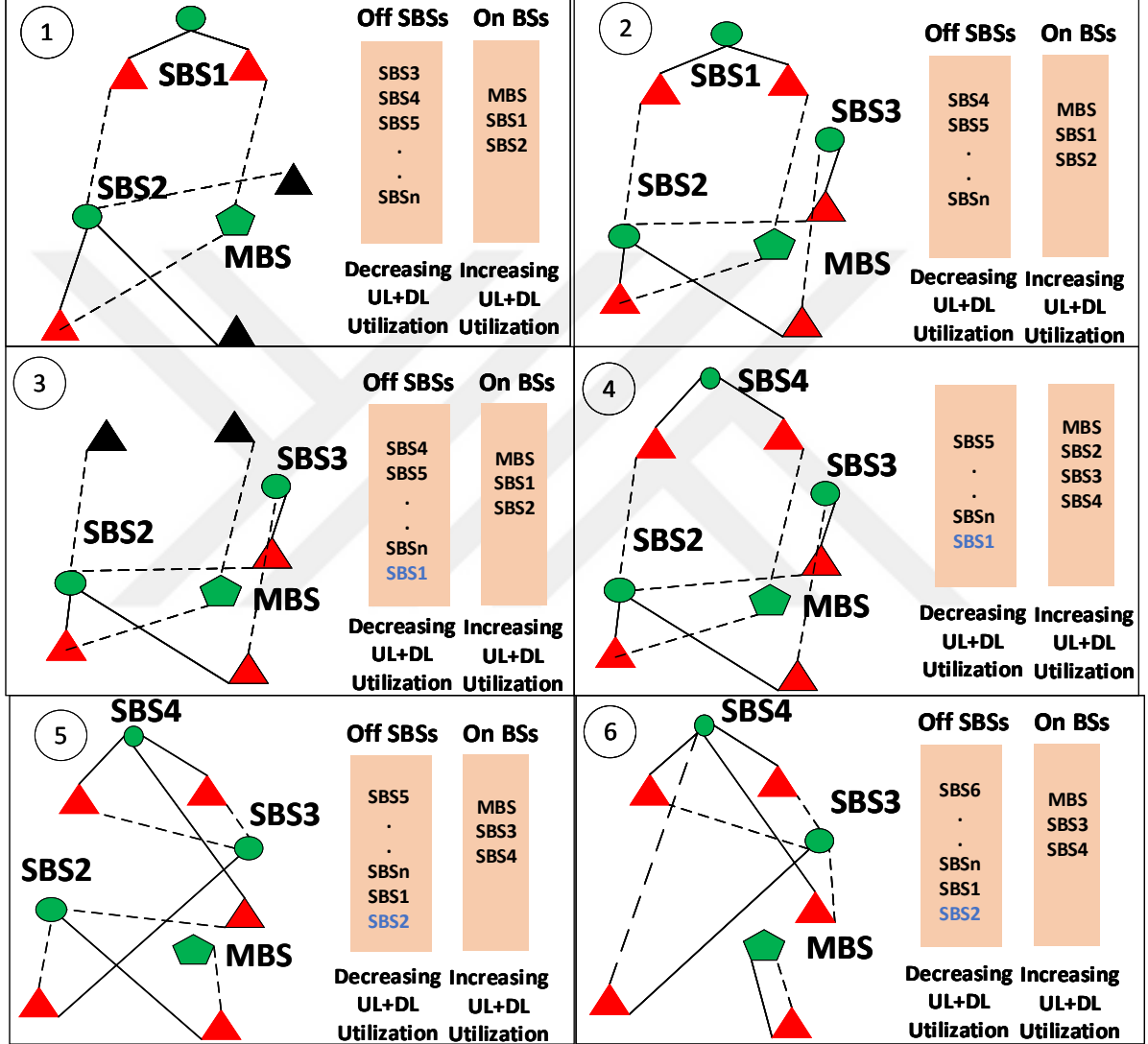


Figure 2.3: Heuristic Example. Green circle represents on SBSs and green pentagon represents on MBS. Red triangle is assigned UE, whereas black triangle is unassigned UE.

power consumption value of UE-BS association in Figure 2.3-5. In the event, where we consider LV to be less than RV, RV is set to LV, SN is less than 2, SBS 2 is turned off and SN becomes 2 in Figure 2.3-6. Heuristic for modified matching is run again, LV is set to the power consumption value of UE-BS association in Figure 2.3-6, the

output is feasible. LV is assumed to be less than RV, RV is set to LV but SN is equal to 2, which is S_{max} . Therefore, the algorithm stops and returns RV.

2.4.2 Algorithm Analysis

Energy efficient UE association is highly dependent on the power consumption and $Q_{d,j}$ and $Q_{u,j}$ threshold values are the most important decision factors which enable UEs to associate with BSs that minimizes the total power consumption. Therefore, in this section, we derive and compare the regions for $Q_{d,j}$ and $Q_{u,j}$ threshold values of UE association cases for the optimal algorithm, SRAA and RMA.

RMA is explained as follows:

- RMA uses the repeated matching approach to form new feasible UE-BS pairs from previously determined ones with the aim of minimizing the total power consumption and the power consumption of each UE-BS association is scaled by cost values, which are obtained by normalizing the distance between each UE-BS association with the minimum distance of UE-BS association attained in the network [34]. The process starts by taking any feasible UE-BS pair and then continues by forming sequence of feasible UE-BS pairs of decreasing cost. When repeated matching fails to yield any further reduction in the power consumption, the UE-BS pair is split so that UEs previously assigned to certain BSs become unassigned. Before the splitting, improved solution is found by applying a heuristic based on solving a GAP, which aims to find improved re-allocation of the UEs by considering all on and off BSs present in the network. After the splitting, a new sequence of feasible UE-BS pairs is generated to facilitate further progress. This process is then repeated until no further progress can be made in a fixed number of splits. The complexity of the algorithm is $\mathcal{O}(mn)$, where n is the number of BSs and m is the number of UEs.

We consider a network, where the UE is located at an equal distance to SBSs and its distance to MBS is larger than its distance to SBSs as depicted in Figure

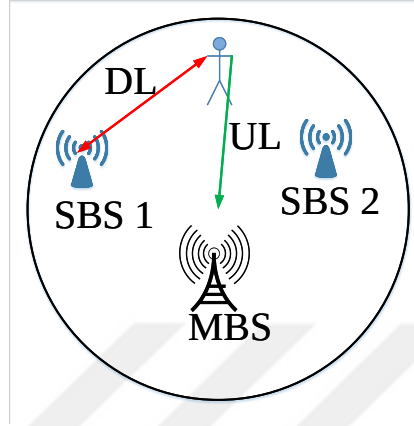


Figure 2.4: Network Topology

2.4. According to the network proposed in Figure 2.4, there exists nine different association cases for a UE to associate with any BS in UL and DL as follows:

1. Association to SBS 1 in DL and MBS in UL
2. Association to SBS 1 in DL and SBS 2 in UL
3. Association to SBS 1 in DL and SBS 1 in UL
4. Association to SBS 2 in DL and MBS in UL
5. Association to SBS 2 in DL and SBS 1 in UL
6. Association to SBS 2 in DL and SBS 2 in UL
7. Association to MBS in DL and SBS 1 in UL
8. Association to MBS in DL and SBS 2 in UL
9. Association to SBS 2 in DL and SBS 2 in UL

Energy efficient UE association for the optimal algorithm is determined based on the comparison of the power consumption values for UE-MBS and UE-SBS association

for both UL and DL in objective function (2.1-01). Then, UE associates with the BS which causes less power consumption by using the formulation of the minimum power consuming association in objective function (2.1-01), the specific ranges are derived for $Q_{d,j}$ and $Q_{u,j}$.

To exemplify the derivation, we assume that UE gets associated with the SBS S in DL and MBS in UL. Detailed explanations on how we derive these values are as follows:

- Since we assume that UE gets associated with the SBS S in DL, the energy consumption corresponding to UE-SBS association is smaller than that of the UE-MBS association in Equation (2.1-01). The inequality proving the statement is then stated as follows:

$$P_S + P_{fhl} * Q_{d,1} < P_l * \beta_{d,M1} + P_{fhl} * Q_{d,1}. \quad (2.3)$$

- $Q_{d,1}$ value should satisfy the inequality (2.3) as follows:

$$Q_{d,1} > R_{d,M1} * \left(\frac{P_S}{P_l} \right) \quad (2.4)$$

- Since there exists no additional UE associated with the SBS S in DL, by taking capacity constraint (2.1-08) into consideration $Q_{d,1}$ takes the maximum value that SBS S can provide to a UE as follows:

$$Q_{d,1} \leq N_{rf,S} * R_{d,S1} \quad (2.5)$$

- To sum up, $Q_{d,1}$ value for the optimal algorithm should be between the $Q_{d,1}$ values stated in Equations (2.4) and (2.5).
- If there exists more than one SBS in the network, then in order to decide on SBS 1, $\beta_{d,11}$ should be less than the rest $\beta_{d,S1}$ values, which guarantees service

to more UEs and forces $R_{d,11}$ to be greater than rest $R_{d,S1}$ values.

$$\beta_{d,11} < \beta_{d,S1}, \forall S \in \{2, K\} \quad (2.6)$$

- In order for a UE to get associated with MBS in UL, the power consumed in UL due to MBS transmission should be less than the power consumed in UL due to SBS transmission. By using the objective function (2.1-01), the inequality proving the statement is stated as follows:

$$P_S + P_{fhl} * Q_{u,1} + \beta_{u,1S} * P_{u,1} > \beta_{u,1M} * (P_l + P_{u,1}) + P_{fhl} * Q_{u,1} \quad (2.7)$$

- $Q_{u,1}$ value supporting the inequality (2.7), which is based on the power consumption comparison, is derived as follows:

$$Q_{u,1} < P_S * \left(\frac{P_l + P_{u,1}}{R_{u,1M}} - \frac{P_{u,1}}{R_{u,1S}} \right)^{-1} \quad (2.8)$$

- Since there exists capacity constraints, comparison of the power consumption values is not sufficient to decide on the appropriate $Q_{u,1}$ value. Therefore, capacity constraints (2.1-08) and (2.1-09) are taken into consideration. There exists no additional UE associated with the MBS in DL and $Q_{u,1}$, which is based on capacity requirements of MBS takes the maximum value that MBS can provide to a UE and it is stated as follows:

$$Q_{u,1} \leq N_{rf,M} * R_{u,1M} \quad (2.9)$$

However, UE is associated with SBS S in DL, therefore the maximum data rate SBS S can provide to UE is proportional to the residual capacity at SBS S, which is

$$Q_{u,1} \leq (N_{rf,S} - C_1) * R_{u,1S} \quad (2.10)$$

- To sum up, $Q_{u,1}$ value for the optimal algorithm should be equal to the minimum of the $Q_{u,1}$ values stated in Equations (2.8), (2.9) and (2.10).

$Q_{d,j}$ and $Q_{u,j}$ threshold values for UE association in SRAA are also derived based on the power consumption values in UL and DL in objective function 2.2-01, respectively. Since there exists one UE in the network and it is assumed to be associated with SBS 1 in DL and MBS in UL, capacity reserved for UE 1 at MBS, C_{M1} , and at the rest of SBSs, C_{S1} , are zero. Therefore, $Q_{d,j}$ and $Q_{u,j}$ threshold values of SRAA are equal to data rate threshold values for the optimal algorithm for $C_{M1} = 0$ and $C_{S1} = 0$.

$Q_{d,j}$ and $Q_{u,j}$ threshold values for UE association in RMA are derived based on the power consumption values in UL and DL by a small difference from SRAA. Unlike SRAA, in RMA, the power consumption of each UE-BS association is scaled by cost values, c_{Sj} or c_{Mj} , which are formulated as $c_{Sj} = \frac{h_{Sj}}{h_{min}}$ and $c_{Mj} = \frac{h_{Mj}}{h_{min}}$, where h_{Mj} corresponds to the distance between MBS and UE j, h_{Sj} is the distance between SBS S and UE j and h_{min} is the minimum distance in the network.

- Since we assume that UE gets associated with the SBS S in DL, the energy consumption corresponding to UE-SBS association is smaller than that of the UE-MBS association in the modified version of objective function (2.1-01), which is modified with c_{Mj} and c_{Sj} scaled the power consumption values of UE-BS association. The inequality proving the statement is stated as follows:

$$P_S + P_{fhl} * c_{S1} * Q_{d,1} < P_l * c_{M1} * \beta_{d,M1} + P_{fhl} * c_{M1} * Q_{d,1} \quad (2.11)$$

- $Q_{d,1}$ value in RMA should satisfy the inequality (2.11) as follows:

$$Q_{d,1} > P_S * \left(c_{M1} * \left(\frac{P_l}{R_{d,M1}} + P_{fhl} \right) - c_{S1} * P_{fhl} \right)^{-1} \quad (2.12)$$

- To sum up, $Q_{d,1}$ value for RMA should be between $Q_{d,1}$ values stated in Equations (2.12) and (2.13).

tions (2.11) and (2.12).

- Since there exists no additional UE associated with the SBS S in DL, by taking capacity constraint (2.1-08) into consideration $Q_{d,1}$ takes the maximum value that SBS S can provide to a UE as follows:

$$Q_{d,1} \leq N_{rf,S} * R_{d,S1} \quad (2.13)$$

- If there exists more than one SBS in the network, then in order to decide on SBS 1 in RMA, $\beta_{d,11}$ scaled with c_{11} should be less than the rest $\beta_{d,S1}$ scaled with c_{S1} values, which guarantees service to more UEs and forces $R_{d,11}$ to be greater than rest $R_{d,S1}$ values.

$$c_{11} * \beta_{d,11} < c_{S1} * \beta_{d,S1}, \forall S \in \{2, K\} \quad (2.14)$$

- In order for a UE to get associated with MBS in UL, the power consumed in UL due to MBS transmission should be less than the power consumed in UL due to SBS transmission. By taking the scaled version of the objective function, Equation (2.1-01) into consideration, the inequality proving the statement is stated as follows:

$$P_S + P_{fhl} * Q_{u,1} * c_{S1} + \beta_{u,1S} * P_{u,1} * c_{S1} > \beta_{u,1M} * c_{M1} (P_l + P_{u,1}) \quad (2.15)$$

- $Q_{u,1}$ value supporting the inequality (2.15), which is based on the power consumption comparison, is derived as follows:

$$Q_{u,1} < P_S * \left(\left(\frac{P_l + P_{u,1}}{R_{u,1M}} + P_{fhl} \right) * c_{M1} - P_{fhl} * c_{S1} - \frac{P_{u,1} * c_{S1}}{R_{u,1S}} \right)^{-1} \quad (2.16)$$

- Since there exists capacity constraints, comparison of the power consumption values is not sufficient to decide on the appropriate $Q_{u,1}$ value. Therefore,

capacity constraints (2.1-08) and (2.1-09) are taken into consideration. There exists no additional UE associated with the MBS in DL, $Q_{u,1}$ takes the maximum value that MBS can provide to a UE and it is stated as follows:

$$Q_{u,1} \leq N_{rf,M} * R_{u,1M} \quad (2.17)$$

However, UE is associated with SBS S in DL, therefore the maximum data rate SBS S can provide to UE is proportional to the residual capacity at SBS S, which is

$$Q_{u,1} \leq (N_{rf,S} - C_1) * R_{u,1S} \quad (2.18)$$

- To sum up, $Q_{u,1}$ value for RMA should be equal to the minimum of the $Q_{u,1}$ values stated in Equations (2.16), (2.17) and (2.18).

Based on the derivations explained above, for the network proposed in Figure 2.4, we demonstrate $Q_{d,j}$ and $Q_{u,j}$ values for the first case for the optimal algorithm, SRAA and RMA in Table 2.1. The remaining cases are derived similarly.

Figures 2.5, 2.6 and 2.7 illustrate the similarities and differences of the optimal algorithm, SRAA and RMA for nine different cases. The optimal algorithm and SRAA tend to have same data rate demand threshold values for association to same BSs in UL and DL. On the other hand, since the power consumption of each association in RMA is scaled, data rate demands for association with the same BS in UL and DL are less than the optimal algorithm and SRAA for all cases. Figures 2.5 and 2.6 demonstrate that the optimal algorithm and SRAA have same network topologies for same data rate demands both in UL and DL but RMA assigns the UE to the same corresponding BS with less data rate demand threshold value. In case of increase in data rate demand either in DL or UL, the frequency of the topology change is high for RMA compared to the optimal algorithm and SRAA.

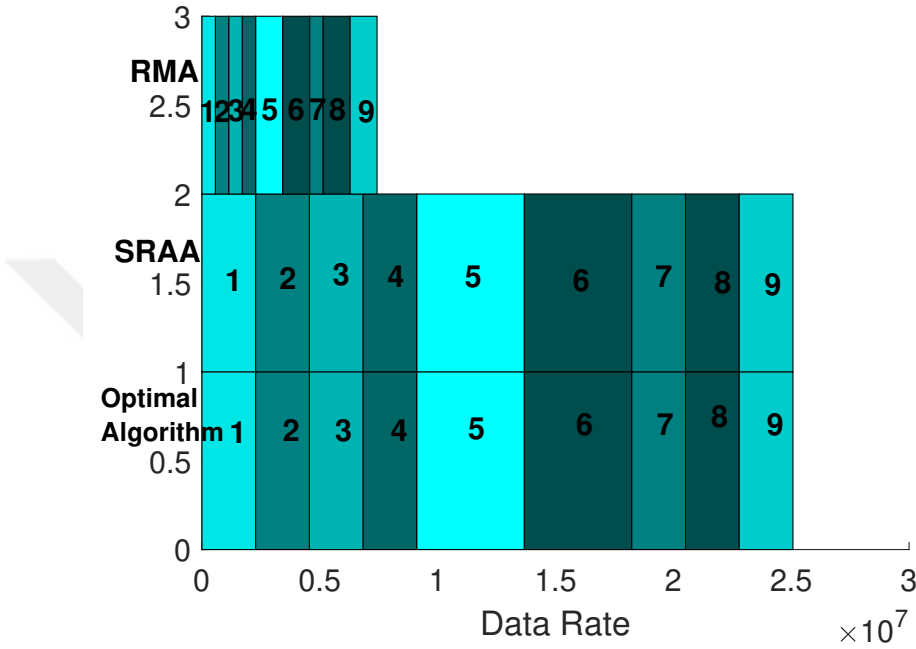


Figure 2.5: UL Data Rate Thresholds

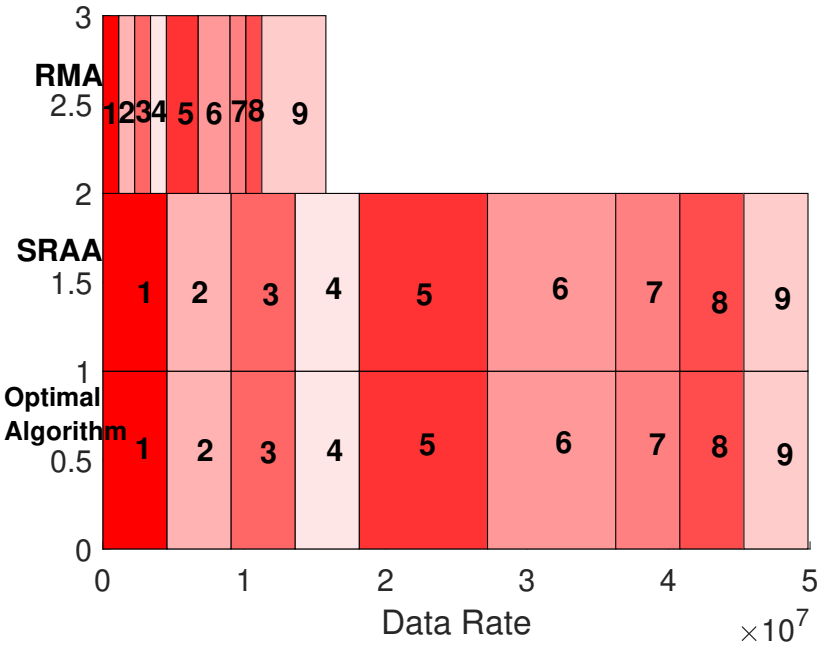


Figure 2.6: DL Data Rate Thresholds

Optimal Algorithm	(a)	(i) $Q_{d,1} > R_{d,M1} * \left(\frac{P_S}{P_l} \right)$
		(ii) $Q_{d,1} \leq N_{rf,1} * R_{d,11}$
		(iii) $\beta_{d,11} < \beta_{d,21}$
	(b)	(i) $Q_{u,1} < \min \left((N_{RF,M} * R_{u,1M}), ((N_{rf,1} - C_1) * R_{u,11}), Q_{u,1} < P_1 * \left(\frac{P_l + P_{u,1}}{R_{u,M}} - \frac{P_{u,1}}{R_{u,11}} \right)^{-1} \right)$
		(ii) $Q_{u,1} < \min \left((N_{RF,M} * R_{u,1M}), ((N_{rf,2} - C_2) * R_{u,12}), P_2 * \left(\frac{(P_{u,M1} + P_l)}{R_{u,1M}} - \frac{P_{u,1}}{R_{u,12}} \right)^{-1} \right)$
SRAA	(a)	(i) $Q_{d,1} > R_{d,M1} * \left(\frac{P_S}{P_l} \right)$
		(ii) $Q_{d,1} \leq N_{rf,1} * R_{d,11}$
		(iii) $\beta_{d,11} < \beta_{d,21}$
	(b)	(i) $Q_{u,1} < \min \left((N_{RF,M} * R_{u,1M}), ((N_{rf,1} - C_1) * R_{u,11}), Q_{u,1} < P_1 * \left(\frac{P_l + P_{u,1}}{R_{u,M}} - \frac{P_{u,1}}{R_{u,11}} \right)^{-1} \right)$
		(ii) $Q_{u,1} < \min \left((N_{RF,M} * R_{u,1M}), ((N_{rf,2} - C_2) * R_{u,12}), P_2 * \left(\frac{(P_{u,M1} + P_l)}{R_{u,1M}} - \frac{P_{u,1}}{R_{u,12}} \right)^{-1} \right)$
RMA	(a)	(i) $Q_{d,1} > P_S * \left(c_{M1} * \left(\frac{P_l}{R_{d,M1}} + P_{fhl} \right) - c_{S1} * P_{fhl} \right)^{-1}$
		(ii) $Q_{d,1} \leq N_{rf,1} * R_{d,11}$
		(iii) $c_{11} * \beta_{d,11} < c_{21} * \beta_{d,21}$
	(b)	(i) $Q_{u,1} < \min \left((N_{RF,M} * R_{u,1M}), ((N_{rf,1} - C_1) * R_{u,11}), P_1 * \left(\left(\frac{P_l + P_{u,1}}{R_{u,1M}} + P_{fhl} \right) * c_{M1} - P_{fhl} * c_{11} \right)^{-1} \right)$
		(ii) $Q_{u,1} < \min \left((N_{RF,M} * R_{u,1M}), ((N_{rf,2} - C_2) * R_{u,12}), P_2 * \left(\left(\frac{P_l + P_{u,1}}{R_{u,1M}} + P_{fhl} \right) * c_{M1} - P_{fhl} * c_{21} \right)^{-1} \right)$

Table 2.1: 1) Association to SBS 1 in DL and MBS in UL

Figure 2.7 illustrates the superiority of the optimal algorithm and SRAA over RMA in terms of minimizing the total power consumption. For the first four cases, the dynamic power consumption of MBS causes increase in the system power consumption and the association of UE to MBS is independent of UL or DL connection to MBS. The underlying difference between the power consumption values of the optimal algorithm, SRAA and RMA is that the power consumption values of each association pair in RMA are scaled with c_{Mj} and c_{ij} . However, in cases five, six, eight and nine (UE association to SBSs in UL and DL), the effect of c_{Mj} is eliminated and all of the algorithms consume the same power.

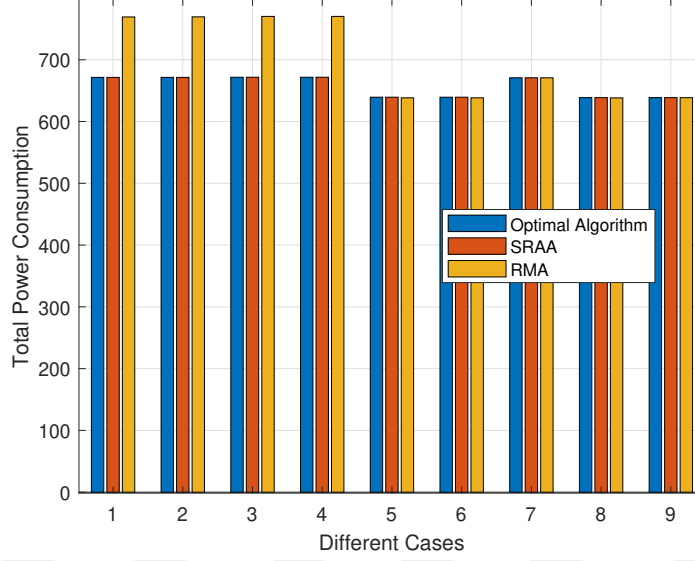


Figure 2.7: Comparison of Association Cases

2.5 Simulations and Performance Evaluation

The goal of this section is to evaluate the performance of the SRAA for various data rate requirements, network topologies and weighting value w compared to previously proposed heuristic algorithms including RMA [34] and PMA [35]; demonstrate the importance of the incorporation of the dynamic power consumption of MBS and the FH link power consumption and decoupling UL and DL in UE association on the optimal power consumption. Besides RMA explained in Subsection 2.4.2, performance of SRAA is also compared to PMA, which is a heuristic algorithm previously proposed for matching problem [35]. This algorithm is based on using random walk to form minimum power consuming UE-BS pairs. Heuristic starts by associating a random UE with a random BS. Then, new association pairs are found by performing random walk based on the current matching. The random walk G , is updated in each turn based on the result of the previously realized random walk. The G is updated as follows: A random UE selects a random BS according to a Markov transition matrix, M . M is obtained by normalizing $\beta_{i,j}$ values with $N_{RF,i}$ values, $\left(\frac{\beta_{i,j}}{N_{RF,i}}\right)$, of the elements of the

current matching. Each UE aims to associate with the minimum power consuming BS. This process is repeated for all UEs until each UE is assigned to the same BS, which it has been associated with in the r^{th} turn. The complexity of the algorithm is $\mathcal{O}(mn)$, where n is the number of BSs and m is the number of UEs.

Simulations are performed by using IBM CPLEX Optimization Studio with MathWorks MATLAB. Simulation results are obtained and averaged based on 5000 random configurations where SBSs and UEs are distributed randomly and uniformly within the circular area of radius within [50,700]m, with the additional restriction of minimum distance of 10m among SBSs.

Uniform random single-path (UR-SP) Channel Model in [67] is adopted capturing the dominant path in directional propagation environments. The links are assumed to be in LoS, where no obstacles reside between transmit and receive antennas, or in NLoS, where partial or full obstructions exist between the transmit and receive antennas, or in outage and we decide on the state randomly. The attenuation of the links are determined considering large scale statistics that arise primarily from the free space loss and the environment affecting the degree of refraction, diffraction, reflection and absorption. The dependence of the path loss on distance summarizing large scale statistics is modeled as $\alpha_{ij} = PL(d_0) + 10 * \eta_j * \log_{10} \left(\frac{d_{du,ij}}{d_0} \right) + X_{\sigma_j}$ in DL and as $\theta_{ij} = PL(d_0) + 10 * \eta_j * \log_{10} \left(\frac{d_{du,ij}}{d_0} \right) + X_{\sigma_j}$ in UL, where $PL(d_0)$ is the free space path loss in dB at a reference distance d_0 , η_j is the path loss exponent, $d_{du,ij}$ is the distance between BS i and UE j and X_{σ_j} is a zero mean Gaussian random variable with σ_j^2 variance. However, path loss is modeled in LOS and NLOS scenarios differently by making use of different η_j and σ_j values in 28 GHz as demonstrated in [37]. We investigate the network with two different data rate demand ranges which are considered to be low and high as compared to maximum achievable data rates in LTE (300 Mbps in DL and 75 Mbps in UL) [52]. The internal hardware power consumption parameters of MBS and SBS are stated in [42] and FH link power consumption is stated in [46]. The simulation parameters follow Table 2.2.

Carrier Frequency	28 GHz SBSs 2.4 GHz for MBS
Bandwidth	800 MHz for 28 GHz [37] 20 MHz for 2.4 GHz
PSD of Noise at each UE	-134 dBm/MHz [41]
DL tx power	MBS: 43 dBm SBS: 33 dBm UE : 23 dBm
BS antenna height	7 m [37]
SBS antenna height	2 m [37]
UE antenna height	1.5 m [37]
Number of RF Chains	MBS: 8 RF Chains SBS: 4 RF Chains
Path loss Model	ITU Urban Macro LOS-NLOS
Fading Model	σ_j MBS : 8.9 dB σ_j SBS-LOS : 1.1 dB [37] σ_j NLOS : 10 dB [37]
Path loss Exponent	η_j MBS : 2 η_j SBS-LOS : 1.9 [37] η_j SBS-NLOS : 4.5 [37]
Capacity of FH Link	4.45 Gbps
DL Data Demand (Low)	U (0.1-0.5)Mbps
DL Data Demand (High)	U (0.15-2)Gbps
UL Data Demand (Low)	U (0.01-0.03)Mbps
UL Data Demand (High)	U (0.2-0.5)Gbps

Table 2.2: System Parameters

2.5.1 Performance Comparison of Different Algorithms

Figure 2.8 shows the system power consumption of different algorithms for increasing number of UEs. For $w=0$, as number of UEs increases, the power consumption of all algorithms increases. The SRAA performs very close to optimal, significantly better than previously proposed algorithms due to controlled on/off operation of SBSs with the repeated use of modified matching heuristic and GAP heuristic. The use of modified matching heuristic with the GAP heuristic reduces UE TX power by finding optimal BSs for the minimum power consumption. Additionally, though high number of on SBSs provides decrease in UE TX power and the UL power consumption, the power consumption of PMA increases due to increase in the operational cost of on SBSs and exceeds the power consumption of RMA. Moreover, as w increases, the power consumption values of all algorithms increase and RMA has an unexpected

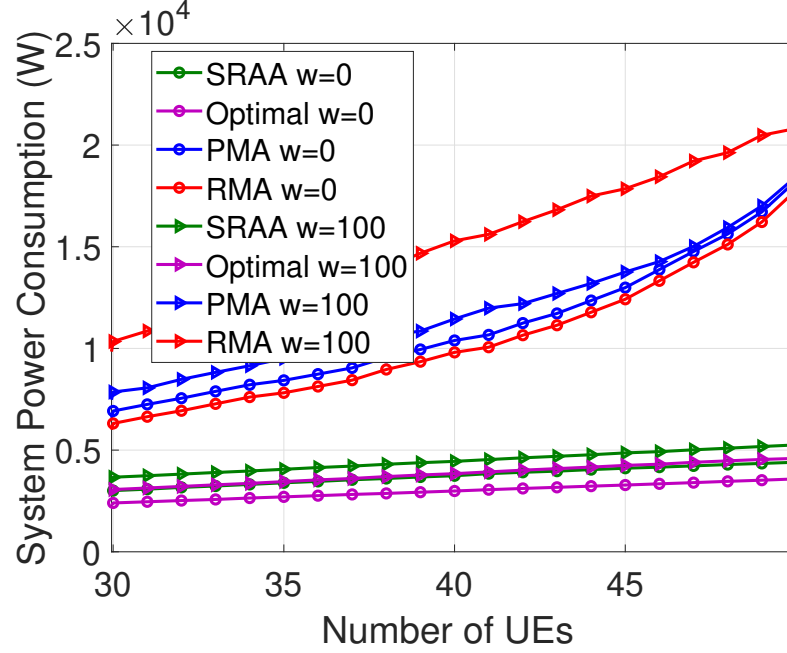
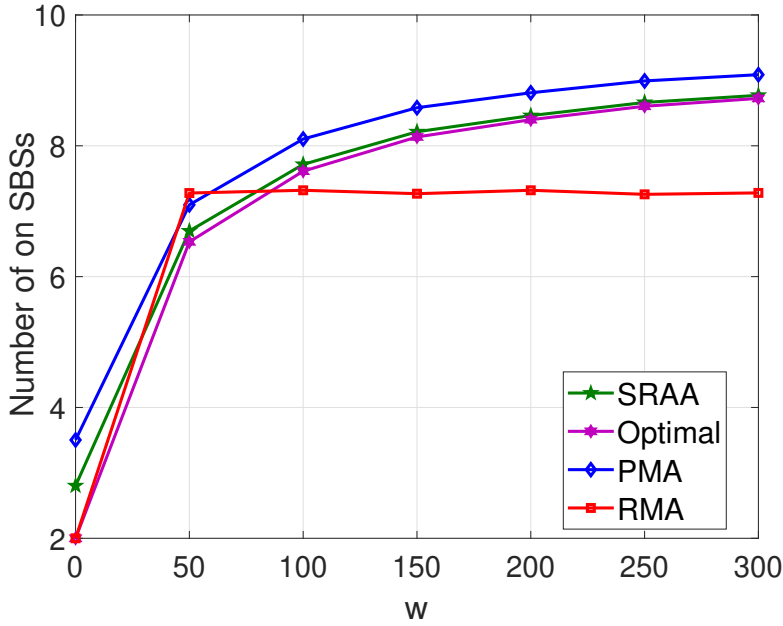


Figure 2.8: System power consumption of different algorithms for different number of UEs and w values

increase in the total power consumption due to constant number of on SBSs as in Figure 2.9, which causes increase in UE TX power.

Figure 2.10 demonstrates the system power consumption of different algorithms for different number of SBSs. For 40 UEs, as the number of SBSs increases, the probability of selecting the minimum power consuming BSs increases, resulting in decrease in total power consumption for all algorithms. The SRAA demonstrates significant improvement compared to RMA and PMA. It minimizes the total power consumption by selecting the SBSs, which provide the most decrease in UE TX power and turning off the unused SBSs to further save operational cost of SBSs. Moreover, as w increases the power consumption of algorithms decreases except in RMA the power consumption increases due to low number of on SBSs as shown in Figure 2.9. Figure 2.11 illustrates the system power consumption of different algorithms for increasing UL data rate demand. The increase in UL data rate leads to an increase in the channel

Figure 2.9: Number of on SBSs of different algorithms for different w

utilization from SBS S to UE j , $\beta_{u,jS}$, values and in the UL power consumption. For this purpose, the algorithms turn on additional SBSs to increase the probability of selecting the minimum power consuming BSs and decreasing $\beta_{u,jS}$, values and the UL power consumption. For $w=0$ and increasing UL data rate demand, the system power consumption increases for all algorithms and SRAA achieves significant improvements compared to PMA and RMA with the help of the controlled on/off operation of SBSs to decrease UE TX power. Moreover, as w increases, the power consumption of all algorithms increase noticeably because high number of on SBSs provides decrease in the UE power consumption but the static power consumption of on SBSs surpasses the power consumption of UEs in UL. At the same time, the number of on SBSs increases to compensate between the UL power consumption and the power consumption of on SBSs. However, the power consumption of RMA increases due to low number of on SBSs, which are not sufficient enough to compensate the power consumed in UL and the power consumption of on SBSs and cause increase in the UE TX power.

Figure 2.12 demonstrates the gain obtained from decoupling UL/DL for the optimal algorithm and the SRAA for different number of UEs. As the number of UEs increases, the system power consumption increases for all algorithms. The SRAA

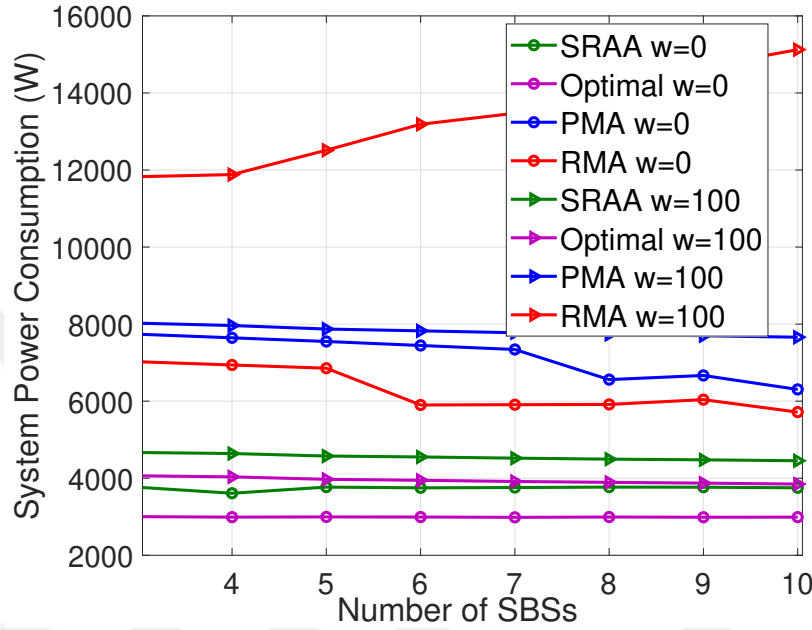


Figure 2.10: System power consumption of different algorithms for different number of SBSs and w values

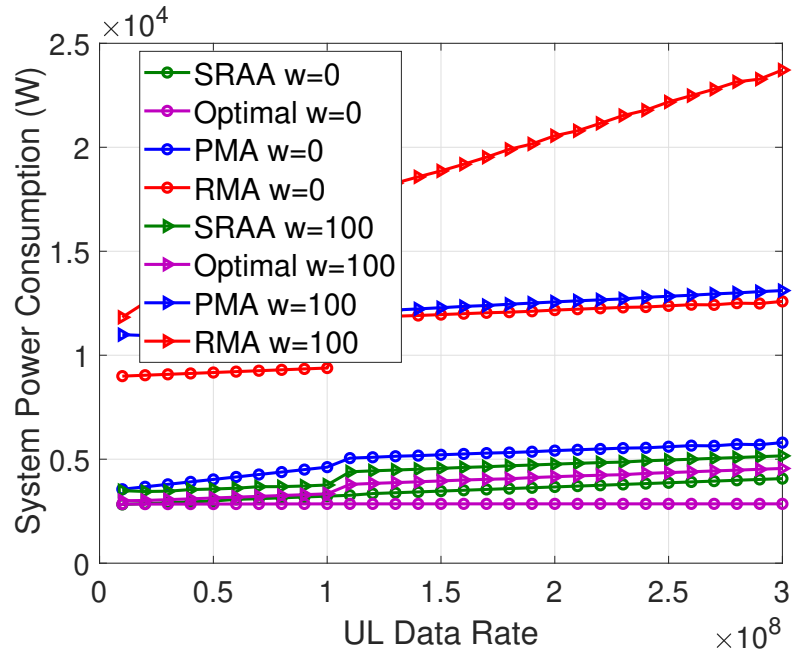


Figure 2.11: System power consumption of different algorithms for different UL data rates and w values

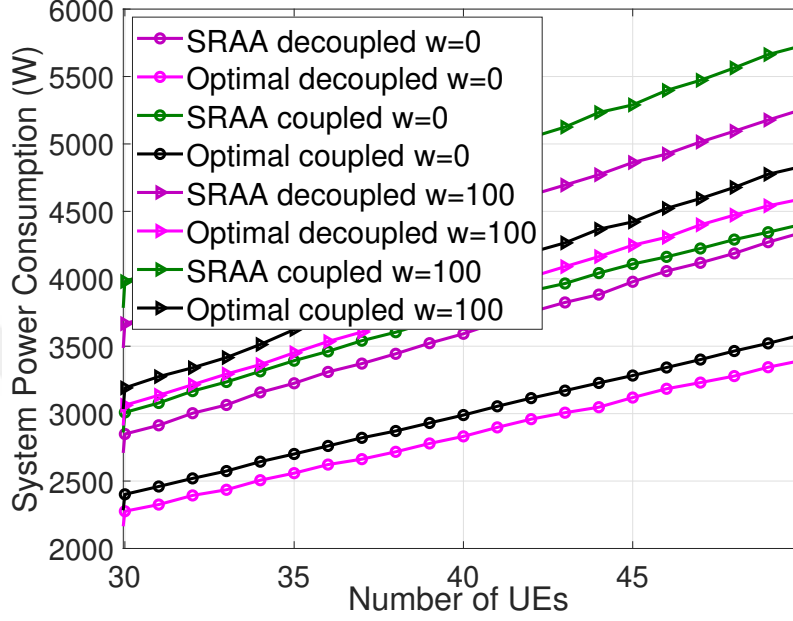


Figure 2.12: System power consumption of coupled and decoupled association schemes of different algorithms for different number of UEs and w values

implemented for both coupled and decoupled UE association perform close to corresponding the optimal algorithms with approximation ratio less than 1.2, where approximation ratio is defined as ratio between the objective function values of proposed heuristic algorithm and the the optimal algorithm. Figure 2.13 illustrates number of on SBSs for different number of w values. As w value increases, the UL power consumption increases and the system turns on additional SBSs to further minimize the total power consumption by decreasing UE TX power.

Figure 2.14 compares the power consumption of the optimal algorithm and the SRAA for decoupled and coupled UL/DL UE association for different number of SBSs. The power consumption decreases as the number of SBSs increases mainly due to increasing number of UL and DL choices for UEs. UEs select the least power consuming SBS for the communication initiation. Moreover, as w increases, UL power consumption increases and additional SBSs are turned on to further minimize the total power consumption by decreasing UE TX power. On the other hand, decoupled UE

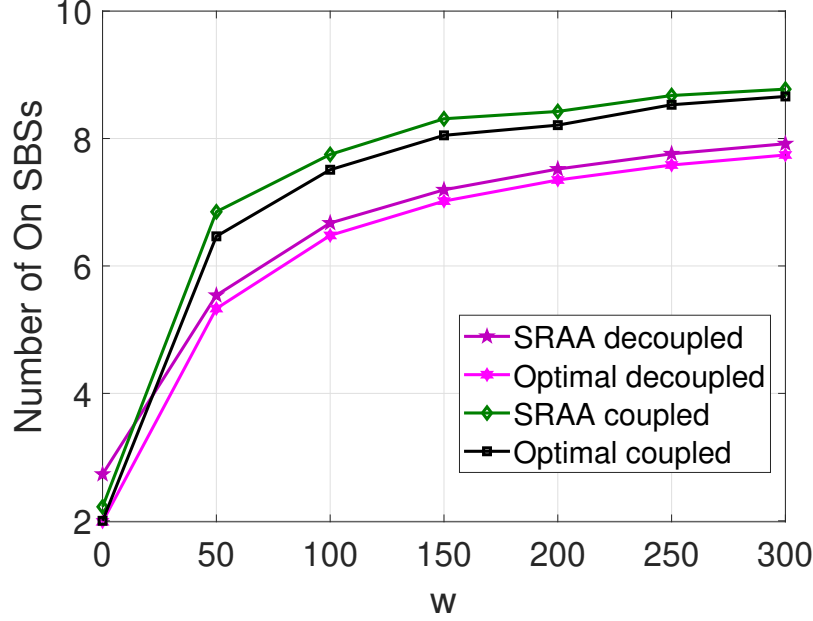


Figure 2.13: Number of on SBSs of coupled and decoupled UE association schemes for different w

association scheme outperforms coupled UE association scheme in terms of the power consumption. Coupled UE association causes UEs to transmit with high TX power as a result of the association to same BSs both in UL and DL though they can have different SINR values in UL and DL.

Figure 2.15 illustrates the effect of UL data rate on the system power consumption of the optimal algorithm and SRAA for decoupled and coupled UL/DL UE association. For increasing UL data rate, the power consumption of the heuristic algorithm with coupled and decoupled UE association is very close to that of the corresponding optimal algorithms with approximation ratio less than 1.2. Additionally, the increase in UL data rate causes an increase in the channel utilization values from MBS and SBS S to UE j in UL $\beta_{u,jM}$ and $\beta_{u,jS}$, respectively and in the UL power consumption of UEs. To decrease the effect of the increase in UE power consumption in UL, the algorithm turns on additional SBSs to reduce the TX power consumption of UEs as

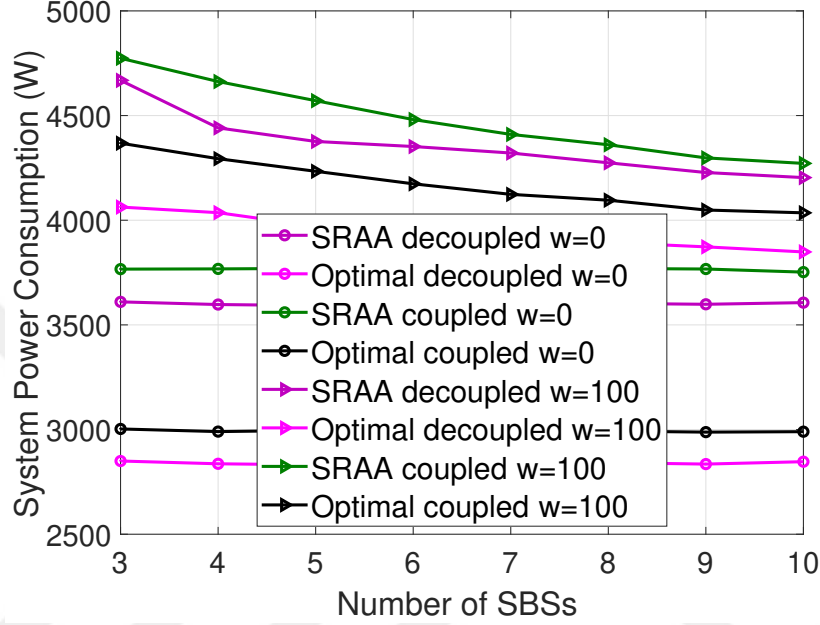


Figure 2.14: System power consumption of coupled and decoupled association schemes of different algorithms for different number of SBSs and w values

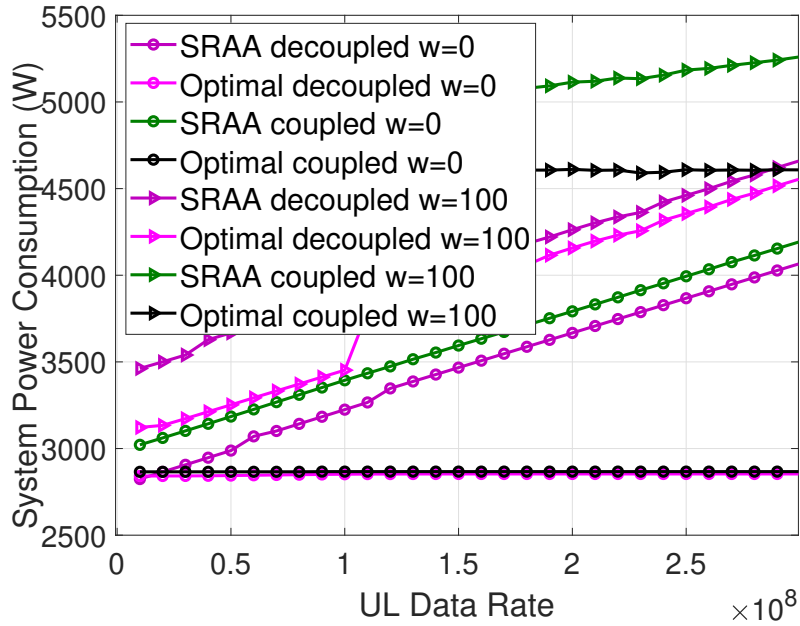


Figure 2.15: System power consumption of coupled and decoupled association schemes of different algorithms for different UL data rate and w values

shown in Figure 2.13.

2.5.2 Effect of incorporating realistic power consumption models

We demonstrate the importance of the incorporation of the dynamic power consumption of MBS and FH link power consumption on the optimal power consumption by investigating the network with the specified data rate demands both in UL and DL as in Table 2.2 for $w=100$.

Low Data Rate Demand

Figure 2.16 demonstrates the effect of the number of UEs on the system power consumption of the optimal algorithm, the optimal algorithm without the dynamic power consumption of MBS and the optimal algorithm without FH link power consumption for 10 SBSs. For increasing number of UEs, the optimal algorithm without the dynamic power consumption of MBS leads to higher power consumption than the power consumption of optimal algorithm and the power consumption of the optimal algorithm without FH link power consumption. Since the dynamic power consumption of MBS does not have an impact on increasing the power consumption in DL, the algorithm assigns all UEs to MBS in DL as long as it provides capacity to UEs and association to MBS causes increase in total power consumption. On the other hand, low data rate demands provide low $\beta_{u,jM}$ and $\beta_{u,jS}$ values in UL, where $\beta_{u,jM} \geq \beta_{u,jS}$, causing low power consumption on UL side. Therefore, the optimal algorithm without the dynamic power consumption of MBS assigns UEs to SBSs in UL as in Figure 2.18. Additionally, the optimal algorithm and the optimal algorithm without FH link power consumption decide in favor of SBS in DL for UE association because in presence of low data rate demanding UEs, the power consumption of UE-SBS association in DL, which is the static power consumption of SBS, is less than the power consumption of UE-MBS association. Moreover, with the same reason stated above for the optimal algorithm without the dynamic power consumption of MBS, on UL side, the power consumption of UE-MBS association is greater than the power consumption of UE-

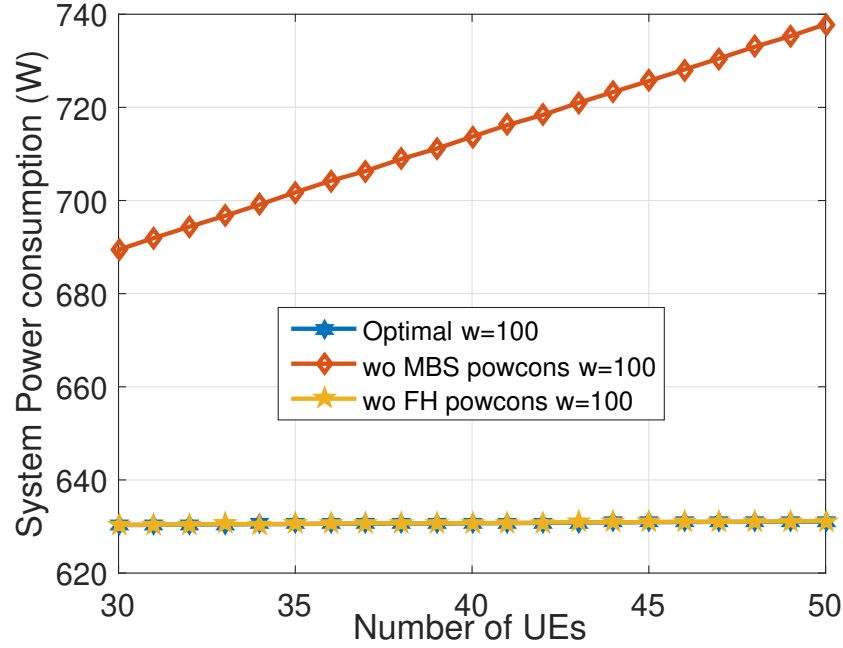


Figure 2.16: Effect of the dynamic MBS power consumption on system power consumption for low data rate demands in DL

SBS association, UEs get also assigned to a SBS in UL as seen in Figure 2.19 and two SBSs are on as in Figure 2.17.

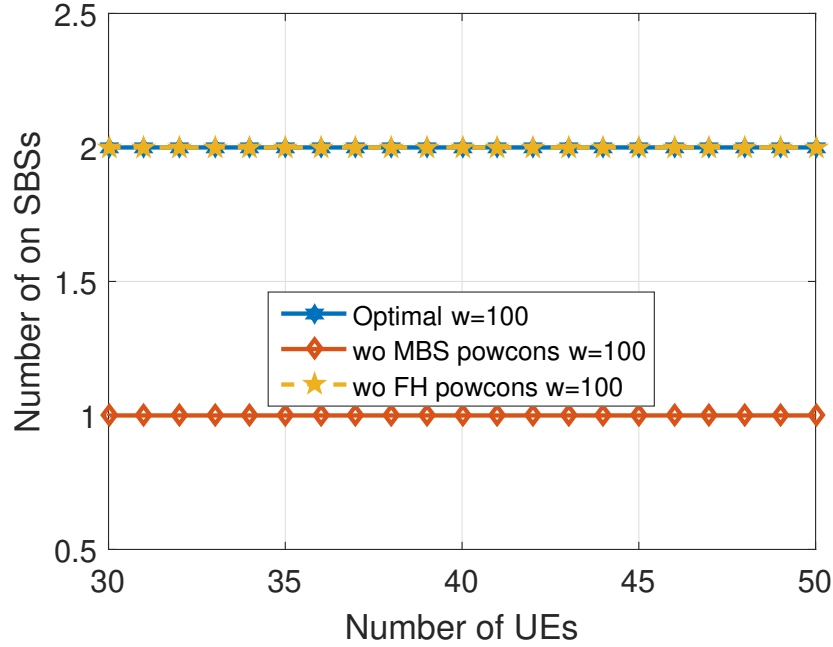


Figure 2.17: Effect of the dynamic MBS power consumption on the number of on SBSs for low data rate demands in DL

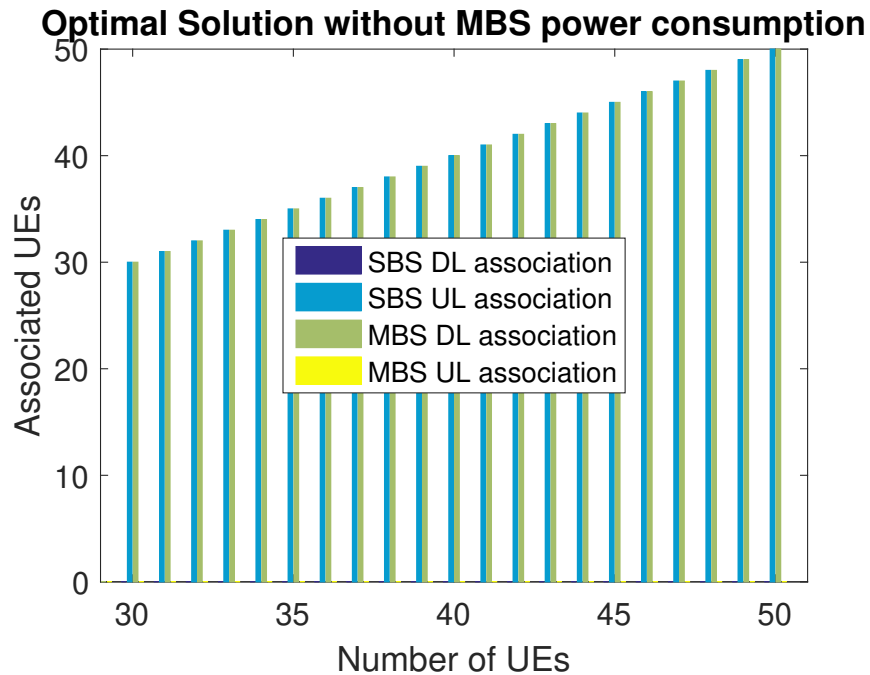


Figure 2.18: Effect of the dynamic MBS power consumption on UE association pattern for low data rate demands in DL

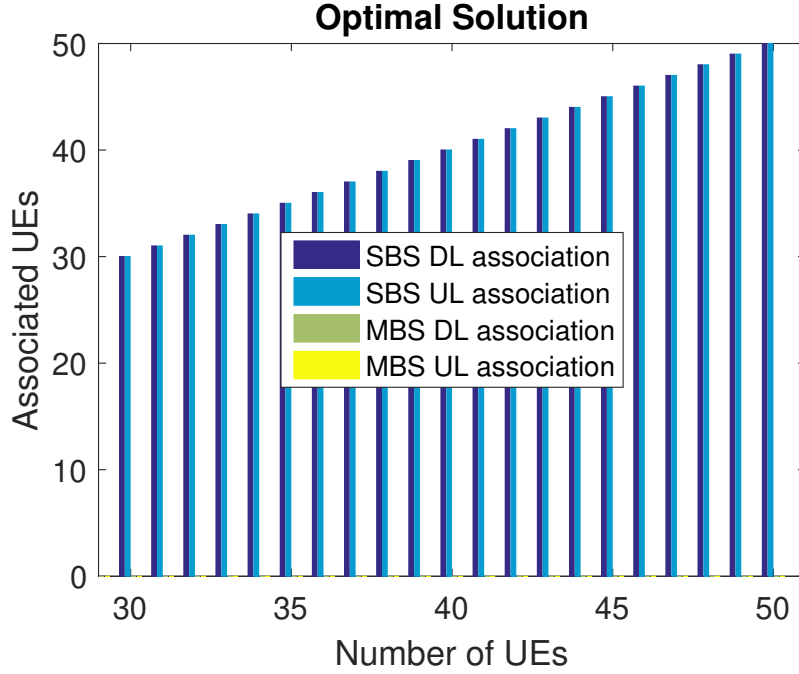


Figure 2.19: UE Association for optimal algorithm for low data rate demands in DL

Figure 2.20 represents the impact of the number of the SBSs on the system power consumption of the optimal algorithm, the optimal algorithm without the dynamic power consumption of MBS and the optimal algorithm without FH link power consumption for 40 UEs. For increasing number of SBSs, the power consumption of all algorithms decreases due to increasing number of UL and DL choices, resulting in decrease in UE TX power. Additionally, total power consumption of the optimal algorithm and the optimal algorithm without the dynamic power consumption of MBS outperform the optimal algorithm without FH link power consumption though the number of on SBSs is constant and equal for all algorithms as shown in Figure 2.21. The underlying reason is the difference between UE-BS association patterns as demonstrated in Figures 2.22 and 2.23.

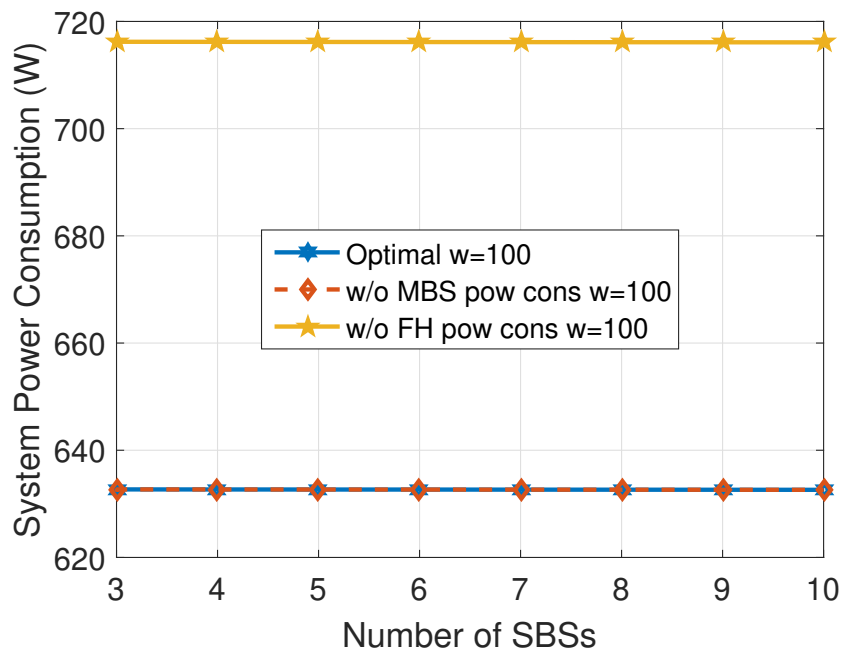


Figure 2.20: Effect of FH link power consumption on system power consumption for low data rate demands in DL

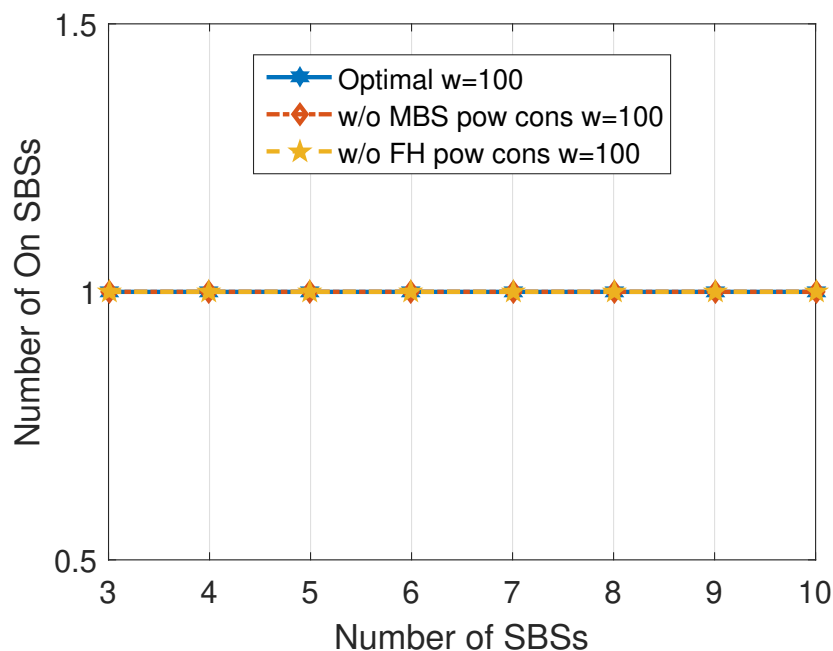


Figure 2.21: Effect of FH link power consumption on the number of on SBSs for low data rate demands in DL

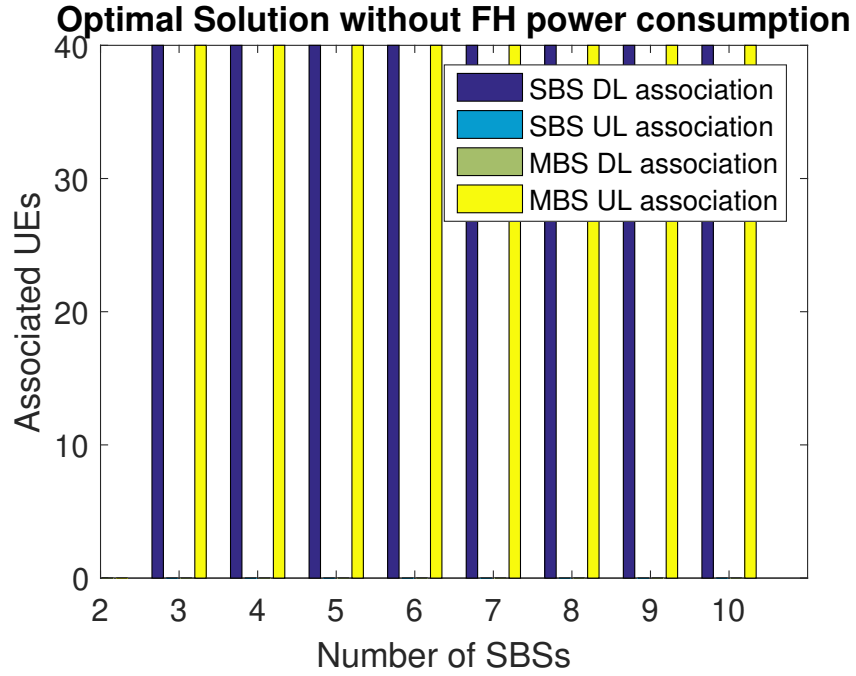


Figure 2.22: Effect of FH link power consumption on UE association pattern for low data rate demands in DL

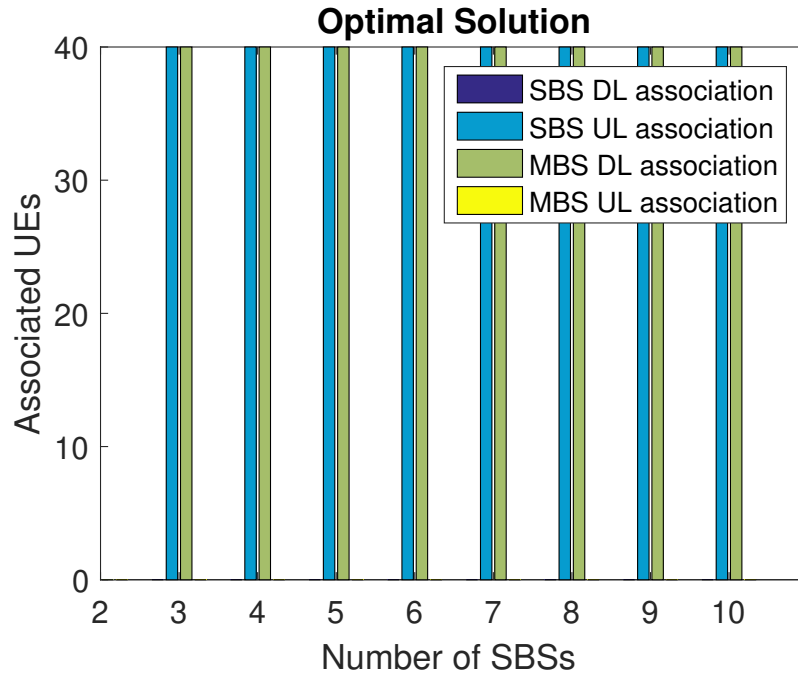


Figure 2.23: UE Association for optimal algorithm for low data rate demands in DL

The optimal algorithm without FH link power consumption assigns UEs to SBSs in DL in Figure 2.22, since the static power consumption of SBSs is less than the dynamic power consumption of MBS according to the DL power consumption part in objective function (2.1-01). On the other hand, the optimal algorithm without FH link power consumption assigns UEs to MBS in UL due to only one on SBS as in Figure 2.21 and insufficient capacity of the corresponding on SBS.

High Data Rate Demand

Figure 2.24 represents the impact of increasing the number of UEs on the system power consumption of the optimal algorithm, the optimal algorithm without the dynamic power consumption of MBS and the optimal algorithm without FH link power consumption for 10 SBSs. For increasing number of UEs, the power consumption of the optimal algorithm with and without the dynamic power consumption of MBS are equal to each other and increase linearly. They outperform the optimal algorithm without FH link power consumption due to the selection of optimal number and optimal location of SBSs. In the optimal algorithm without the dynamic power consumption of MBS, exclusion of the dynamic power consumption of MBS does not lead to the assignment of the UEs to MBS in DL, since $\beta_{d,Mj}$ values are so high such that the capacity requirements are not fulfilled. Therefore, the UEs associate with SBS in DL. The power consumption of DL association to SBS is dependent on power consumed on the FH links which is formulated as a function of data rate. As the number of UEs associated to SBS in DL increases and the number of on SBSs increases as in Figure 2.25, the power consumption also increases. The dynamic power consumption also affects UL association to MBS. Sum of $\beta_{u,jM}$ values for high UL data rate demands exceeds the capacity of MBS, therefore UEs associate with different SBSs in UL than the SBSs in DL as shown in Figure 2.26. Besides, the optimal algorithm also assigns UEs to SBSs in UL and DL due to high $\beta_{d,Mj}$ and $\beta_{u,jM}$ values. The power consumption of the optimal algorithm without FH link power consumption demonstrated in Figure 2.24 increases linearly as the number of UEs increases. In

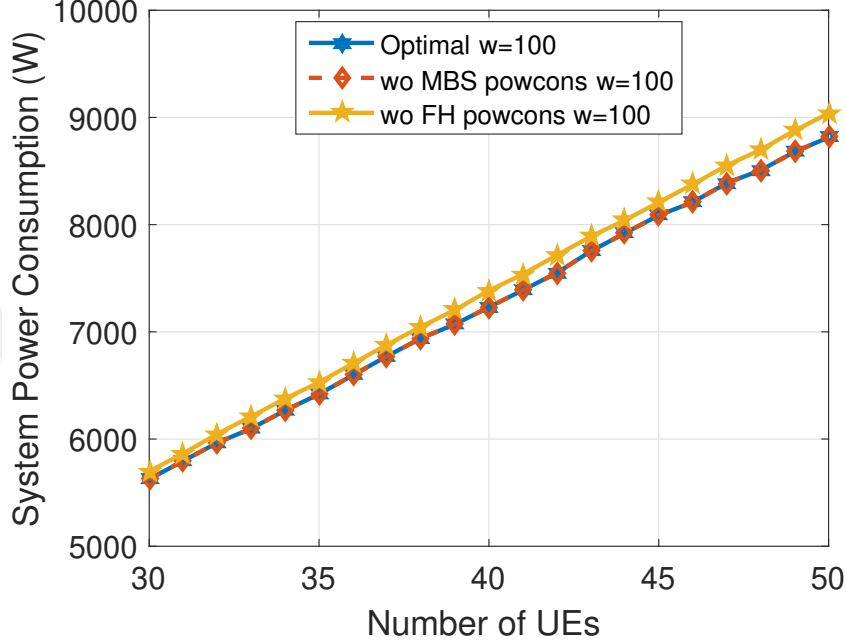


Figure 2.24: Effect of the dynamic MBS power consumption on the system power consumption for high data rate demands in DL

case of increase in the number of UEs, the number of on SBSs increases to provide more capacity to UEs as in Figure 2.25. Furthermore, the capacity of MBS is not sufficient to provide service to high data rate demanding UEs both in UL and DL with high $\beta_{d,Mj}$ and $\beta_{u,jM}$. Therefore, UEs associate with different SBSs in UL and DL as illustrated in Figure 2.27.

Figure 2.28 demonstrates the effect of number of SBSs on the system power consumption of the optimal algorithm, the optimal algorithm without the dynamic power consumption of MBS and the optimal algorithm without FH link power consumption for 40 UEs. For increasing number of SBSs, the power consumption of the optimal algorithm with and without the dynamic power consumption of MBS outperform the power consumption of the optimal algorithm without FH link power consumption. The uncontrolled increase in the static power consumption of SBSs and the negligible effect of the reduction in UE power consumption causes increase in the total power consumption of the optimal algorithm without FH link power consumption. Also,

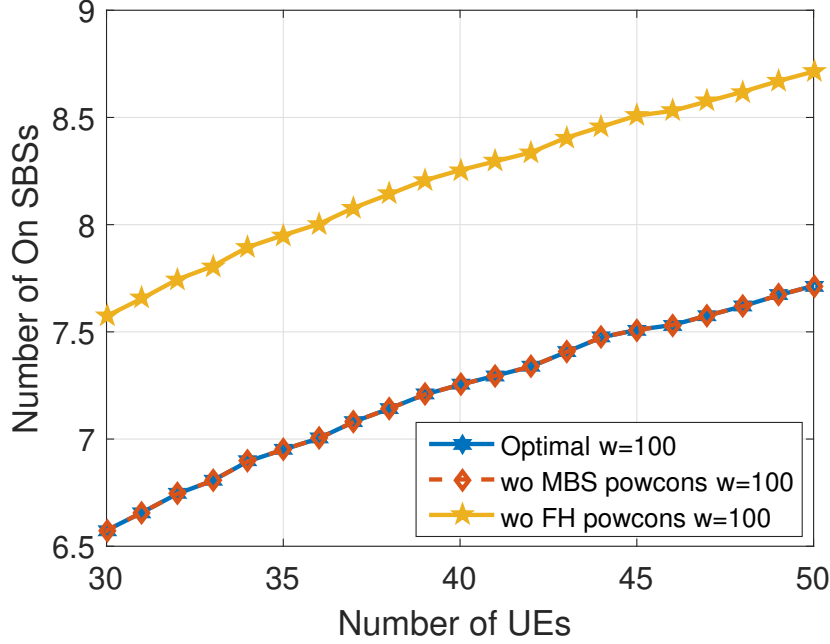


Figure 2.25: Effect of the dynamic MBS power consumption on on SBS for high data rate demands in DL

the power consumption values and association graphs of the optimal algorithm and the optimal algorithm without the dynamic power consumption of MBS are equal to each other as illustrated in Figure 2.28. The power consumption values decrease unlike the decrease as in Figure 2.20 due to high data rate demand of UEs that forces the system to turn on more SBS to fulfill high capacity requirements. Moreover, the number of on SBSs increases with increasing number of SBSs. Increasing number of SBSs enables UEs to select different SBSs both in UL and DL, which reduce their power consumption as in Figure 2.29.

As seen in Figure 2.30 and in Figure 2.31, both algorithms assign UEs to SBSs both in UL and DL. Additionally, high data rate demands both in UL and DL generate large $\beta_{u,jM}$ and $\beta_{d,Mj}$ values which exceed capacity limits of MBS. Therefore the system does not allow UEs to associate with MBS. As the number of SBSs increases, $\beta_{u,jM}$ and $\beta_{d,Mj}$ values are constant but the algorithms have the opportunity to select

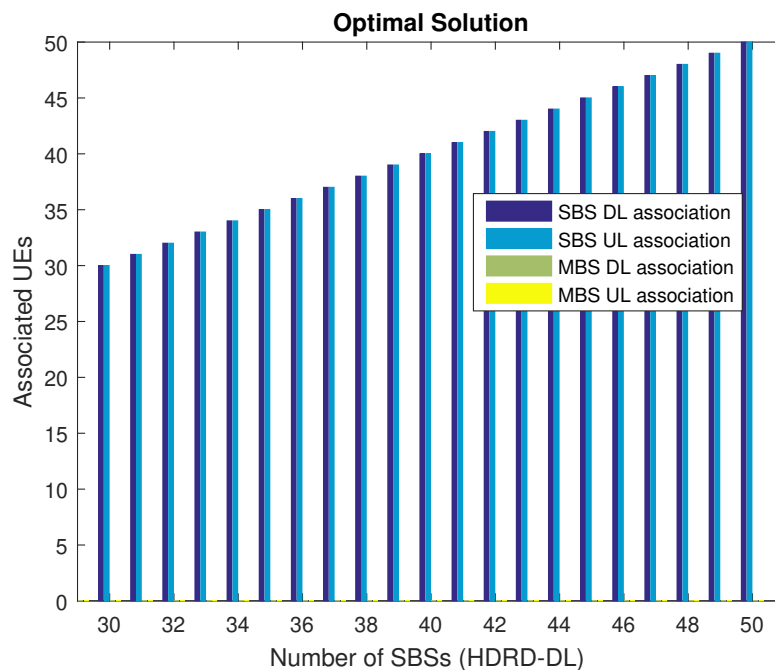


Figure 2.26: Effect of the dynamic MBS power consumption on UE association pattern for high data rate demands in DL

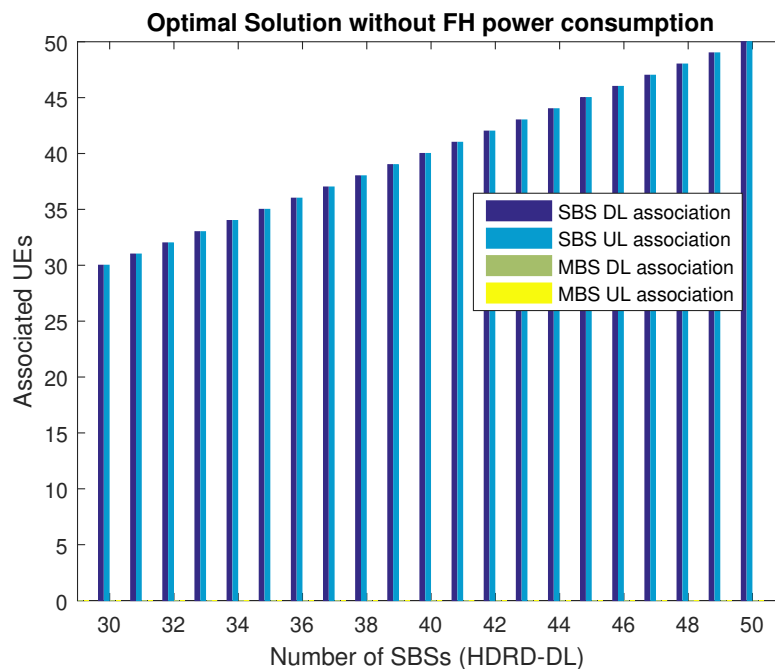


Figure 2.27: UE Association for optimal algorithm for high data rate demands in DL

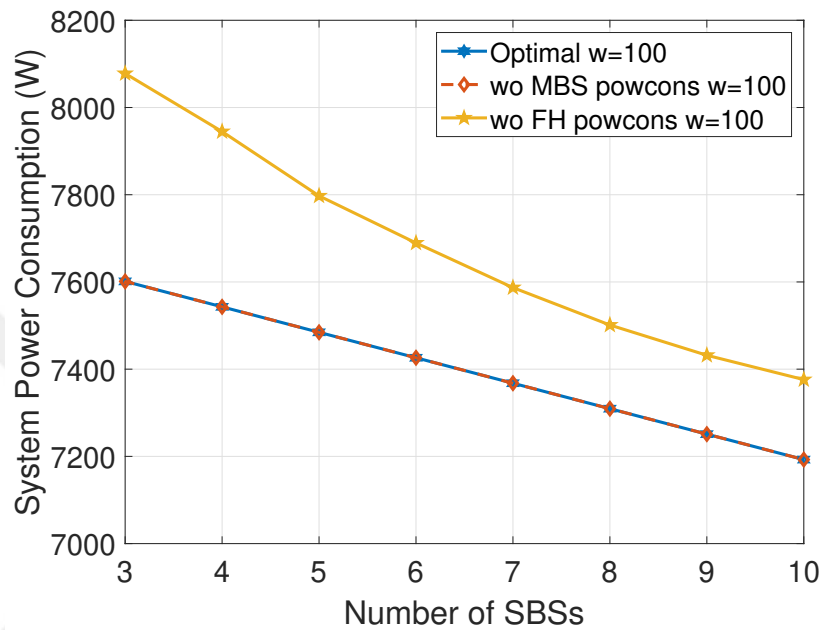


Figure 2.28: Effect of FH link power consumption on the system power consumption for high data rate demands in DL

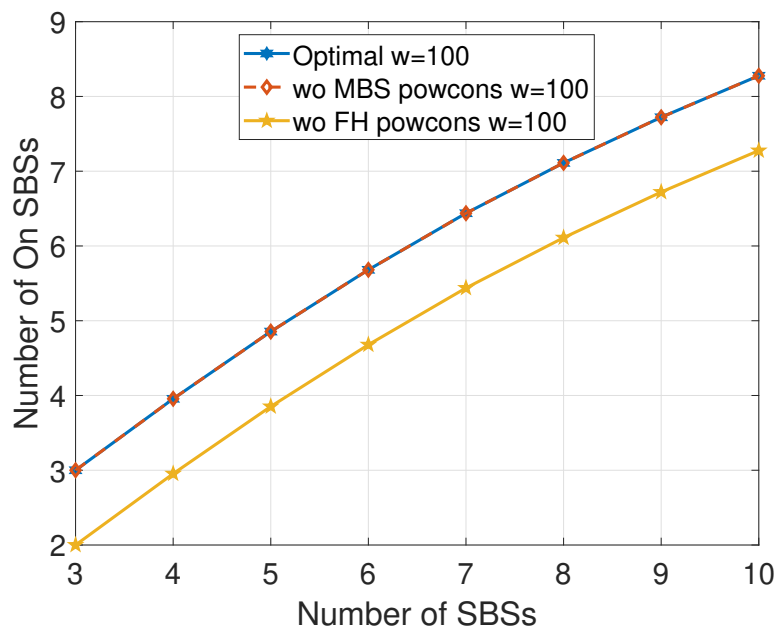


Figure 2.29: Effect of FH link power consumption on the number of on SBSs for high data rate demands in DL

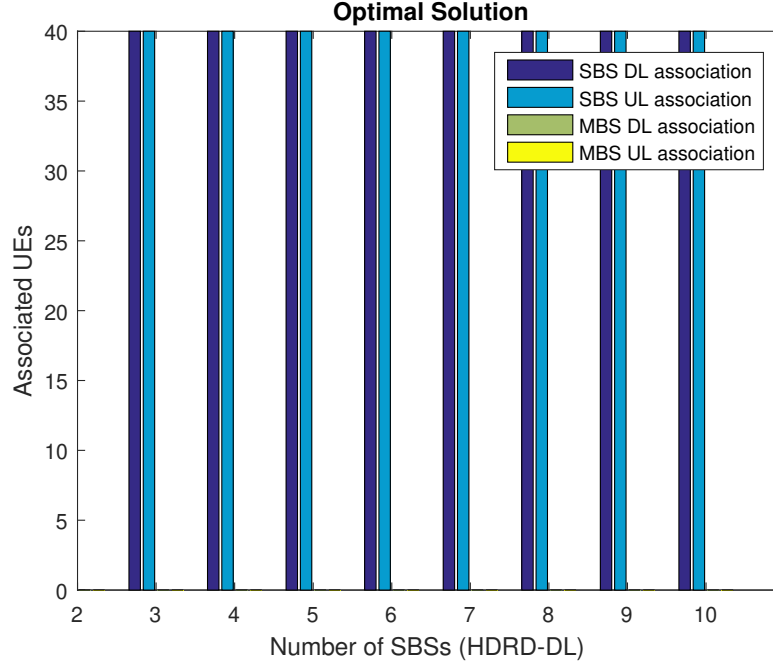


Figure 2.30: UE Association for optimal algorithm for high data rate demands in DL

smaller $\beta_{u,jS}$ values from the on SBS set. For this reason, the UEs get associated with SBSs in UL and DL due to insufficient capacity of MBS.

2.5.3 Delay and Fairness Performance

We demonstrate the delay and fairness performance of different algorithms by investigating the network with the specified data rate demands both in UL and DL as in Table 2.2 for $w=100$.

Delay Performance

Figure 2.32 compares the end-to-end delay of different algorithms for different number of UEs. In HCRAN, end-to-end delay components comprise of BBU Pool processing delay [53], BBU Pool-BS transmission delay on FH link [54], BS on/off delay for control plane and data plane signaling [55], BS-UE wireless communication

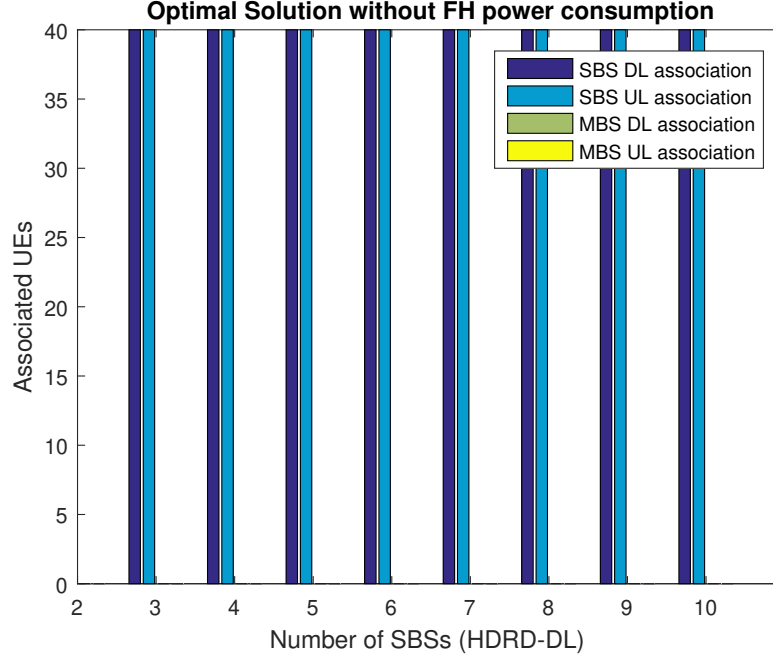


Figure 2.31: Effect of FH link power consumption on UE association pattern for high data rate demands in DL

delay [54] and waiting time of UEs in the BBU Pool processing patch [56]. BBU Pool processing delay determines the delay performance of a protocol since the rest of the delay components are the same for different algorithms. BBU Pool processing delay increases as the number of UEs increases mainly due to long period of searching for the least power consuming UE-BS pairs, which enables UEs to transmit with less transmit power. SRAA performs very close to optimal, significantly better than previously proposed algorithms, RMA and PMA, since SRAA associates UEs with pre-selected on BSs and offloads UEs among them instead of turning on each BS and trying each candidate BS for association. However, selection of random BSs according to a Markov transition matrix by random UEs without constraining the number of on BSs in PMA exceeds the BBU Pool processing delay experienced by SRAA whereas BBU Pool processing delay experienced in RMA exceeds that experienced by the rest of the algorithms since brute force nature of the algorithm turns on each BS and

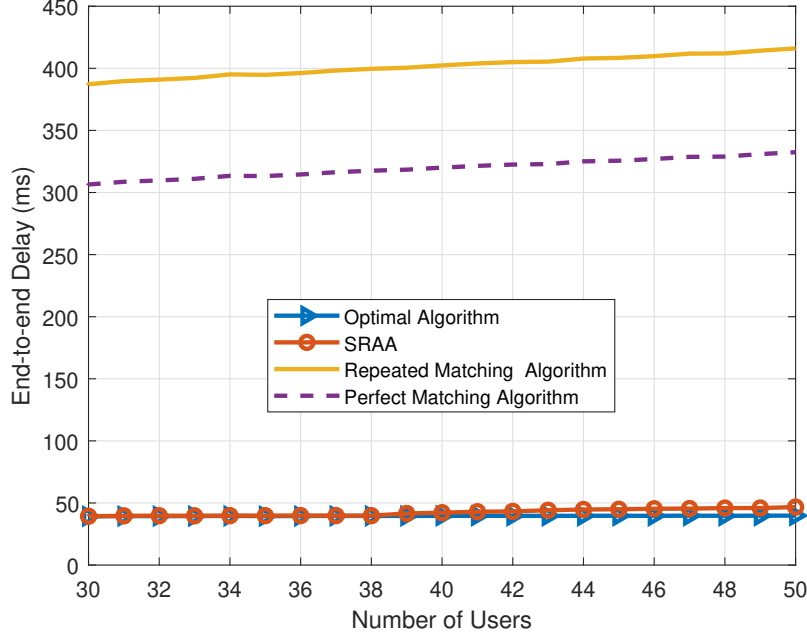


Figure 2.32: End-to-End Delay experienced in algorithms for increasing number of UEs

forces UEs to get assigned with each candidate BS, repeatedly.

Fairness Performance

In the literature, Fairness index measures the equality of resource allocation among UEs and if not equal, it represents how far the resource allocation is from equality. It is defined as Jain's Formula [57] and [58], $Jain = \frac{\left(\sum_{i=1}^N \kappa_i\right)^2}{N * \left(\sum_{i=1}^N \kappa_i^2\right)}$, where κ_i represents a resource allocation that UE i receives in case when a network allocates resources to N UEs. However, in our case Jain's index corresponds to the satisfaction of the requirements of UEs, κ_j represents the satisfaction of the data rate requirement of UE j and Jain's index is formulated as $Jain = \frac{\left(\sum_{j=1}^{N_b} \kappa_j\right)^2}{N_b * \left(\sum_{j=1}^{N_b} \kappa_j^2\right)}$. If the rate provided to UE j by BS i is greater than demanded data rate, κ_j will be 1, indicating that the requirements of UE j is fulfilled, and UE j is associated with BS i . It is formulated as

follows:

$$\kappa_j = \begin{cases} 1, & \text{if } \beta_{i,j} \leq 1 \\ 0, & \text{otherwise} \end{cases}$$

Jains index equals to 1 if the optimization problem is feasible otherwise equals to zero.

Figure 2.33 demonstrates the fairness index of different algorithms for different number of UEs. SRAA outperforms previously proposed heuristic algorithms in terms of fairness because it allocates the resources to all UEs efficiently, such that each UE gets the corresponding demanding data rate. However, RMA cannot provide fair utilization in a pre-determined iteration number though all BSs are on. The reason is the selection of any UE-BS pair at the beginning and improvement of the feasibility of the pair by choosing another BS for the UE and testing the feasibility repeatedly until feasible and fair allocation is done. Last, PMA does not support fair allocation due to random formation of UE-BS pairs all along the algorithm which causes inefficient use of network resources for all UE-BS pairs in terms of providing demanding data rates.

2.5.4 Performance Comparison of UEs and Machines

In this section, we compare the system power consumption performances of the optimal algorithm, SRAA, PMA and RMA for decoupled UL/DL UE association for increasing number of machines and decreasing number of UEs, which sum up to 50 equipments. Machines are assumed to demand UL data rates which are uniformly distributed between 100 Mbps and 300 Mbps and low DL data rates. UEs are assumed to demand DL data rates which are uniformly distributed between 200 Mbps and 3 Gbps and low UL data rates.

Figure 2.34 depicts the system power consumption of the optimal algorithm, SRAA, PMA and RMA for 10 SBSs and $w=1$. As the number of machines increases and the number of UEs decreases, the system power consumption decreases linearly

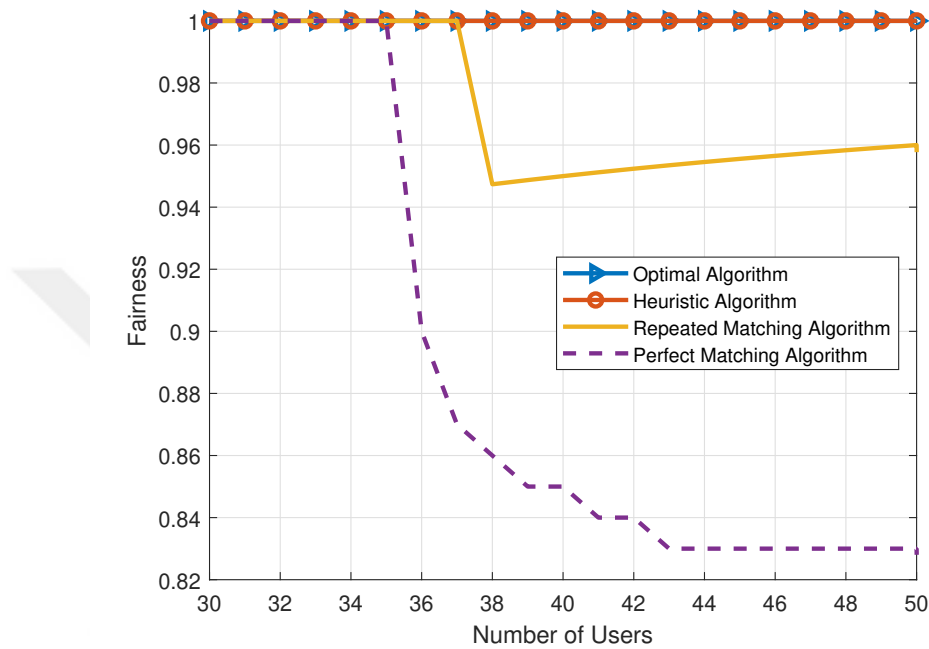


Figure 2.33: Jain's Index of the algorithms for increasing number of UEs

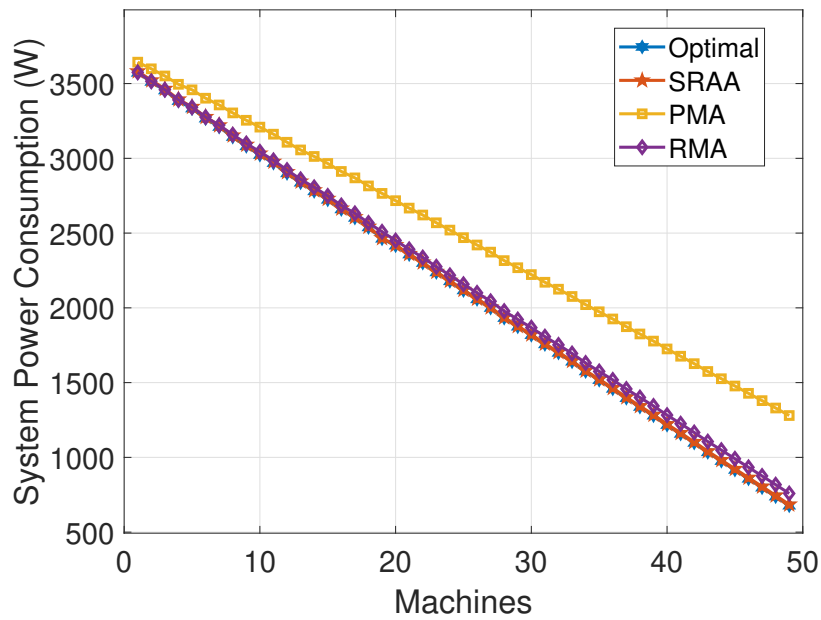


Figure 2.34: The system power consumption of different algorithms for different number of machines

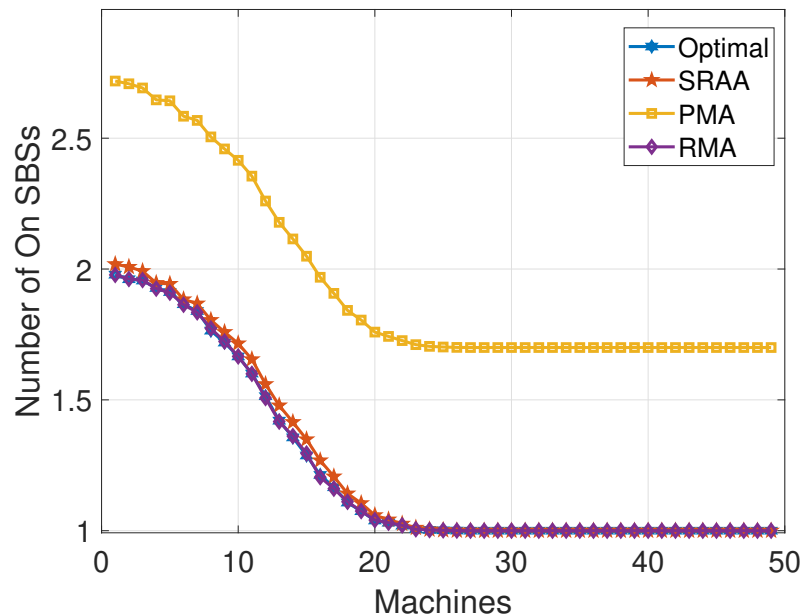


Figure 2.35: Number of on SBSs of different algorithms for different number of machines

mainly due to reduction in FH link power consumption caused by UEs not associating with SBSs in DL and negligible increase in UL power consumption of machines. According to results, the optimal algorithm, SRAA and RMA can carry the same traffic with less number of on SBSs than PMA and the UEs associate with MBS only in DL as demonstrated in Figure 2.35.

Chapter 3

MULTI-CONNECTIVITY BASED UPLINK/DOWNLINK DECOUPLED ENERGY EFFICIENT USER ASSOCIATION IN 5G HETEROGENOUS CRAN

3.1 Introduction

5G HCRAN consists of MBSs, which operate at conventional cellular frequencies and provide coverage, and SBSs, which operate at mmWave frequencies and are densely deployed in hot spots to provide high data rates to UEs. Signal processing in MBS and SBS is coordinated by BBU-Cloud, which provides network controllability and flexibility [3]. Since RSS at mmWave is extremely susceptible to blockages due to short wavelengths, MC is proposed to mitigate the resulting QoS degradation by associating a single UE with multiple network layers and multiple radio access technologies, simultaneously [59].

MC has been studied with the objectives increasing data rate, providing higher reliability and decreasing outage probability. Extremely high data rates are achieved by multiple 5G BSs [60]; highly reliable transmission is facilitated by combining multiple links [61]; and outage probability is decreased [62]. However, the usage of MC increases the power consumption, since in dense networks large number of BSs are activated in an uncontrolled manner to satisfy the aforementioned research objectives. None of the previous studies incorporates MC into the minimization of the system power consumption.

The minimization of the power consumption problem has been extensively studied for the case, where each UE associates with only one BS. The system power consumption is minimized by planning the activation/deactivation periods of SBSs in

a controlled manner while satisfying the QoS constraints of UEs, which are minimum rate requirement [63], [64], outage probability [65] and latency of data transmission between UE and BSs [66]. However, methods implemented for single BS-UE associations cannot be applied to MC scenarios, since MC requires a centralized system with shared MAC layer to provide instant information about the timing of any topology changes to all UE-BS pairs in the network and facilitates rapid connection shifting if the connection is blocked unexpectedly.

This paper proposes a MC based UL/DL Decoupled energy efficient UE association in HCRAN for the first time in the literature. The proposed framework encompasses realistic power consumption models, including both signaling overhead and transmissions within the BBU-Cloud, which is key in the analysis of the advantage of the usage of multiple BSs. Moreover, UL/DL decoupled UE-BS association and transmission with effective rate are used to further improve the performance through higher system flexibility.

3.2 System Model and Assumptions

We consider a HCRAN architecture in Figure 3.1, consisting of a MBS with $N_{RF,M}$ RF chains, which is operating at conventional cellular frequencies and K SBSs with $N_{RF,S}$ RF chains, which are operating at mmWave frequencies in the service area of MBS. Additionally, N_b mobile UEs exist in the service area of MBS and have a single antenna. UEs can get service from more than one BS, which are operating at conventional cellular frequencies and mmWave frequencies and can cooperate to serve UEs both in DL and UL, therefore, UE demand is splittable. The signal processing is managed by the BBU-Cloud, where the BSs are assumed to be connected to the BBU-Cloud through FH links, that have limited capacity, C_{fh}

α_{Mj}^t and α_{Sj}^t represent the attenuation levels at time t in DL from MBS and SBS S to UE j , respectively [67]. θ_{Mj}^t and θ_{Sj}^t indicate the attenuation levels in UL at time t from UE j to MBS and SBS, respectively [67].

The power assignment at the UE j at time t is executed to overcome ϵ fraction

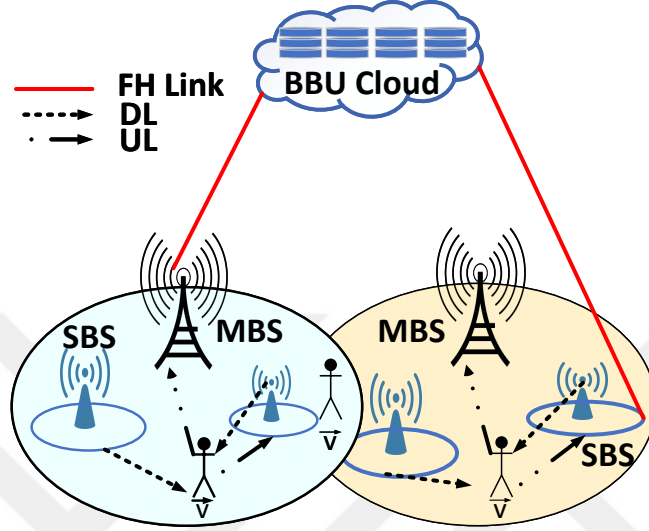


Figure 3.1: HCRAN with Multi-connectivity

of the path loss with respect to a reference received power per resource block at 0 dB path loss, P_0 , below P_{max} and is formulated as $P_{t,UE}^t = \min\{P_{max}, P_0 + \epsilon * \alpha_{\gamma,j}^t\}$, where γ is S or M [39].

The effective achievable rate at time t for N_c cooperating BSs in DL is formulated as $\tilde{R}_{d,\gamma,j}^t = \frac{1}{N_c} (\sum_{i=1}^{N_c} R_{d,\gamma,j,i}^t * \phi)$ [68], where γ is S or M, and $R_{d,S,j,i}^t$ and $R_{d,M,j,i}^t$ are the achievable rates at time t in DL at UE j by the i^{th} cooperating SBS S and MBS, respectively. Achievable rate is formulated as $B_{\gamma,i} * \log(1 + \frac{P_{t,\gamma,i} * \alpha_{\gamma,j,i}^t}{|N_{RF,\gamma,i}| * N_0 * B_{\gamma,i} + P_{j,Idl}^t})$, where $B_{S,i}$ and $B_{M,i}$ denote bandwidth required for transmission for the i^{th} cooperating SBS S and MBS, respectively [67], $N_{RF,S,i}$ and $N_{RF,M,i}$ are numbers of RF chains and are equivalent to the number of UEs at maximum that can be provided service by the i^{th} cooperating SBS S and MBS, respectively [33]. $P_{t,S,i}$ or $P_{t,M,i}$ demonstrate the transmit power of i^{th} cooperating SBS S and MBS, respectively, N_0 is the power spectral density of the noise and $P_{j,Idl}^t$ represents the power of interference at time t in DL. ϕ is the value indicating how much $R_{d,\gamma,j,i}^t$ degrades due to orthogonal and pre-coded pilots used by UEs to estimate and feedback channel matrix and for equalization and decoding, respectively. It is formulated as $(1 - \rho * 3 * N_c) - \delta$, where ρ represents the average pilot density in time and frequency and δ denotes the average control

overhead [68].

The effective achievable rate at time t in UL for N_c cooperating BSs reduces on average to $\tilde{R}_{u,\gamma,j}^t = \frac{1}{N_c} (\sum_{i=1}^{N_c} R_{u,\gamma,j,i}^t * \Theta)$ [68], where γ is S or M, and $R_{u,S,j,i}^t$ and $R_{u,M,j,i}^t$ are the achievable rates at time t in UL at UE j by the i^{th} cooperating SBS S and MBS, respectively. Achievable rate is formulated as $B_{\gamma,i} * \log(1 + \frac{P_{t,j,i}^t * \theta_{\gamma,j,i}^t}{N_0 * B_{\gamma,i} + P_{j,Iul}^t})$, where γ is S or M, $P_{t,j,i}$ represents the transmit power of UE j to the i^{th} cooperating SBS S or MBS; and $P_{j,Iul}^t$ represents the power of interference at time t in UL at UE j [67]. Θ is an expression of how much $R_{u,\gamma,j,i}^t$ degrades due to pilot signaling and CSI feedback rate, which are both scaled with the total number of UL transmit antennas within a cluster linearly. The amount of degradation in UL rate is formulated as $(1 - \rho * N_c) - (2 * N_c * \rho * q)$, where q represents the feedback bits that are used to calculate CSI for QoS [68].

$Q_{d,j}^t$ and $Q_{u,j}^t$ are data rates requested by UE j at time t in DL and UL, respectively.

MBS power consumption at time t encompasses static power consumption, P_{St} and dynamic power consumption at time t , P_{dyn}^t [42]. P_S is the power consumption of SBS S for all traffic load [42]. $P_{u,fhl}^t$ and $P_{d,fhl}^t$ represent the power consumption values of FH link at time t , in UL and DL, respectively [46]. $P_{u,j}^t$ is the power consumption of a UE j at time t [47]. P_{SP} is the power consumption of baseband digital signal processing [68].

3.3 Optimization of MC based UE Association

The optimization of MC based UL/DL decoupled UE association scheme with the objective of minimizing the power consumption by incorporating static and dynamic power consumption of MBS, power consumption of FH links and UEs in UL, activation/deactivation operation of SBSs and signal processing is formulated as:

$$\min \sum_{j=1}^{N_b} \left(\frac{Q_{d,j}^t}{R_{d,Mj}^t} \right) * P_{dyn} * x_{Mj}^t + \sum_{S=1}^K P_S * T_S^t + P_{fh} * \sum_{j=1}^{N_b} Q_{d,j}^t * x_{Mj}^t +$$

$$\begin{aligned}
 & \sum_{S=1}^K P_{fh} * \left(\sum_{j=1}^{N_b} Q_{d,j}^t * x_{Sj}^t \right) + P_{SP} + w * \left(\sum_{S=1}^K P_{fh} * \left(\sum_{j=1}^{N_b} Q_{u,j}^t * y_{Sj}^t \right) \right) + \\
 & \left(\sum_{j=1}^{N_b} ((P_{u,j}^t + P_{dyn}) * \frac{Q_{u,j}^t}{R_{u,Mj}^t}) * y_{Mj}^t + \sum_{j=1}^{N_b} P_{u,j}^t \sum_{s=1}^K \frac{Q_{u,j}^t}{R_{u,Sj}^t} * y_{Sj}^t \right) + P_{st} \\
 \text{s.t.} \quad & \frac{1}{N_c} * (\phi * R_{d,Mj}^t * H_{Mj}^t + \sum_{S=1}^K \phi * R_{d,Sj}^t * C_{Sj}^t) \geq Q_{d,j}^t, \\
 & j \in \{1, N_b\}, t \in \{1, T\}
 \end{aligned} \tag{3.3-01}$$

$$\begin{aligned}
 & \frac{1}{N_c} * (\Theta * R_{u,Mj}^t * G_{Mj}^t + \sum_{S=1}^K \Theta * R_{u,Sj}^t * Z_{Sj}^t) \geq Q_{u,j}^t, \\
 & j \in \{1, N_b\}, t \in \{1, T\}
 \end{aligned} \tag{3.3-02}$$

$$\sum_{j=1}^{N_b} \frac{Q_{d,j}^t}{R_{d,Mj}^t} * x_{Mj}^t + \sum_{j=1}^{N_b} \frac{Q_{u,j}^t}{R_{u,Mj}^t} * y_{Mj}^t \leq N_{RF,M}, t \in \{1, T\} \tag{3.3-03}$$

$$\sum_{j=1}^{N_b} \frac{Q_{d,j}^t}{R_{d,Sj}^t} * x_{Sj}^t + \sum_{j=1}^{N_b} \frac{Q_{u,j}^t}{R_{u,Sj}^t} * y_{Sj}^t \leq N_{RF,S}, S \in \{1, K\}, t \in \{1, T\} \tag{3.3-04}$$

$$\sum_{j=1}^{N_b} Q_{d,j}^t * x_{Sj}^t + \sum_{j=1}^{N_b} Q_{u,j}^t * y_{Sj}^t \leq C_{fh}, S \in \{1, K\}, t \in \{1, T\} \tag{3.3-05}$$

$$\sum_{j=1}^{N_b} Q_{d,j}^t * x_{Mj}^t + \sum_{j=1}^{N_b} Q_{u,j}^t * y_{Mj}^t \leq C_{fh}, S \in \{1, K\}, t \in \{1, T\} \tag{3.3-06}$$

$$x_{Sj}^t \leq T_S^t, j \in \{1, N_b\}, S \in \{1, K\}, t \in \{1, T\} \tag{3.3-07}$$

$$y_{Sj}^t \leq T_S^t, j \in \{1, N_b\}, S \in \{1, K\}, t \in \{1, T\} \tag{3.3-08}$$

$$x_{Sj}^t \leq C_{Sj}^t, j \in \{1, N_b\}, S \in \{1, K\}, t \in \{1, T\} \tag{3.3-09}$$

$$y_{Sj}^t \leq Z_{Sj}^t, j \in \{1, N_b\}, S \in \{1, K\}, t \in \{1, T\} \tag{3.3-10}$$

$$x_{Mj}^t \leq H_{Mj}^t, j \in \{1, N_b\}, t \in \{1, T\} \tag{3.3-11}$$

$$y_{Mj}^t \leq G_{Mj}^t, j \in \{1, N_b\}, t \in \{1, T\} \tag{3.3-12}$$

$$H_{Mj}^t + \sum_{S=1}^K C_{Sj}^t \leq N_c, j \in \{1, N_b\}, t \in \{1, T\} \tag{3.3-13}$$

$$G_{Mj}^t + \sum_{S=1}^K Z_{Sj}^t \leq N_c, j \in \{1, N_b\}, t \in \{1, T\} \tag{3.3-14}$$

$$\forall s \quad T_S^t, C_{Sj}^t, Z_{Sj}^t, H_{Mj}^t, G_{Mj}^t, x_{Mj}^t, x_{Sj}^t, y_{Mj}^t, y_{Sj}^t \in \{0, 1\},$$

where K is the number of SBSs, N_b is the number of UEs and T is the number of time-slots. The decision variables are T_S^t , that is a binary variable with value 1 in case SBS S is activated when UE is assigned with the corresponding SBS S at time t in DL and UL and 0 otherwise; C_{Sj}^t and H_{Mj}^t , that are binary variables with values 1 in case SBS S and MBS cooperates with other BSs to serve UE j at time t in DL, respectively, and 0 otherwise; Z_{Sj}^t and G_{Mj}^t , that are binary variables with values 1 in case SBS S and MBS cooperates with other BSs to serve UE j at time t in UL, respectively, and 0 otherwise; x_{Sj}^t and x_{Mj}^t , that are binary variables with values 1 when UE j is assigned to SBS S and MBS at time t in DL, respectively, and 0 otherwise; y_{Sj}^t and y_{Mj}^t , that are binary variables with values 1 when UE j is assigned to SBS S and MBS at time t in UL, respectively, and 0 otherwise.

Constraints (3.3-01) and (3.3-02) represent that the data rate requested by UE j at time t in DL and UL are provided by one BS or more than one BS, respectively. Constraints (3.3-03) and (3.3-04) indicate that the numbers of RF chains are equivalent to the number of UEs at maximum that can be provided service by the MBS and SBS S , respectively, at time t . Constraints (3.3-05) and (3.3-06) demonstrate that the data flow of the UEs on FH link at time t both in DL and UL cannot be greater than the total FH link capacity. Constraints (3.3-07) and Constraints (3.3-08) imply that if any UE associates with SBS S at time t in DL and UL, SBS S is activated. Additionally, constraints (3.3-09) and (3.3-10) ensure that SBS S can cooperate with other BSs to provide service to UE j at time t in DL and UL, respectively. Constraints (3.3-11) and (3.3-12) ensure that MBS can cooperate with other BSs to provide service to UE j at time t in DL and UL, respectively. Constraints (3.3-13) and (3.3-14) represent that number of BSs that cooperate to serve UE j at time t in DL and UL is at most N_c .

Theorem 2. *The optimization problem (3.3) is NP-hard.*

Proof. We reduce our optimization problem to NP-Hard uncapacitated k-facility me-

dian problem.

Let us define a problem instance, where the number of cooperating BSs, N_e , is equal to one. Then, only one BS becomes active to serve a UE in UL and DL, which constrains variables H_{Mj}^t , G_{Mj}^t , C_{Sj}^t and B_{Sj}^t to be binary and make the constraints (3.3-09)-(3.3-12) redundant. The problem reduces to the cost minimization problem in [69], in which k facilities are activated, where k is also the number of active BSs in our problem instance, and clients are associated with active facilities, such that demands of clients and capacity of facilities are satisfied, while minimizing the sum of transportation and facility location costs. It is proven to be NP-Hard, as a result of the reduction of the problem to NP-Hard uncapacitated k -facility median problem. $\square$

3.3.1 MC based UE Association Algorithm

MCUAA, is proposed to solve the optimization problem (3.3) in polynomial time. The objective of MCUAA is to improve the initial solution, which is attained by using LPR-R and GAP heuristic, which takes the output of LPR-R as input and checks if it is possible to decrease the power consumption further [70]. In previously proposed VNS based heuristic algorithm to solve CKFLP [69], the UE-BS association and activation/deactivation of BSs is encoded as a random binary string, where each bit in the string may correspond to one potential activated/deactivated BS or assigned UE-BS pair. The current solution is improved by selecting a pre-defined UE-BS association method, changing the current UE-BS association with respect to pre-defined association method and then applying local search. On the contrary, in MCUAA, $LPR - R$ provides input, where the input consists of inactive BSs, unassigned UEs and assigned UE-BS pairs, to the following GAP heuristic to solve many-to-many assignment problem. The complexity is reduced by using $LPR - R$ and GAP heuristic, fast and extensive search for the minimum is enabled and MCUAA provides results, which are close to optimal.

MCUAA is demonstrated in Fig. 3.2. The flowchart begins with the introduction of the CN at time t , C_{TH} , the LV at time t , the MV at time t and the RV at time

t (RV^t). CN^t considers the number of times the heuristic runs with the value LV^t less than RV^t at time t , C_{TH} is the number of count processes at maximum, LV^t and MV^t are equal to the values of power consumption at time t , attained from GAP heuristic and MCUAA, respectively, and RV^t is obtained by the summation of power consumption values attained by $LPR - R$, and association of unassigned UEs with any random active BS at time t .

Problem (3.3), BILP, is resolved with the help of $LPR - R$ and the attained power consumption value is introduced as RV^t . Next, the solution demonstrates sets consisting of inactive BSs, unassigned UEs and assigned UE-BS pairs. The solution of $LPR - R$ is received by the GAP heuristic, where the main objective is to associate unassigned UEs with active BSs. In case where the active BSs cannot serve the unassigned UEs, an inactive BS is activated randomly. Otherwise, UEs, which are unassigned, are associated with the active BSs and LV^t becomes equal to the power consumption value of assigned UE-BS pairs. Providing that the solution of GAP heuristic has less value than RV^t , an active BS is deactivated by MCUAA randomly, the UEs associated with the deactivated BS get unassigned and GAP heuristic is employed to examine, if it is possible to decrease the power consumption further by deactivating an active BS, considering CN^t has a lower value than C_{TH} . Conversely, in case when GAP heuristic cannot enable reduction in power consumption, MCUAA activates a BS randomly and examines if it is possible to decrease power consumption by activating inactive BSs, considering CN^t has a lower value than C_{TH} at time t .

Since a BS is selected from a set of active BSs, randomly, finding minimum power consuming BSs from the BS set, which consists of m BS, is completed in $\mathcal{O}(\log m)$ time. Each of n UEs is assigned to the active BSs, individually, where the association is completed in $\mathcal{O}(n)$ time. As a result, MCUAA is completed in $\mathcal{O}(n \log m)$ time.

Main functions of MCUAA are stated as follows:

1) *Formation of Feasible Packings:* Problem (3.3) is resolved with the help of $LPR - R$ and the solution demonstrates sets consisting of inactive BSs, unassigned UEs and assigned UE-BS pairs. These sets are obtained as follows:

After applying $LPR - R$, more than N_c BSs cooperate to serve UEs. For each UE, we calculate the minimum power consuming N_c BSs. The decision variable of the selected UE-BSs pair is set to 1 and the rest are set to zero.

After applying $LPR - R$, none of the UEs are associated with any BS and BSs are inactive. The decision variables are equal to zero.

After applying $LPR - R$, each UE is getting a service from an active BS or from a cooperating set of BSs. The decision variables of the corresponding association pairs are set to one and the rest is set to zero.

2) *Heuristic for GAP*: The solution of $LPR - R$, which demonstrates sets consisting of inactive BSs, unassigned UEs and assigned UE-BS pairs, is received by the GAP heuristic, where the main objective is to associate unassigned UEs with active BSs. GAP heuristic is employed to examine, if it is possible to decrease the power consumption further by deactivating an active BS.

The GAP heuristic functions as the following: Desirability measures c_{scj}^t , c_{mcj}^t , c_{Sj}^t and c_{Mj}^t , at time t are introduced, which are assumed to be the values of power consumption of associating UE j with cooperating set of SBSs, cooperating set of BSs including MBS, SBS S and MBS, respectively. First, all unassigned UEs are considered and the corresponding BS is determined based on the maximum value of the difference between two smallest values of c_{Sj}^t and c_{scj}^t or c_{Mj}^t and c_{mcj}^t values. The BS is then assigned to the UE j for which c_{Sj}^t , c_{scj}^t , c_{Mj}^t or c_{mcj}^t , is a minimum. The assignment is done for all unassigned UEs, iteratively. Next, current assignment scheme is improved by shifting, which considers each BS or cooperating BSs and re-assigns it to the UE j with minimum c_{Sj}^t , c_{scj}^t , c_{Mj}^t or c_{mcj}^t .

3.4 Performance Evaluation

The objective of the Section 3.4 is to assess MCUAA compared to VNS-based heuristic algorithm, which is proposed for CKFLP [69]. VNS-based heuristic starts with an initial solution, which consists of inactive BSs, unassigned UEs and assigned UE-BS pairs. Then, by using one of the three neighborhood methods, which are active

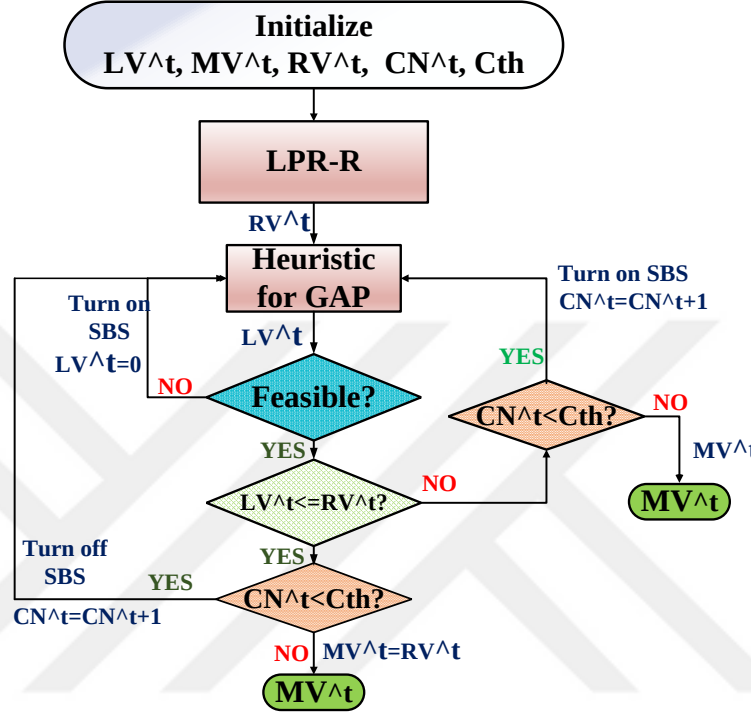


Figure 3.2: MC based UE Association

BS swapping, activating SBSs and deactivating SBSs, randomly, initial solution is improved and new assigned UE-BS pairs are obtained as output. The output of the selected neighborhood method is used as the input to the local search. Last, local search is used to search for the minimum power consuming solution in the corresponding neighborhood method and searches for the neighborhood method until the first improvement is found.

Simulation results are obtained by using IBM CPLEX Optimization Studio with MathWorks MATLAB and by averaging 10000 random configurations. Within the radius of 50 m to 700 m, 40 SBSs are randomly and uniformly located with the minimum distance of 10 meters among each other and 100 UEs are deployed randomly and uniformly around BSs, which form hot spots, with velocities distributed between 0.1 m/s and 0.5 m/s randomly and uniformly. The links are assumed to be in LoS or in NLoS or in outage and the state changes with distance and mmWave-related environmental parameters [37]. The attenuation levels are stated using the path loss

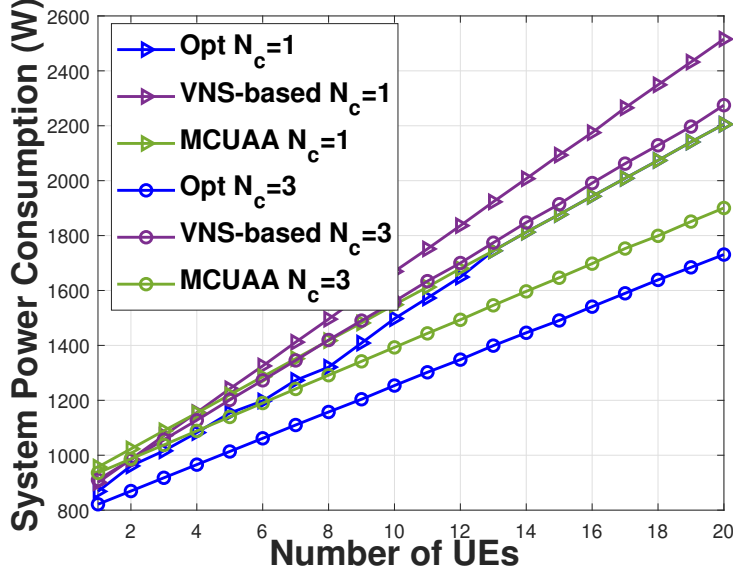


Figure 3.3: number of the UEs

model and formulated as $\psi_{\gamma,j}^t = PL(d_0)^t + 10 * \eta_j^t * \log_{10}(\frac{d_{\gamma,j}^t}{d_0}) + X_{\sigma_j}^t$, where γ is S or M, $PL(d_0)^t$ is the free space path loss in dB at a reference distance d_0 , η_j^t is the path loss exponent, $d_{\gamma,j}^t$ is the distance between BS γ and UE j , and $X_{\sigma_j}^t$ is a zero mean Gaussian random variable with $(\sigma_j^t)^2$ variance. The parameters for the mmWave path loss model at time t are stated in [37] and the rest are as follows: $B_M=20$ MHz and $B_S=800$ MHz, $N_0=-134$ dBm/MHz, $C_{fh}=4.45$ Gbps, $N_{RF,M}=8$, $N_{RF,S}=4$, $P_{fh}=0.1$ W/Mbps, $\rho=8/168$, $\delta=3/14$, $q=8$, $P_{dyn}=768.9$ $P_S=12.1$ W $P_{St}=605$ W [42] and $Q_{d,j}^t$ and $Q_{u,j}^t$ are uniformly distributed between $[0.15,2]$ Gbps and $[0.2,0.5]$ Gbps, respectively.

Fig. 3.3 shows the power consumption comparison results obtained for increasing number of the cooperating BSs and UEs. As the number of the UEs increases, the power consumption increases due to the increase in the total FH link power consumption and UE power consumption. In addition, the total system power consumption decreases as the number of the cooperating BSs increases because UEs are free to choose BSs that enable them to transmit with lower transmit power. Furthermore, MCUAA outperforms VNS algorithm mainly due to the utilization of GAP heuristic. With GAP heuristic, the solution is improved within a closed set of minimum power

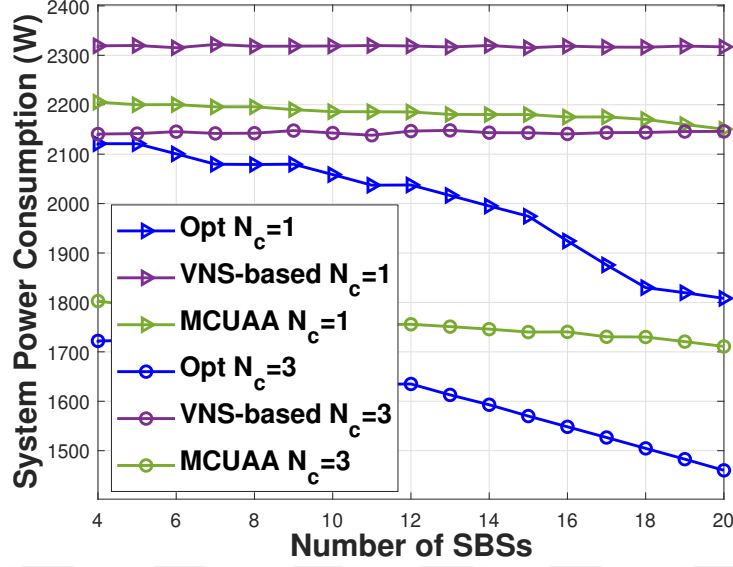


Figure 3.4: number of the SBSs

consuming BSs determined for each UE. In VNS, the UEs are assigned to any SBSs in their neighborhood randomly and the solution is improved in a pre-defined number of the changes of neighborhood.

Fig. 3.4 demonstrates the power consumption comparison results obtained for increasing number of the cooperating BSs and SBSs. Increase in the number of the cooperating BSs enables UEs to transmit with less transmit power and provides decrease in total power consumption. Furthermore, MCUAA accomplishes important improvement in comparison to VNS in terms of total power consumption. On the other hand, increase in the number of the SBSs provides decrease in total power consumption since DL and UL association alternatives increase for UEs. As a result, UEs choose the least power consuming BSs for association.

Fig. 3.5 illustrates runtime analysis obtained for increasing number of the UEs in Matlab. As the number of the UEs increases, the runtimes of all algorithms increase. However, MCUAA demonstrates significant improvements compared to optimal and VNS-based algorithms since MCUAA is polynomial time and finds the most energy efficient cooperation set of BSs in less time than VNS-based algorithm since it tries to

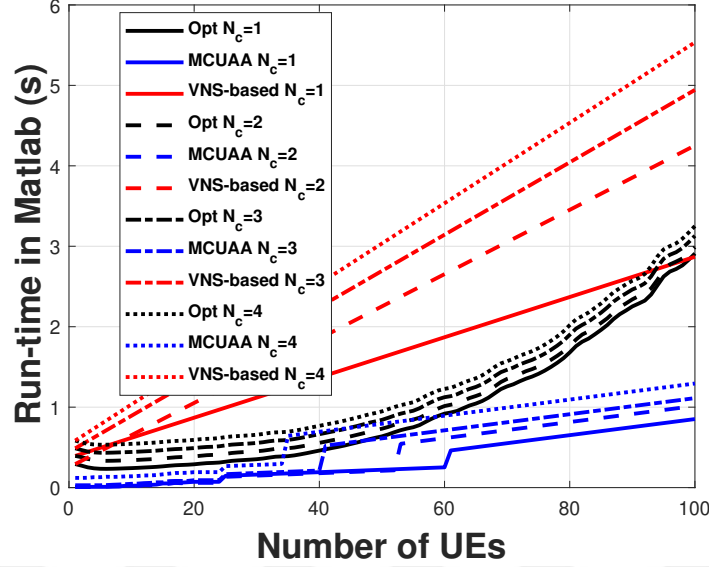


Figure 3.5: Effect of number of the UEs on the runtime in Matlab

assign UEs only to on BSs rather than trying each BS regardless of whether it is on or off, respectively. Moreover, the runtime increases, as the number of the BSs in the cooperation set increases since selection of a larger cooperation set takes more time.

Fig. 3.6 demonstrates the effect of increase in the number of the cooperating BSs on the achievable rate in the system. As the number of the cooperating BSs increases, achievable rate increases both in DL up to a point. However, it decreases after reaching a specific number of the cooperating BSs due to increase in interference and overhead, in which increasing amount of rate has to be invested into DL orthogonal pilot signaling. Furthermore, the rates achieved by the VNS-based algorithm is less than MCUAA due to selection of cooperating BSs, where the interference inside and outside of the cooperating set is high. Moreover, for the given network architecture with specific number of the UEs, BSs and demanding data rates, 5 cooperating BSs are necessary to get the highest rate.

Fig. 3.7 illustrates the relationship between threshold rate and number of the cooperating BSs. As threshold rate increases, the number of the cooperating BSs increases, which also causes increase in overhead, to fulfill QoS requirements of UEs.

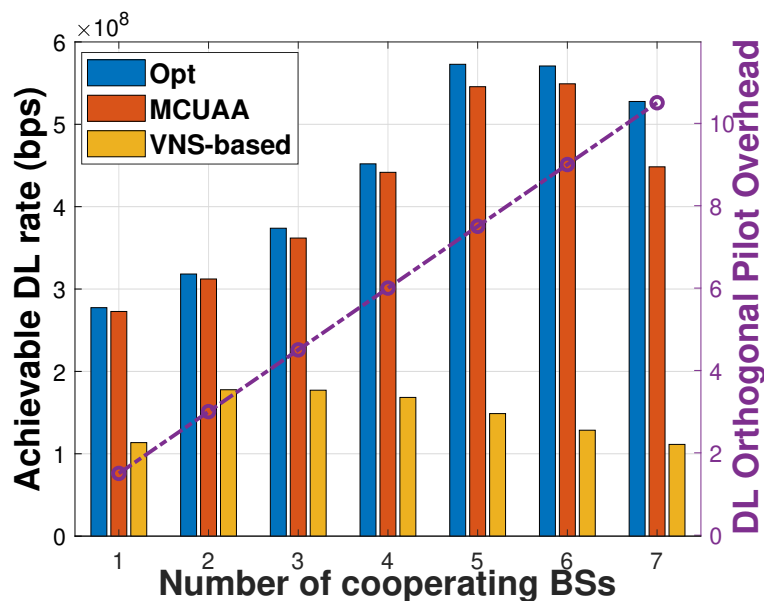


Figure 3.6: Achievable DL Rate

However, for increasing threshold rate, the number of the cooperating BSs for VNS-based algorithm becomes zero since the algorithm cannot provide the demanded QoS.

Fig. 3.8 shows the effect of blockage on UE behavior. As the distance increases, the probability of LoS decreases and probability of NLoS and probability of outage increase. On the other hand, the increase in the distance causes decrease in achievable rate and the number of the cooperating BSs increases to provide the data rate that the UE is demanding. In every condition, MCUAA supports the demanded data rate with less number of the cooperating BSs than VNS-based heuristic since it tries to assign UEs to on BSs rather than turning on additional BSs, which can support the demanded data rate.

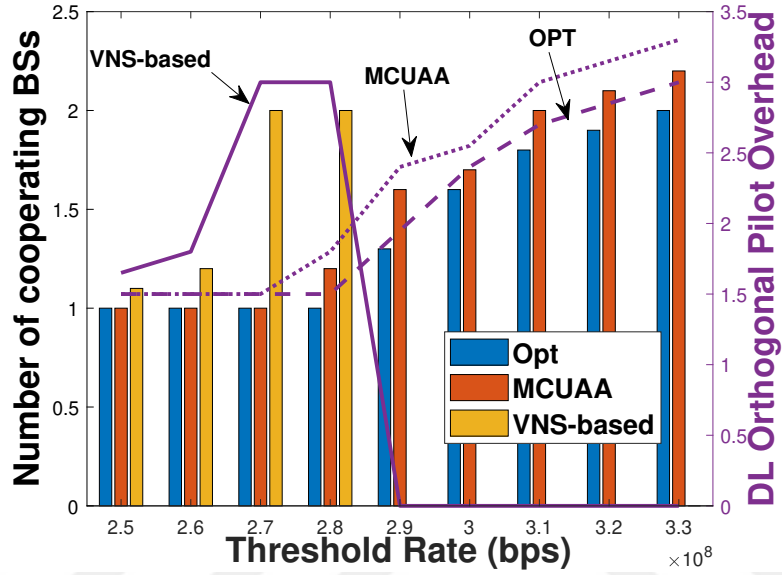


Figure 3.7: DL Threshold Rate

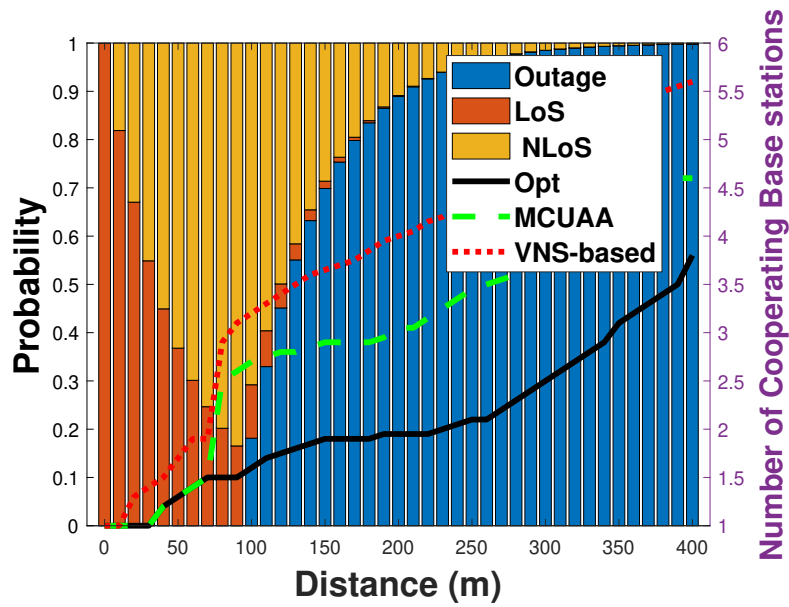


Figure 3.8: Distance vs. number of the cooperating BSs

Chapter 4

MINIMIZATION OF THE NUMBER OF HANDOVERS IN MULTI-CONNECTIVITY BASED ENERGY CONSTRAINED UL/DL DECOUPLED HCRAN

4.1 Introduction

5G systems are expected to manage high density of mobile UEs, that are demanding high data rates, support ultra-reliable low-latency communications and save up to 90 percent of power consumption as compared to present LTE system. One of the most promising approaches to fulfill the requirements of the aforementioned goals is HCRAN and it is the unification of MBSs, which operate at LTE cellular frequencies, and SBSs, which operate at mmWave frequencies, with cloud infrastructures, where the signal processing in BSs is controlled by the BBU-Cloud. However, in spite of the tremendous advantages of SBSs in enhancing capacity by the high bandwidth available in millimeter wave spectrum and providing network coverage in the gaps that cannot be covered by MBSs, extreme susceptibility of RSS to blockages at mmWave frequencies and small coverage region of SBSs result in high number of HOs in high mobility scenarios.

Number of HOs in a network is highly engaged with UE-BS association rules and UE-BS Association rules proposed for preventing high number of HOs in LTE HetNets include RSS-based UE association rules [73]- [75] and velocity based UE association rules [76] and [77]. First, in the context of RSS-based UE association rule, UEs do not change the BS, that provides service, unless the RSS falls below the threshold RSS [73]. In addition to threshold RSS, at the cost of sacrificing best RSS, the UEs bypasses some BSs along the UE trajectory and gets associated with the BS that

provides the third or fourth best RSS [74]. Moreover, UEs exploit advantages of BS cooperation by choosing next two consecutive cells, which have a BS in common with the current associated BS, along its trajectory to have a RSS value above threshold RSS value [75]. Second, HO is avoided, as long as the SINR value of the serving cell remains above the predefined threshold value and velocity is below a specified velocity threshold value [76] or as long as the velocity values of UEs are in between predetermined thresholds [77]. However, in 5G networks these association rules lead to an unbalanced BS loads and introduce unnecessary HOs, which is likely to occur between the adjacent BSs.

In highly directional 5G HetNets, number of HOs is minimized by adjusting direction of beams according to UE trajectory. The techniques used for the adjustment of the direction of the beams to minimize the number of HOs include formation of a SINR based candidate BS list, which is formed by utilizing the distance between UEs and candidate BSs and the angle of movement of UEs [80], tracking UE trajectory through the achievable data load and forming BS sets based on beam alignment cost and propagation effects of outage and NLOS. [81] and designing beam patterns based on the speed and position information of UEs and adjusting beam forming gains [82]. However, application of BS scanning in order to adjust direction of beams according to UE trajectory leads to an increase in signaling overhead that causes degradation in the overall QoS of the mobile network.

Unlike techniques aiming to minimize HO but causing increase in signaling overhead, MC based UE association techniques provide decrease in the number HOs as well as the signaling overhead. MC mode in the cell is activated to avoid an abrupt decrease in the signal strength received by forming base station clusters in case when a user surpasses a certain threshold of velocity [87], by assigning the UE to a cluster of BS, in which the BS, that provides the best RSS among the neighboring BSs, is selected as the HO control point [88], by activating a certain number of BSs nearby the UEs for data transmission and selecting BS that provides the best RSS, as the HO control point [89] and by forming BS clusters based on the information of UE

position and velocity with the help of BBU Pool [90]. Meanwhile, signaling overhead is assumed to be proportional to delay occurring during the sending or processing of a signaling message and is decreased compared to previous studies [87]- [90]. However, none of the studies about MC with signaling overhead consider about the increase in power consumption due to utilization of resources in multiple cells, simultaneously.

Energy efficiency based UE association methods reduce the number of HOs while reducing power consumption. The proposed methods to reduce power consumption include turning off the resource blocks completely rather than keeping them in idle mode after HO [79], allowing the HO process to take place only if the expected energy saving amount through HO is greater than the energy loss at BS during HO execution phase [78], dynamic turning on/off the BSs based on a direct request from the UE to the target BS, which bypasses the source BS [91] and offloading UEs from heavily loaded cells in order to allow saving of UE power with the help of future data contents, which are stored in advance for utilization when resources are not sufficient [92]. Nonetheless, none of the studies consider to minimize the total number of HOs ensuring that the energy consumption difference between consecutive time slots is less than a pre-defined value without the mobility information.

This paper formulates and proposes an efficient solution framework for the optimization problem of MC based energy constrained UL/DL decoupled UE Association with the goal of minimizing the number of HOs in 5G HCRAN, while considering accurate power consumption model encompassing transmissions in the BBU-Cloud and signaling overhead, UL/DL decoupled UE-BS association and transmission with effective rate. The main contributions of this paper are listed as follows:

- We provide a holistic framework for the minimization of HO number in HCRAN by using an ECHO execution policy to overcome the limitations of RSS based and velocity based HO policies for the first time in literature. The framework incorporates realistic power consumption models encompassing transmissions in the BBU-Cloud and signaling overhead, which are crucial points in analyzing the benefits of MC, UL/DL decoupled UE association and transmission with

effective rate. We constrain the number of simultaneous transmissions by the number of RF chains [33].

- We formulate the HO problem as a BILP. The problem is proven to be NP-Hard. Since it is NP-Hard, a heuristic algorithm called as ECHO algorithm is proposed. Instead of executing HO based on RSS or Velocity, ECHO algorithm executes HO based on checking if the difference of the energy consumption in consecutive time-slots is below a pre-defined power value. Moreover, at each given time-slot, ECHO algorithm forms feasible UE-BS or UE-BS cooperation pairs by LP Relaxation and solves GAP heuristic to assign unassigned UEs with UE-BS or UE-BS cooperation pairs to find the least power consuming UE-BS association pattern
- We analyze number of HOs, time complexity and effect of distance and blockage on the HO behavior of the proposed algorithm. We demonstrate the supremacy of the ECHO algorithm over existing methods by simulations in terms of closeness to the optimal for different networks sizes and various data rate requirements via extensive simulations.

4.2 System Model

The system model is detailed as follows:

4.2.1 HCRAN Architecture

In this subsection, HCRAN architecture is proposed in Fig. 4.1. There are F MBSs, where MBSs take charge of Control Plane and User Plane signaling, operate at LTE cellular frequencies and have $N_{RF,M}$ RF chains. Inside the coverage region of MBSs, there exists K SBSs containing $N_{RF,S}$ RF chains and operating at mmWave frequencies. SBSs are mainly responsible for data transmissions, implementing the U-plane and achieving less control overhead as well as lower HO delay in hot spots. Furthermore, there exists N_b mobile UEs with single antenna. Along the UE moving

trajectory, as depicted in Fig. 4.2 UEs can get service from more than one BS, which are operating at conventional cellular frequencies and mmWave frequencies and can cooperate to serve UEs both in DL and UL, therefore, UE demand is splittable. Lastly, SBSs get activated and send beacon signals for a pre-determined time slot to indicate that they can serve UEs and switch to inactive for another pre-determined time slot in an alternating manner [93].

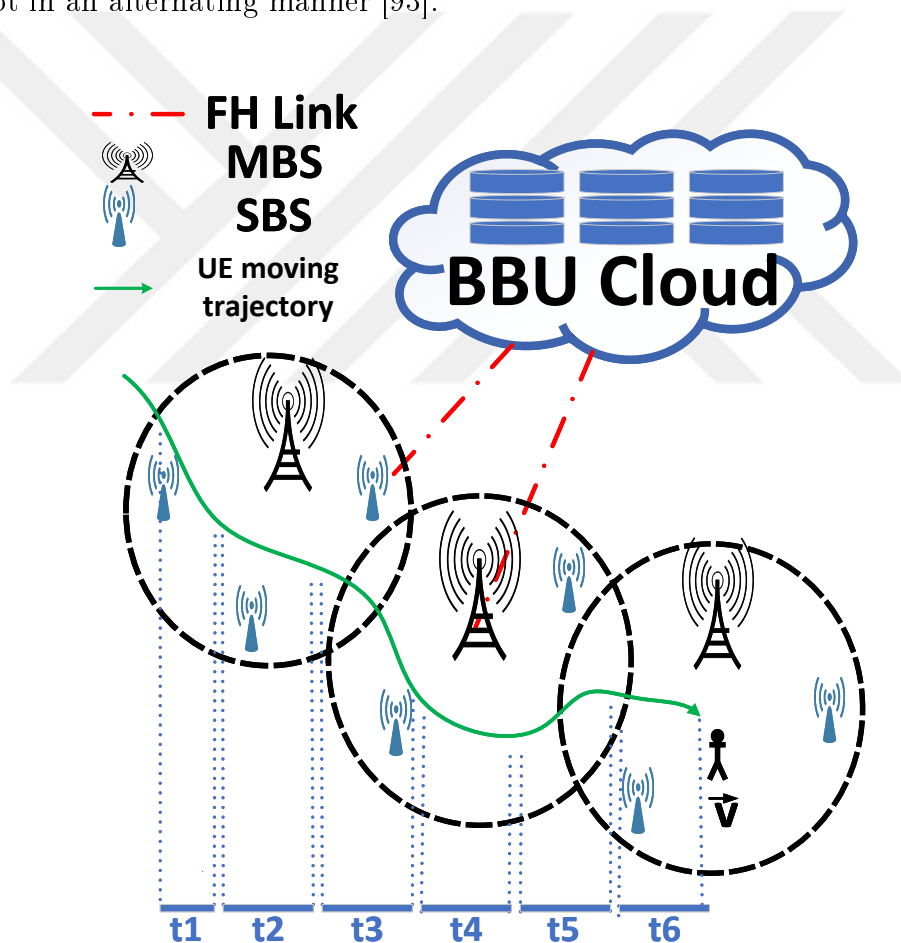


Figure 4.1: Handover in HCRAN

The signal processing in BSs is managed by the BBU-Cloud, where the BSs are connected to the BBU-Cloud through FH links, that have limited capacity, C_{fh} .

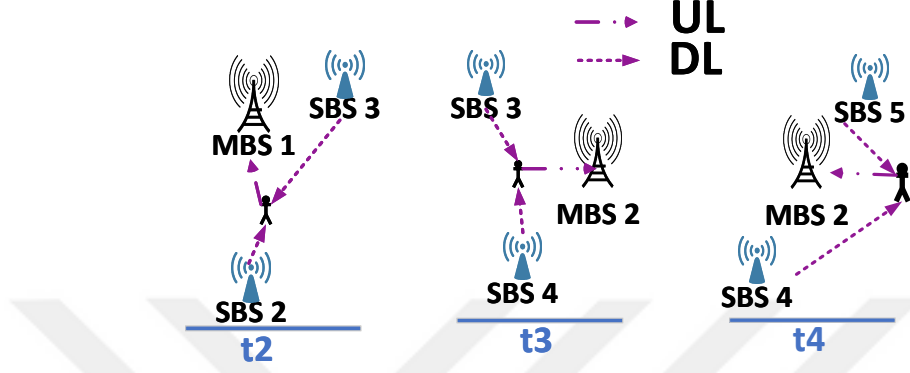


Figure 4.2: Multi-connectivity for specific time-slots

4.2.2 HCRAN Channel Characteristics

The levels of signal attenuation at time t in DL from MBS M and SBS S to UE j are demonstrated as α_{Mj}^t and α_{Sj}^t , respectively [67], whereas θ_{Mj}^t and θ_{Sj}^t represent the levels of signal attenuation at time t in UL from UE j to MBS M and SBS S , respectively [67].

Small wavelengths of mmW frequencies allow for the implementation of a large number of antenna elements in a small space to make narrow beams, which are highly directional. A positive side effect of highly directional transmissions is that the interference is greatly reduced, but it cannot be set to zero. Therefore, each UE j is exposed to interference power at time t in DL by the BSs, which are located outside of the cooperation cluster, and it is formulated as in [68]:

$$P_{j,Iout,dl}^t = \frac{N_c}{2} \cdot \sum_{i=1}^{2 \cdot ((K+F)-N_c)} P_{TX,\gamma}^t \cdot \alpha_{\gamma j}^t \quad (4.1)$$

where N_c represents the number of cooperating BSs, which form a cluster, γ is M or S. $P_{TX,M}^t$ and $P_{TX,S}^t$ express the transmission powers of MBS M and SBS S , which are located outside of the cooperation cluster, at time t in DL, respectively and α_{Mj}^t and α_{Sj}^t are the levels of signal attenuation at time t in DL from interfering MBS M and SBS S to UE j , respectively.

The interference power at time t in DL by the BSs, which form the cooperation cluster, and it is formulated as in [68]:

$$P_{j,Ins,dl}^t = \sum_{\substack{\gamma'=1 \\ \gamma' \neq \gamma}}^{K+F} P_{TX,\gamma'}^t \cdot \alpha_{\gamma'j}^t \quad (4.2)$$

where γ is M or S, $P_{TX,M'}^t$ and $P_{TX,S'}^t$ are the transmit powers of interfering MBS M or SBS S at time t in DL, respectively, and $\alpha_{M'j}^t$ and $\alpha_{S'j}^t$ are the levels of signal attenuation at time t in DL from interfering MBS M and SBS S to UE j , respectively.

For N_c cooperating BSs, the effective achievable rate at time t in DL is formulated as in [94],

$$\tilde{R}_{d,\gamma,j}^t = \frac{1}{N_c} \left(\sum_{i=1}^{N_c} R_{d,\gamma,j,i}^t \cdot \phi \right) \quad (4.3)$$

where γ is M or S and $R_{d,M,j,i}^t$ and $R_{d,S,j,i}^t$ are the achievable rates at time t in DL at UE j by the i^{th} cooperating MBS and SBS S, respectively. ϕ is the value indicating how much $R_{d,\gamma,j,i}^t$ degrades due to orthogonal and pre-coded pilots used by UEs to estimate and feedback channel matrix and for equalization and decoding, respectively. It is formulated as $(1 - \rho \cdot 3 \cdot N_c) - \delta$, where ρ represents the average pilot density in time and frequency and δ denotes the average control overhead [68]

Since BSs operate at different transmission bandwidths with different powers, they support different achievable rates at time t in DL and they are formulated as in [94]:

$$R_{d,\gamma,j,i}^t = B_{\gamma,i} \cdot \log \left(1 + \frac{P_{TX,\gamma,i}^t \cdot \alpha_{\gamma,j,i}^t}{|N_{RF,\gamma,i}| \cdot N_0 \cdot B_{\gamma,i} + P_{j,I,dl}^t} \right) \quad (4.4)$$

where γ is M or S, $B_{MS,i}$ and $B_{S,i}$ denote bandwidth required for transmission for the i^{th} cooperating MBS and SBS S, respectively [67], $P_{j,I,dl}^t$ represent the DL interference power, which corresponds to the summation of the interference powers at time t in DL by the BSs, which form the cooperation cluster and, which are located outside of the cooperation cluster, $P_{j,Ins,dl}^t$ and $P_{j,Iout,dl}^t$, respectively. $N_{RF,S,i}$ and $N_{RF,M,i}$

are numbers of RF chains and are equivalent to the number of UEs at maximum that can be provided service by the i^{th} cooperating SBS S and MBS, respectively [33]. $P_{TX,S,i}$ or $P_{TX,M,i}$ demonstrate the transmit power of i^{th} cooperating SBS S and MBS, respectively, N_0 is the power spectral density of the noise.

The transmit power allocation of UE j at time t is carried out to get over ϱ fraction of the path loss with respect to a reference received power per resource block at 0 dB path loss, P_0 , below P_{max} and is formulated as in [39]:

$$P_{TX,j,\gamma}^t = \min\{P_{TX,UE,max}, P_0 + \varrho \cdot \alpha_{\gamma,j}^t\} \quad (4.5)$$

where γ is M or S.

The interference power coming from UEs inside the cluster generated at UE j at time t in UL, $P_{j,Ins,ul}^t$, is calculated as in [68]:

$$P_{j,Ins,ul}^t = \sum_{\substack{j'=1 \\ j' \neq j}}^{N_{b,cluster}^t} P_{TX,j'}^t \cdot \theta_{\gamma j'}^t \quad (4.6)$$

where γ is M or S and $\theta_{Mj'}^t, \theta_{Sj'}^t$ is the UL path loss measured at the UE j' based on the UL transmit power of the reference symbols for MBS M and SBS S at time t, respectively and $N_{b,cluster}^t$ is the number of UEs in the cluster that is formed by BS at time t.

The interference power coming from UEs outside the cluster generated at UE j at time t in UL, $P_{j,Iout,ul}^t$, is calculated as in [68]:

$$P_{j,Iout,ul}^t = \sum_{\substack{j'=1 \\ j' \neq j}}^{N_b - N_{b,cluster}^t} P_{TX,j'}^t \cdot \theta_{\gamma j'}^t \quad (4.7)$$

For N_c cooperating BSs, the effective achievable rate at time t in UL is formulated

as in [94]:

$$\tilde{R}_{u,\gamma,j}^t = \frac{1}{N_c} \left(\sum_{i=1}^{N_c} R_{u,\gamma,j,i}^t \cdot \Theta \right) \quad (4.8)$$

where γ is M or S and $R_{u,M,j,i}^t$ and $R_{u,S,j,i}^t$ are the achievable rates at time t in UL at UE j by the i^{th} cooperating MBS M and SBS S, respectively. Θ is an expression of how much $R_{u,\gamma,j,i}^t$ degrades due to pilot signaling and CSI feedback rate, which are both scaled with the total number of UL transmit antennas within a cluster linearly. The amount of degradation in UL rate is formulated as $(1 - \rho \cdot N_c) - (2 \cdot N_c \cdot \rho \cdot q)$, where q represents the feedback bits that are used to calculate CSI for QoS [68].

Achievable rates in UL are formulated as in [94]:

$$R_{u,\gamma,j}^t = B_{\gamma,i} \cdot \log \left(1 + \frac{P_{TX,j,i}^t \cdot \theta_{\gamma,j,i}^t}{N_0 \cdot B_{\gamma,i} + P_{j,I,ul}^t} \right) \quad (4.9)$$

where γ is M or S, $P_{TX,j,M}$ and $P_{TX,j,S}$ represent the transmit powers of UE j to the MBS M and SBS S, respectively; and $P_{j,I,ul}^t$ represent the UL interference power, which corresponds to the summation of the interference powers coming from UEs outside the cluster and inside the cluster generated at UE j at time t in UL, $P_{j,Iout,ul}^t$ and $P_{j,Iins,ul}^t$, respectively, [67].

$Q_{d,j}^t$ and $Q_{u,j}^t$ are demanded data rate of UE j in DL and in UL at time t, respectively.

4.2.3 Power Consumption Models of Network Components

MBS power consumption at time t, P_M^t , consists of static power consumption $P_{St,M}$ and dynamic power consumption at time t $P_{Dyn,M}^t$ [42], [43]. $P_{St,M}$ consists of the power consumption of rectifier, air conditioner. $P_{Dyn,M}^t$ is formulated as $F_M^t \cdot P_{lM}$, where $F_M^t = \frac{\sum_{j=1}^{N_b} \frac{Q_{d,j}^t}{R_{d,Mj}^t} + \frac{Q_{u,j}^t}{R_{u,Mj}^t}}{N_{rf,M}}$ is the load factor that represents the ratio of the sum of channel utilization of the active UEs both in DL and UL to the total capacity of MBS M in terms of RF chains at time t, and P_{lM} consists of power consumption of

power amplifier, the transceiver, the digital signal processing unit.

Each SBS S with coverage range less than 30 meters is assumed to consume P_S^t , at time t as in [42]. P_S^t encompasses static power consumption and dynamic power consumption. $P_{St,S}$ includes power consumed in rectifier and air conditioner. Dynamic power consumption in SBS at time t , $P_{Dyn,S}^t$, is formulated as $F_S^t \cdot P_{lS}$, where $F_S^t = \frac{\sum_{j=1}^{N_b} \frac{Q_{d,j}^t}{R_{d,Sj}^t} + \frac{Q_{u,j}^t}{R_{u,Sj}^t}}{N_{rf,S}}$ is the load factor that represents the ratio of the sum of channel utilization of the active UEs both in DL and UL to the total capacity of SBS in terms of RF chains at time t , and P_{lS} consists of power consumption of power amplifier, the transceiver, the digital signal processing unit.

Due to decoupled UL/DL transmission, the power consumed on FH link in DL at time t is denoted as $P_{d,fhl}^t$ and is a linear function of $Q_{d,j}^t$ [46], whereas the power consumed on FH link in UL is denoted as $P_{u,fhl}^t$ and is a linear function of $Q_{u,j}^t$.

The power consumption of a UE at time t , $P_{u,j}^t$, consists of circuit power consumption $P_{circuit}$ and power consumed in the power amplifier P_{amp} . P_{amp} is formulated as $\frac{P_{TX,UE}}{\rho}$ in [47], where ρ is power amplifier efficiency.

Power consumption of baseband digital signal processing is denoted as P_{SP} , depends on the amount of cooperation between BSs as shown in [68]:

$$P_{SP} = p_{sp} \cdot (0.87 + 0.1 \cdot N_c + 0.03 \cdot N_c^2) \quad (4.10)$$

where p_{sp} is the base value and N_c is the number of cooperating BSs.

Total power consumption of the system at time t is denoted as E^t and includes power consumption in DL, UL and BBU Pool:

$$\begin{aligned} E^t = & P_M^t + P_S^t + P_{d,fhl,M}^t + P_{u,fhl,M}^t + P_{d,fhl,S}^t + P_{u,fhl,S}^t \\ & + P_{UE}^t + P_{SP} \end{aligned} \quad (4.11)$$

4.3 Problem Formulation

The joint optimization of UE association and switching on/off the SBSs with the objective of minimizing the number of HOs in MC based decoupled UL/DL UE association given the capacity, effective transmission rate, power consumption incorporating signal processing power in BBU-Cloud and number of cooperating BSs constraints is formulated as the following BILP:

$$\begin{aligned}
 \min \quad & \frac{1}{2} \cdot \sum_{t=1}^T \left(\sum_{M=1}^F A_M^t + D_M^t + \chi_M^t + \gamma_M^t + \sum_{S=1}^K V_S^t + L_S^t + \kappa_S^t + \zeta_S^t \right) \\
 \text{s.t.} \quad & \frac{1}{N_c} \cdot (\phi \cdot R_{d,Mj}^t \cdot H_{Mj}^t + \sum_{S=1}^K \phi \cdot R_{d,Sj}^t \cdot C_{Sj}^t) \geq Q_{d,j}^t, \\
 & j \in \{1, N_b\}, t \in \{1, T\}
 \end{aligned} \tag{4.4-01}$$

$$\begin{aligned}
 & \frac{1}{N_c} \cdot (\Theta \cdot R_{u,Mj}^t \cdot G_{Mj}^t + \sum_{S=1}^K \Theta \cdot R_{u,Sj}^t \cdot Z_{Sj}^t) \geq Q_{u,j}^t, \\
 & j \in \{1, N_b\}, t \in \{1, T\}
 \end{aligned} \tag{4.4-02}$$

$$\sum_{j=1}^{N_b} \frac{Q_{d,j}^t}{R_{d,Mj}^t} \cdot x_{Mj}^t + \sum_{j=1}^{N_b} \frac{Q_{u,j}^t}{R_{u,Mj}^t} \cdot y_{Mj}^t \leq N_{rf,M}, M \in \{1, F\}, t \in \{1, T\} \tag{4.4-03}$$

$$\sum_{j=1}^{N_b} \frac{Q_{d,j}^t}{R_{d,Sj}^t} \cdot x_{Sj}^t + \sum_{j=1}^{N_b} \frac{Q_{u,j}^t}{R_{u,Sj}^t} \cdot y_{Sj}^t \leq N_{rf,S}, S \in \{1, K\}, t \in \{1, T\} \tag{4.4-04}$$

$$\sum_{j=1}^{N_b} Q_{d,j}^t \cdot x_{Mj}^t + \sum_{j=1}^{N_b} Q_{u,j}^t \cdot y_{Mj}^t \leq C_{fh}, M \in \{1, F\}, t \in \{1, T\} \tag{4.4-05}$$

$$\sum_{j=1}^{N_b} Q_{d,j}^t \cdot x_{Sj}^t + \sum_{j=1}^{N_b} Q_{u,j}^t \cdot y_{Sj}^t \leq C_{fh}, S \in \{1, K\}, t \in \{1, T\} \tag{4.4-06}$$

$$x_{Sj}^t \leq T_S^t, j \in \{1, N_b\}, S \in \{1, K\}, t \in \{1, T\} \tag{4.4-07}$$

$$y_{Sj}^t \leq T_S^t, j \in \{1, N_b\}, S \in \{1, K\}, t \in \{1, T\} \tag{4.4-08}$$

$$x_{Sj}^t \leq C_{Sj}^t, j \in \{1, N_b\}, S \in \{1, K\}, t \in \{1, T\} \tag{4.4-09}$$

$$y_{Sj}^t \leq B_{Sj}^t, j \in \{1, N_b\}, S \in \{1, K\}, t \in \{1, T\} \quad (4.4-10)$$

$$x_{Mj}^t \leq H_{Mj}^t, j \in \{1, N_b\}, M \in \{1, F\}, t \in \{1, T\} \quad (4.4-11)$$

$$y_{Mj}^t \leq G_{Mj}^t, j \in \{1, N_b\}, M \in \{1, F\}, t \in \{1, T\} \quad (4.4-12)$$

$$\sum_{M=1}^F H_{Mj}^t + \sum_{S=1}^K C_{Sj}^t \leq N_c, j \in \{1, N_b\}, t \in \{1, T\} \quad (4.4-13)$$

$$\sum_{M=1}^F G_{Mj}^t + \sum_{S=1}^K B_{Sj}^t \leq N_c, j \in \{1, N_b\}, t \in \{1, T\} \quad (4.4-14)$$

$$A_M^t \geq x_{Mj}^t - x_{Mj}^{t-1}, j \in \{1, N_b\}, M \in \{1, F\}, t \in \{\{1, T\} - \{t-1\}\} \quad (4.4-15)$$

$$\chi_M^t \geq -(x_{Mj}^t - x_{Mj}^{t-1}), j \in \{1, N_b\}, M \in \{1, F\}, t \in \{\{1, T\} - \{t-1\}\} \quad (4.4-16)$$

$$V_S^t \geq x_{Sj}^t - x_{Sj}^{t-1}, j \in \{1, N_b\}, S \in \{1, K\}, t \in \{\{1, T\} - \{t-1\}\} \quad (4.4-17)$$

$$\kappa_S^t \geq -(x_{Sj}^t - x_{Sj}^{t-1}), j \in \{1, N_b\}, S \in \{1, K\}, t \in \{\{1, T\} - \{t-1\}\} \quad (4.4-18)$$

$$D_M^t \geq y_{Mj}^t - y_{Mj}^{t-1}, j \in \{1, N_b\}, M \in \{1, F\}, t \in \{\{1, T\} - \{t-1\}\} \quad (4.4-19)$$

$$\gamma_M^t \geq -(y_{Mj}^t - y_{Mj}^{t-1}), j \in \{1, N_b\}, M \in \{1, F\}, t \in \{\{1, T\} - \{t-1\}\} \quad (4.4-20)$$

$$L_S^t \geq y_{Sj}^t - y_{Sj}^{t-1}, j \in \{1, N_b\}, S \in \{1, K\}, t \in \{\{1, T\} - \{t-1\}\} \quad (4.4-21)$$

$$\zeta_S^t \geq -(y_{Sj}^t - y_{Sj}^{t-1}), j \in \{1, N_b\}, S \in \{1, K\}, t \in \{\{1, T\} - \{t-1\}\} \quad (4.4-22)$$

$$A_M^t + \chi_M^t = 1, M \in \{1, F\}, t \in \{1, T\} \quad (4.4-23)$$

$$D_M^t + \gamma_M^t = 1, M \in \{1, F\}, t \in \{1, T\} \quad (4.4-24)$$

$$V_S^t + \kappa_S^t = 1, S \in \{1, K\}, t \in \{1, T\} \quad (4.4-25)$$

$$L_S^t + \zeta_S^t = 1, S \in \{1, K\}, t \in \{1, T\} \quad (4.4-26)$$

$$E^t \leq E^{t-1} + \epsilon, \quad t \in \{1, T\} \quad (4.4-27)$$

$$\begin{aligned} \text{Vs} \quad & T_S^t, C_{Sj}^t, H_{Mj}^t, B_{Sj}^t, G_{Mj}^t, A_M^t, V_S^t, D_M^t, L_S^t, \chi_M^t, \gamma_M^t, \kappa_S^t, \zeta_S^t, \\ & x_{Mj}^t, x_{Sj}^t, y_{Mj}^t, y_{Sj}^t \in \{0, 1\} \end{aligned} \quad (4.4-28)$$

where K is the number of SBSs, N_b is the number of UEs, F is the number of MBSs and T is the number of time periods. The decision variables of the problem are stated as follows: T_S^t , is a binary variable, which takes value 1 in case SBS S is switched on in UL or in DL at time t and 0 otherwise; C_{Sj}^t and H_{Mj}^t are binary variables, which take value 1, if there exist a collaboration between SBS S and other BSs to serve UE j and MBS M and other BSs to serve UE j in DL at time t , respectively and 0 otherwise; B_{Sj}^t and G_{Mj}^t are binary variables, which take value 1, if there exist a collaboration between SBS S and other BSs to serve UE j and MBS M and other BSs to serve UE j in UL at time t , respectively and 0 otherwise; A_M^t and V_S^t are binary variables, which take value 1 if HO takes place from MBS M and SBS S in DL at time t , respectively and 0 otherwise; D_M^t and L_S^t are binary variables, which take value 1 if HO takes place from MBS M and SBS S in UL at time t , respectively and 0 otherwise; χ_M and κ_S are binary variables, which take value 1 if HO takes place from MBS M and SBS S in DL at time t , respectively and 0 otherwise; γ_M and ζ_S are binary variables, which take value 1 if HO takes place from MBS M and SBS S in UL at time t , respectively and 0 otherwise; x_{Mj}^t and x_{Sj}^t are binary variables, which take value 1 if UE j gets associated with MBS M and SBS S in DL at time t , respectively and 0 otherwise; y_{Mj}^t and y_{Sj}^t , are binary variables, which take value 1 if UE j gets associated with MBS M and SBS S in UL at time t , respectively and 0 otherwise.

Constraints (4.4-01) and (4.4-02) assure that the data rate requirement of UE j at time t in DL and in UL can not be greater than or equal to the effective rate the cooperation set provides, respectively. Constraints (4.4-03) and (4.4-04) indicate that maximum number of UEs that can be simultaneously served by a BS at time t in DL and UL is less than or equal to the number of RF chains that belong to MBS M , $(N_{rf,M})$, or to SBS S , $(N_{rf,S})$, respectively. Constraints (4.4-05) and (4.4-06) indicate

that the entire data transmitted through FH link at time t in DL and UL cannot surpass the total capacity of FH link of MBS M and SBS S , respectively. Constraints (4.4-07) and (4.4-08) imply that if a UE gets associated with SBS S at time t in DL and in UL, SBS S is switched on. Additionally, constraints (4.4-09) and (4.4-10) indicate that SBS S is a collaboration partner if there exists a collaboration set including the corresponding SBS S to serve UE j in DL and in UL at time t , respectively, whereas constraints (4.4-11) and (4.4-12) demonstrate that MBS M is a collaboration partner if there exists a collaboration set including the corresponding MBS M to serve UE j in DL and in UL at time t , respectively. Constraints (4.4-13) and (4.4-14) imply that the total number of collaboration partners to provide service to UE j cannot be greater than N_c at time t in UL and DL, respectively. Moreover, constraints (4.4-15) and (4.4-16) demonstrate that HO occurs if UE j , which is associated with MBS M in DL at time $t-1$, is not associated with MBS M in DL at time t . Constraints (4.4-17) and (4.4-18) represent that HO occurs, if UE j , which is associated with SBS S in DL at time $t-1$, is not associated with SBS S in DL at time t . On the other hand, constraints (4.4-19) and (4.4-20) represent that HO occurs if UE j , which is associated with MBS M in UL at time $t-1$, is not associated with MBS M in UL at time t . Constraints (4.4-21) and (4.4-22) indicate that HO occurs, if UE j , which is associated with SBS S in UL at time $t-1$, is not associated with SBS S in UL at time t . Furthermore, constraints (4.4-23) and (4.4-24) represent that only one HO occurs at time t and at the same MBS M in DL and in UL, respectively. Moreover, constraints (4.4-25) and (4.4-26) represent that only one HO occurs at time t and at the same SBS S in DL and in UL, respectively. Lastly, constraint (4.4-27) indicates that HO takes place if the energy consumption of UE association at time t is less than the energy consumption at time $t - 1$ by ϵ value.

4.4 NP-Hardness of the Minimization Problem

Theorem 3. *The problem in Section 4.3 is NP-hard.*

Proof. We reduce the minimization problem to NP-Hard uncapacitated p-median

problem [95], [96].

Let us define a problem instance, where we analyze HO problem at a specific time instance t . Then, the HO problem at a specific time instance t corresponds to UE association problem at a time instance t . The objective of the problem is then to associate UEs with at most N_c BSs while ensuring the power consumption between consecutive time slots to be less than ϵ . Next, we assume that the number of cooperating BSs, N_c , is limited to one, which constrains variables H_{Mj}^t , G_{Mj}^t , C_{Sj}^t and B_{Sj}^t are binary without the contribution of constraints 4.4-09-4.4-12. In this case, our optimization problem is reduced to CKFLP as in [69], where k BSs are switched on and UEs are assigned to on BS so that UE data rate requirements are satisfied and capacity limits of BSs are not exceeded, while minimizing the sum of power consumption. It is proven to be NP-Hard, as a result of the reduction of the problem to NP-Hard uncapacitated k -facility median problem. $\square$

4.5 Solution Methodology

ECHO algorithm is proposed to solve the optimization problem (4.3) in polynomial time. The aim of ECHO algorithm is to develop the initial solution, that is acquired by using LPR-R and GAP heuristic, which picks up the output of LPR-R as input and examines if it is feasible to find other allocation models that enable to decrease the number of HOs further within pre-specified power consumption range. To minimize the number of HOs in previously proposed RSS-based [73] and V-based [77] algorithms, RSS and velocity are the only constraints that have effect on the HO rate. Additionally, the inputs to the corresponding heuristic algorithms are unassigned UEs and inactive BSs. Conversely, ECHO algorithm utilizes the green association criteria, which allows the algorithm to consume power upto a specific value, and inputs to the heuristic algorithm are a set of associated UE-BS pairs, unassigned UEs and inactive BSs. This reduces the complexity of the algorithm, enables comprehensive and fast search for the minimum and allows the algorithm perform close to optimal.

4.5.1 Energy Constrained HO Algorithm

The flowchart of the ECHO algorithm is depicted in Fig. 4.3. The ECHO algorithm is initialized with the introduction of the MV at time t , LV at time t , XL^t , XG^t , XH^t and XS^t , Energy consumption at time t (E^t), E_l^t , E^0 and E_s^t present time slot (t), period (T) and ϵ . MV^t is equal to the number of HOs of the ECHO Algorithm, LV^t corresponds to UE-BS association at time t , XL^t , XG^t , XH^t and XS^t correspond to UE-BS association matrices obtained after LPR-R, GAP heuristic and HO Execution and SRAA [64], respectively. E^t is the summation of energy consumption values of LPR-R, E_l^t , and heuristic for GAP at time t , E^0 is set to zero, E_s^t is the energy consumption value of SRAA and ϵ is a power value.

First, we run SRAA to have an initial UE-BS association pattern and corresponding energy consumption value. For the upcoming time-slots, we relax the BILP in Equation (4.4) by using LP-Relaxation. We make use of Rounding process to get a set of assigned UE-BS pairs, unassigned UEs and off BSs. The attained sets are input to the heuristic for GAP and GAP is utilized to assign unassigned UEs with UE-BS or UE-BS cooperation pairs to find the least power consuming UE-BS association pattern. In the event that BSs cannot fulfill the requirements of UEs, a random inactive BS is switched on and GAP is utilized again. On the other hand, energy consumption of UE-BS association is calculated. The energy consumption value is an essential input on deciding if it is energy efficient to execute handover. In case it is energy efficient, HO is executed and heuristic runs until specified time period T has expired. Otherwise, HO is not executed and heuristic starts again.

The selection process to find the least power consuming BSs out of n BSs consumes $O(\log n)$ time, since we divide n BSs into two sets, which contain active and inactive BSs. There exists m UEs and we assign each UE to the active BSs, where it takes $O(m)$ time. Therefore, the complexity of the algorithm is $\mathcal{O}(m \log n)$, where n is the number of BSs and m is the number of UEs. The detailed description of the main functions of the ECHO algorithm is stated as follows:

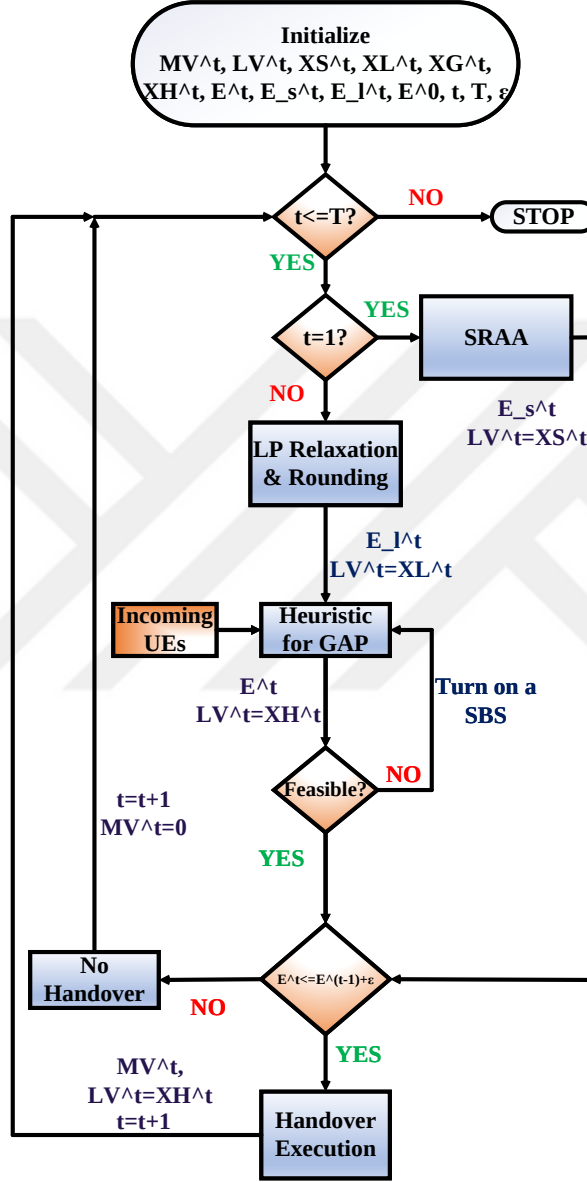


Figure 4.3: General Structure of the ECHO Algorithm

4.5.2 Selection and Repetition based UE Association Algorithm (SRAA)

SRAA aims to minimize the total power consumption of UE-BS association while considering accurate power consumption models, rate, capacity and effect of FH links [64]. The minimum power consuming UE-BS association or UE-BS association pair is found as the by running the heuristic, which encompasses LP-Relaxation and rounding

process and repeated use of two algorithms, that are denoted as heuristic for modified matching and heuristic for re-allocation of UEs. The power consumption of the UE-BS association pairs is shown as E^1 .

LP Relaxation & Rounding

The BILP in Equation (4.4) is relaxed by using LP-Relaxation and a set of assigned UE-BS pairs, unassigned UEs and off BSs is attained by the help of rounding as an output. Nonetheless, there exist infeasible cases, in which LPR-R brings out since some constraints of the optimization problem are violated. Comprehensive definitions on how we get feasible setts are as follows:

- After relaxing the problem with LP-Relaxation, the decision variables have values greater than 0.5. Right after the rounding process, all values are rounded up to 1 indicating that each UE is assigned to a cooperation cluster, each with more than N_c BSs. The constraints (4.4-13) and (4.4-14) are violated in this instance. To constrain the elements of the cooperation set with N_c BSs, we calculate the power consumption value of association of UE with each N_c BSs at time t as in Equation (4.11) while taking pre-defined capacity constraints into consideration. The BSs providing a lower power consumption value is set to 1 while the others are set to 0.
- Values of all decision variables are less than 0.5 indicating all UEs are unassigned and all BSs are off.

Heuristic for GAP

The aim of the heuristic for GAP is to find the minimum power consuming UE-BS association by assigning unassigned UEs or incoming UEs to UE-BS pairs or to on BSs. Moreover, the capacity constraints at SBS i , MBS M and FH link at time t are updated as $N_{RF,i} - C_i^t$, $N_{RF,M} - C_M^t$, and $C_{fh,i} - N_i^t$, respectively, where C_i^t , C_M^t and

N_i^t are the capacities allocated to assigned UEs at SBS i , MBS M and FH link at time t , respectively. The optimization problem is formulated as:

$$\begin{aligned} \min \quad & \sum_{i=1}^R \sum_{j=1}^P Q_{d,j}^t \left(P_{fh} + \frac{P_{li}}{R_{d,ij}^t} \right) z_{ij}^t + \sum_{M=1}^F \sum_{j=1}^P Q_{d,j}^t \left(\frac{P_{lM}^t}{R_{d,Mj}^t} + P_{fh} \right) z_{Mj}^t + \\ & \left(\sum_{j=1}^P \sum_{i=1}^R \left(P_{u,j}^t \frac{Q_{u,j}^t}{R_{u,ij}^t} + Q_{u,j}^t P_{fh} \right) v_{ij}^t + \sum_{M=1}^F (P_{u,j}^t + P_l) \frac{Q_{u,j}^t}{R_{u,Mj}^t} v_{Mj}^t \right) \\ & + P_{St,M} + P_{St,S} \\ \text{s.t.} \quad & \sum_{j=1}^P \frac{Q_{d,j}^t}{R_{d,ij}^t} z_{ij}^t + \frac{Q_{u,j}^t}{R_{u,ij}^t} v_{ij}^t \leq N_{RF,i} - C_i^t, i \in \{1, R\} \quad t \in \{1, T\} \end{aligned} \quad (4.5-01)$$

$$\begin{aligned} & \sum_{j=1}^P \frac{Q_{d,j}^t}{R_{d,Mj}^t} z_{Mj}^t + \frac{Q_{u,j}^t}{R_{u,Mj}^t} v_{Mj}^t \leq N_{RF,M} - C_M^t, M \in \{1, F\}, t \in \{1, T\} \end{aligned} \quad (4.5-02)$$

$$\sum_{j=1}^P Q_{d,j}^t z_{ij}^t + \sum_{j=1}^P Q_{u,j}^t v_{ij}^t \leq C_{fh,i} - N_i^t, i \in \{1, R\} \quad t \in \{1, T\} \quad (4.5-03)$$

$$z_{ij}^t \leq C_{ij}^t, j \in \{1, P\}, i \in \{1, R\}, t \in \{1, T\} \quad (4.5-04)$$

$$v_{ij}^t \leq B_{ij}^t, j \in \{1, P\}, i \in \{1, R\}, t \in \{1, T\} \quad (4.5-05)$$

$$z_{Mj}^t \leq H_{Mj}^t, j \in \{1, P\}, M \in \{1, F\}, t \in \{1, T\} \quad (4.5-06)$$

$$v_{Mj}^t \leq G_{Mj}^t, j \in \{1, P\}, M \in \{1, F\}, t \in \{1, T\} \quad (4.5-07)$$

$$\sum_{M=1}^F H_{Mj}^t + \sum_{i=1}^R C_{ij}^t \leq N_c, j \in \{1, P\}, t \in \{1, T\} \quad (4.5-08)$$

$$\sum_{M=1}^F G_{Mj}^t + \sum_{i=1}^R B_{ij}^t \leq N_c, j \in \{1, P\}, t \in \{1, T\} \quad (4.5-09)$$

$$z_{ij}^t, v_{ij}^t, z_{Mj}^t, v_{Mj}^t \in \{0, 1\} \quad (4.5-10)$$

where R is the number of on SBSs at time t , P is the number of unassigned UEs at time t and F is the number of MBSs at time t . The decision variables of the problem are z_{ij}^t and v_{ij}^t , which are binary variables taking values 1, when an on SBS i and an unassigned UE j gets associated with each other in DL and UL at time t , respectively

and 0 otherwise; z_{Mj}^t and v_{Mj}^t , which are binary variables taking values 1 when MBS and an unassigned UE j gets associated with each other in DL and UL at time t , respectively and 0 otherwise.

The BILP problem in Subsection 4.5 aims to minimize power consumption in time-period T . Unlike the capacity constraints in Equations (4.4-04), (4.4-03) and (4.4-06), capacity constraints in Equations (4.5-01), (4.5-02) and (4.5-03) provide less capacity due to capacity reserved for assigned UEs at SBS i , MBS and in FH link at time t . Additionally, constraints (4.5-04) and (4.5-05) indicate that SBS S is a collaboration partner if there exists a collaboration set including the corresponding SBS S to serve UE j in DL and in UL at time t , respectively, whereas constraints (4.5-06) and (4.5-07) demonstrate that MBS M is a collaboration partner if there exists a collaboration set including the corresponding MBS M to serve UE j in DL and in UL at time t , respectively. Constraints (4.5-08) and (4.5-09) imply that the total number of collaboration partners to provide service to UE j cannot be greater than N_c at time t in UL and DL, respectively. The optimization problem in Subsection 4.5.2 has the form GAP. GAP is NP-Hard and it cannot be solved to optimality in polynomial time [50]. We utilize the Hungarian method proposed in [97] to solve the problem. First, cost matrix is formed, which is composed of power consumption values for assigning the UE j to MBS M , SBS i , cooperation set including MBS M and cooperation set including SBS i . The size of the matrix is $\left(j * \binom{Total\ BS\ number - 1}{N_c}, 2 * (Total\ BS\ number)\right)$. The smallest entry in each row of the cost matrix is subtracted from all the entries of the corresponding row and the smallest entry in each column is subtracted from all the entries of the corresponding column. Then, rows and columns, which contain zero entries, are selected. If the total number of selected row-column pairs is equal to number of unassigned UEs, then minimum power consuming UE-BS pairs are found. In case when the number of selected row-column pairs is less than the number of unassigned UEs, the smallest entry among all row-column pairs is selected. This procedure is repeated until the number of row-column pairs is equal to number of unassigned UEs. Otherwise, the UE-BS association pair with the highest

power consumption is discarded from the selected UE-BS association pairs list until the number of row-column pairs is equal to number of unassigned UEs.

4.6 Simulations and Performance Evaluation

This section aims to assess the performance of the ECHO algorithm for various network sizes compared to previously proposed algorithms including V-based algorithm [77] and RSS-based algorithm [73]; demonstrate the effect of number of cooperating BSs on the number of HO and show the efficiency of the ECHO algorithm in terms of run time, achievable rate and overhead. The V-based and RSS-based algorithms are explained as follows:

- In **V-based** algorithm, UE velocity and SNR measurements in the UL and DL channels are utilized to control the HO procedure. UEs are categorized as vehicular UEs, where the velocity is more than 10 m/s, pedestrian UEs, where the velocity is less than 1.4 m/s and as regular UEs which have the velocity between 1.4 m/s and 10 m/s [77]. HO is rejected for vehicular UEs, executed for pedestrian UEs and executed for regular UEs with the help of green approach explained as follows: BSs serve UEs as long as the UE-BS associations do not cause an increase in the intra-BS interference and instead of allocating the power to satisfy demanded SNR, it allocates the power which guarantees the minimum SNR. Therefore, in case when a UE is in need to execute HO, first the velocity is checked by the random target BS, then, for the corresponding target BS, intra-BS interference is calculated. If the power allocated to the UE by the target BS, fulfills the requirements of the UE, the HO is executed. Otherwise, any other random BS is selected. This process is repeated until all HO requesting UEs get associated with their corresponding target BSs.
- In **RSS-based** algorithm, RSS is used to control the HO procedure. The algorithm starts with the case, where the RSS of the UE-BS connection falls below a certain threshold value [73]. UE measures the RSS of the neighboring BSs

and makes a list consisting of candidate MBSs and SBSs to execute the HO to. In order to ensure that the BS selected from the candidate list is able to serve the UE and provides the demanded data rate, reserved capacity at the target BS must be greater than or equal to the sum of capacity necessary for active UEs and requested capacity by the UE willing to execute HO. In case when the condition is met, HO is triggered from source BS to the target BS, otherwise the corresponding BS is removed from the list and the subsequent BS in the candidate list is chosen as the target BS. This process is repeated until all HO requesting UEs get associated with their corresponding target BSs.

We use IBM CPLEX Optimization Studio with MathWorks MATLAB to obtain the simulation results. Simulation results are obtained and averaged based on 100000 random configurations, where 2 MBS are located in the center of each cell, 20 SBSs and 50 UEs are distributed randomly and uniformly within the circular area of radius within [0,750]m. The UEs are assumed to travel with velocities which are distributed around BSs uniformly and randomly between 0.1 m/s and 20 m/s. The UEs are assumed to experience three different link states, which are LoS state, where there does not exist any impediment between the transmitter and the receiver, or in NLoS state, where there exists partial or full impediments between the transmitter and the receiver, or in outage and the state changes with distance and mmWave-related environmental parameters [37]. The attenuation of the links are determined considering large scale statistics that arise primarily from the free space loss and the environment affecting the degree of refraction, diffraction, reflection and absorption. The dependence of the path loss on distance summarizing large scale statistics is modeled as $\psi_{\gamma,j}^t = PL(d_0)^t + 10 * \eta_j^t * \log_{10}(\frac{d_{\gamma,j}^t}{d_0}) + X_{\sigma_j}^t$, where γ is S or M, $\psi_{\gamma,j}$ can be replaced with $\alpha_{\gamma,j}$ in DL, $\theta_{\gamma,j}$ in UL, $PL(d_0)^t$ is the free space path loss in dB at a reference distance d_0 , η_j^t is the path loss exponent, $d_{\gamma,j}^t$ is the distance between BS γ and UE j , and $X_{\sigma_j}^t$ is a zero mean Gaussian random variable with $(\sigma_j^t)^2$ variance. The parameters for the mmWave path loss model at time t are stated in [37] and the rest are as follows: $B_M=20$ MHz and $B_S=800$ MHz, $N_0=-134$ dBm/MHz, $C_{fh}=4.45$

Gbps, $N_{RF,M}=8$, $N_{RF,S}=4$, $P_{fh}=0.1\text{W}/\text{Mbps}$, $\rho=8/168$, $\delta=3/14$, $q=8$, $P_{dyn,M}=768.9$, $P_{St,M}=605\text{W}$, $P_{dyn,S}=216.6\text{W}$, $P_{St,S}=160\text{W}$, [42], $P_{TX,M}=43\text{ dBm}$, $P_{TX,S}=33\text{ dBm}$ and $P_{TX,UE,max}=23\text{ dBm}$, $P_0=-50\text{dBm}$, $\varrho=0.6$, $\epsilon=1000\text{ W}$; and $Q_{d,j}^t$ and $Q_{u,j}^t$ are uniformly distributed between $[0.15,2]\text{ Gbps}$ and $[0.2,0.5]\text{ Gbps}$, respectively.

Fig. 4.4 demonstrates effect of number of UEs on the run time in MATLAB. For all algorithms, run time in MATLAB increases. Nonetheless, ECHO algorithm illustrates important improvements compared to optimal, RSS-based and V-based algorithms. ECHO algorithm assigns UEs to the most energy efficient cooperation set of BSs that can provide less number of HOs in less time than RSS-based and V-based algorithms since in ECHO algorithm the UEs associate only with on BSs and the energy consumption constraint does not lead frequent cell change. Any change in RSS or in velocity causes RSS-based and V-based algorithms to search for additional on BSs. Furthermore, selection of a broader and more energy efficient BS cooperation set, that leads to less number of HOs, takes long time.

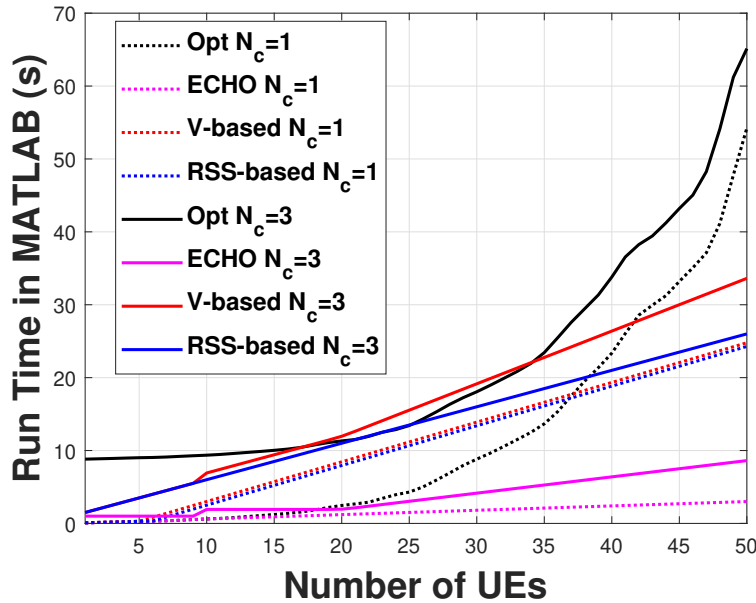


Figure 4.4: Number of the UEs vs run time in MATLAB

Fig. 4.5 demonstrates the number of HO for increasing ϵ values. As ϵ value increases, the number of HOs decreases since the UE-BS association is allowed to

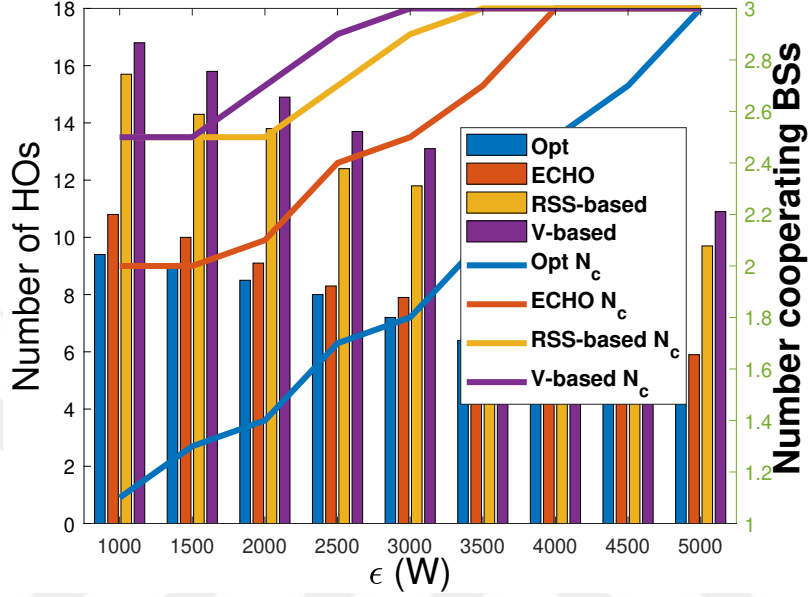


Figure 4.5: Number of HO for different power difference values

consume more power and mobile UEs do not change the association pairs even though TX power of UEs and dynamic power consumption of BSs increase. The ECHO algorithm performs very close to optimal, significantly better than previously proposed algorithms due to controlled on/off operation of BSs with the use of heuristic for GAP and HO execution metric which depends on the ϵ value between two consecutive time-slots. ϵ value allows the system to consume more UE transmit power and BS dynamic power to have the same UE-BS association pair in the consecutive time slots, which provides decrease in the number of HOs. Next, the number of HOs in RSS-based algorithm exceeds the number of HOs in ECHO algorithm since in case of increasing ϵ value, the algorithm allows mobile UEs to change BS connections frequently to get the demanded RSS easily. Moreover, number of HOs with V-based algorithm has the highest number of HOs due to utilization of green approach only for UEs with velocity between 5m/s and 10 m/s and allowing UEs with velocity below 5 m/s to execute HO. Since velocity of UEs are distributed between 0.1 m/s and 20 m/s, some UEs change cells more frequently, which causes an increase in HO number, as compared to other algorithms. On the other hand, as ϵ increases the number of cooperating

BSs increases because the system allows BSs to consume more power to decrease HO number

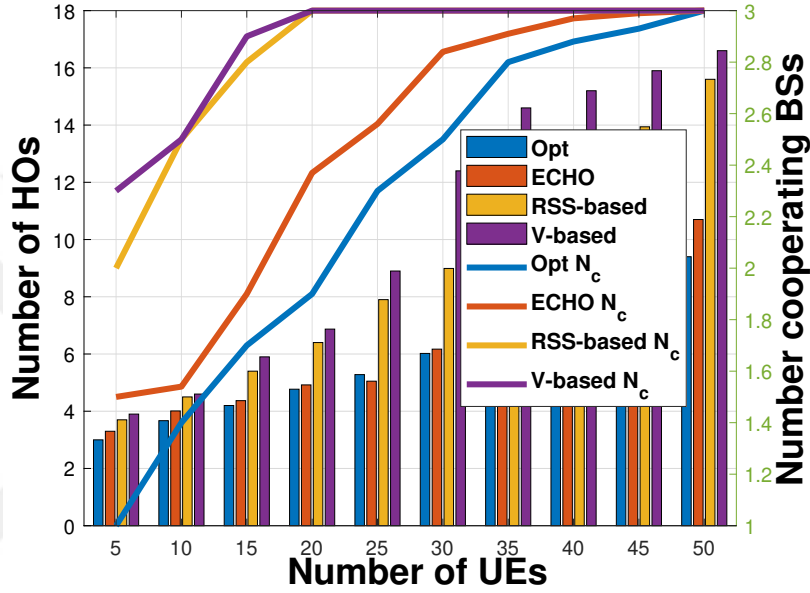


Figure 4.6: Number of handover for different number of UEs

Fig. 4.6 illustrates number of HOs and number of cooperating BSs for increasing number of UEs. As the number of UEs increases, the number of HOs increases. The ECHO algorithm performs very close to optimal, significantly better than previously proposed algorithms due to utilization of GAP heuristic with the subsequent green association criteria. Heuristic for GAP assigns unassigned UEs to optimal BSs, as the number of UEs increases the number of on BSs increases to decrease UE TX power and the probability that each UE executes HO from the serving BS to the target BS increases. Next, in RSS-based algorithm, as the number of UEs increases, the number of HOs increases since the capacities of on BSs are insufficient, additional BSs are turned on and the UEs are offloaded to other BSs to further use DL or UL resources. Additionally, number of HOs with V-based algorithm exceeds the number of HOs of all algorithms since as the number of UEs increases the probability of UEs having velocity higher than 5m/s increases, which leads to an increase in the number of HOs. Moreover, as the number of UES increases, the number of cooperating BSs

increases to minimize the number of HOs since the increase in the capacity with the help of cooperating BSs provides fair resource allocation and prevents the offloading of UEs from one BS to another BS frequently.

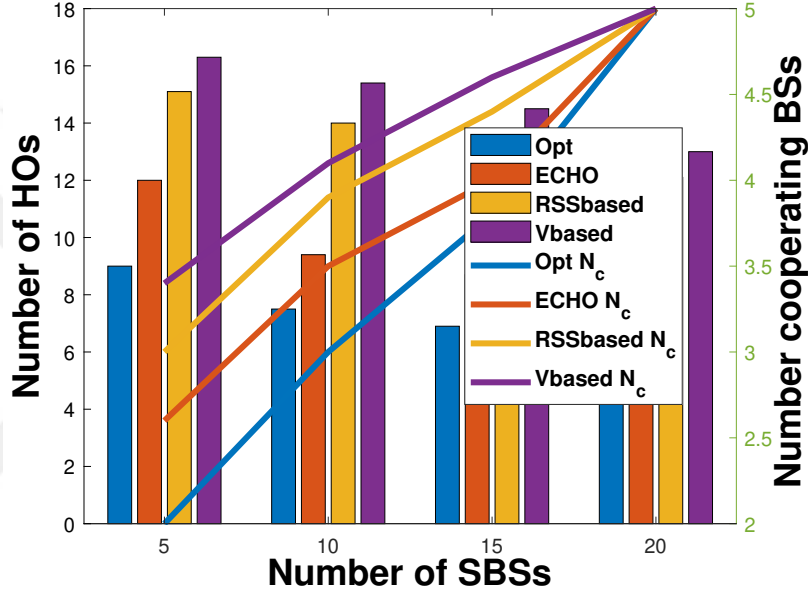


Figure 4.7: Number of handover vs. number of SBSs

Fig. 4.7 shows the number of HOs of different algorithms for increasing number of SBSs. As the number of SBSs increases, the probability of choosing the optimal BS increases, UE TX power decreases and decrease in number of HOs is observed for all algorithms. The ECHO algorithm demonstrates noteworthy improvement compared to RSS-based algorithm and V-based algorithm. It aims to select the optimal SBSs for the specified T, which provide decreases UE TX power the most and consumes power up to $\epsilon=1000W$ to further minimize the number of HOs. Moreover, as the number of SBSs increases, number of HOs decreases for increasing number of N_c because there exists opportunity to form power efficient and capacity achieving cooperating BS set which do not cause the UE to handover frequently and decrease in the UE TX power.

Fig. 4.8 demonstrates the effect of distance and blockage on the HO behavior. Probability of NLoS and probability of outage increase and the probability of LoS decreases, as the distance increases. On the other hand, achievable rate degrades as

the distance between the UE-BS pairs increases. However, the data rate that the UE is demanding is provided by the increase in the number of the cooperating BS set elements. The increase in the number of BSs that form the cooperating BS decreases the number of HOs. In every condition, ECHO algorithm supports the demanded data rate with less number of HOs than RSS-based algorithm and V-based algorithm, since it tries to assign UEs to the cooperating set of BSs consisting of higher number of members, which can provide the achievable rate and do not exceed the pre-defined power consumption levels.

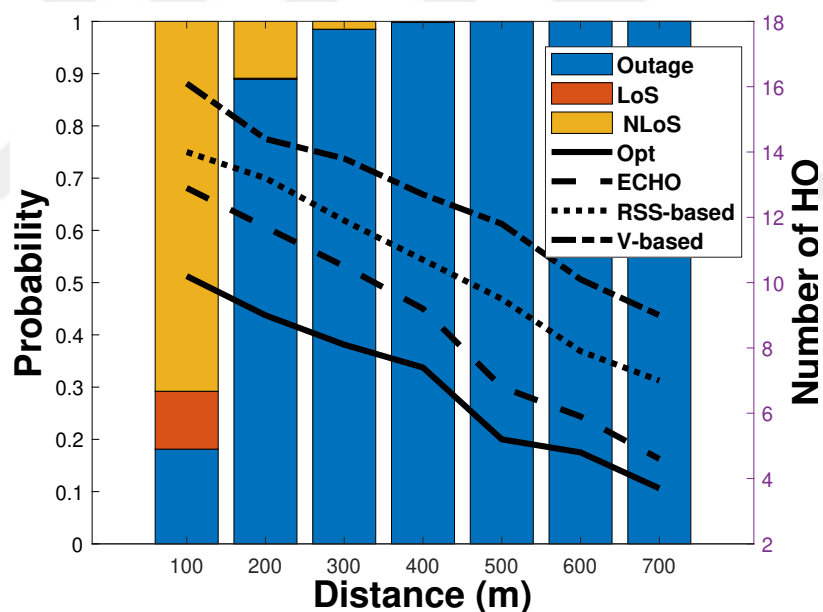


Figure 4.8: Distance vs. number of HOs

Fig. 4.9 represents the relationship between number of HOs and number of the cooperating BSs. As the number of cooperating BSs increases, the number of HOs decreases. At the same time, overhead in all algorithms increases proportional to the number of cooperating BSs.

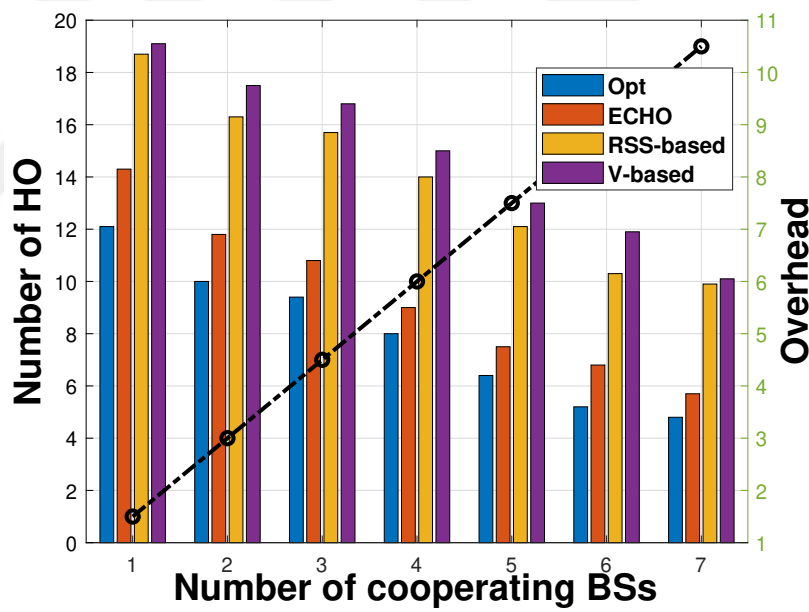


Figure 4.9: Number of handover vs Number of cooperating BSs

Chapter 5

POWER EFFICIENT TRANSMISSION MODE SELECTION FOR CELLULAR VEHICLE TO EVERYTHING COMMUNICATIONS

5.1 Introduction

C-V2X communications is an important technology for future ITS and aims to implement improvements in road safety [98]. C-V2X communications allow VUEs to exchange information with other elements of the traffic system around them, which incorporate VUE-VUE, VUE-Pedestrian, VUE-interface and VUE-Network by using LTEUu traditional cellular interface (UL and DL) or 5G or PC5 radio interface SL [99]. This structure allows high data rate demanding VUEs, which have only limited battery capacity, to select the transmission mode according to their QoE requirements. However, the increasing interest in high data rate demand causes high power consumption in vehicular networks, which can deteriorate the QoE performance instantly.

With the selection of transmission mode by VUE, the energy efficiency is maximized while satisfying the QoE requirements of VUEs. QoE requirements include delay in DL and UL [100], delay in UL [101], reliability [102] and SNR [103]. However, none of the studies consider to minimize system power consumption by including realistic power consumption models of the whole network infrastructure in C-V2X networks and propose an energy efficient transmission mode selection heuristic, jointly.

In this paper, we propose an efficient heuristic for the optimization problem of the UL/DL decoupled energy efficient VUE association or VUE-VUE association in SL with the aim of minimizing total network power consumption subject to rate,

capacity and effect of FH links. The distinction of the proposed heuristic algorithm to previously proposed solution methods is demonstrated in terms of closeness to the optimal via extensive simulations.

5.2 System Model

- The architecture of Cloud Network is shown in Figure 5.1. MBS supports C-Plane signaling for the network transmits at conventional LTE cellular frequencies with $N_{RFc,M}$ RF chains. There exist K SBSs possessing $N_{RFc,S}$ RF chains and transmitting at mmWave frequencies. SBSs provide high speed data transmission with D-Plane to fulfill QoE requirements of the VUEs. Additionally, there are N_b VUEs with velocity $\vec{V}$ in the coverage of SBS with single RF chain $N_{RFc,VUE}$. A VUE can get assigned to a VUE in SL or to a BS in DL and UL.

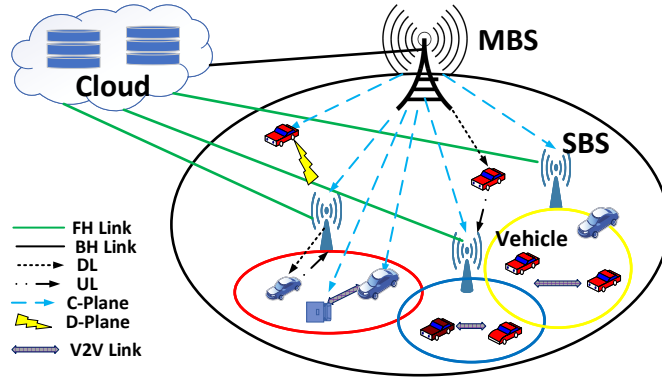


Figure 5.1: C-V2X communication based Cloud Network.

- There are two communication modes in C-V2X communication networks, which are network-assisted mode specified by 3GPP for C-V2X communications over the SL [104] and direct communication between VUEs [105].
- The connection between MBS and Cloud is provided by a BH link whereas the connection between SBSs and Cloud are performed through FH links. Capacity of FH links is denoted by C_{fh} .

- Channel State Information Reference Signal is utilized to estimate the channels between MBS-VUE and SBS-VUE [106]. α_{Mj}^t and α_{Sj}^t indicate attenuation from MBS and SBS S to VUE j at time t, respectively. θ_{Mj}^t and θ_{Sj}^t shows the attenuation from VUE j to MBS and SBS S in UL at time t, respectively. The attenuation from VUE j to VUE j' in SL within coverage of SBS S is denoted as $\theta_{jj'S}^t$.
- Directional transmission is assumed and each VUE j is exposed to interference power by other BSs, that do not serve VUE j. The interference power at VUE j in DL at time t, $P_{j,Idl}^t$, is calculated as in [107]:

$$P_{j,Idl}^t = \sum_{i'=1, i' \neq i}^{K+1} P_{t,i'}^t * \alpha_{i'j}^t \quad (5.1)$$

where i is M or S, $P_{t,M'}^t$ and $P_{t,S'}^t$ indicate the transmission power of interfering MBS and SBS S at time t, respectively.

- Different achievable rates as $R_{dl,Mj}^t$ and $R_{dl,Sj}^t$, are provided by the BSs, from MBS and SBS S to VUE j at time t in DL, respectively since bandwidths and transmission powers of BSs are different. They are formulated as in [67]:

$$R_{dl,ij}^t = B_i * \log \left(1 + \frac{P_{tx,i}^t * \alpha_{ij}^t}{|N_{RF,i}| * (N_0 * B_i + P_{j,Idl}^t)} \right) \quad (5.2)$$

where i is M or S. Transmission bandwidths of MBS and SBS S at time t are represented with B_M and B_S , respectively and transmission power of MBS and SBS S at time t is indicated by $P_{tx,M}^t$ and $P_{tx,S}^t$, respectively. Power spectral density of the noise is denoted by N_0 . $N_{RF,S}$ and $N_{RF,M}$ specify the number of VUEs, which are handled at the same time by SBS S and MBS, respectively [33].

- The transmit power of VUE is allocated to reduce the effect of the γ fraction of the path loss in comparison to received power at 0 dB path loss, P_0 , below

P_{max} [39] to:

$$P_{t,UE}^t = \min\{P_{max}, P_0 + \gamma * \alpha_{ij}^t\} \quad (5.3)$$

- The interference power at VUE j in UL at time t , $P_{j,Iul}^t$, is calculated as in [107]:

$$P_{j,Iul}^t = \sum_{i'=1, i \neq i'}^{N_b} P_{t,UE'}^t * \theta_{i'j}^t \quad (5.4)$$

where i is M or S and $\theta_{M'j}^t$ and $P_{t,UE'}^t$ indicate the transmission power of interfering VUEs at time t .

- $R_{ul,Mj}^t$ and $R_{u,jS}^t$ are the achievable rates in UL at time t and formulated as in [67]:

$$R_{u,ji}^t = B_i * \log \left(1 + \frac{P_{t,UE}^t * \theta_{ij}^t}{N_0 * B_i + P_{j,Iul}^t} \right) \quad (5.5)$$

where i is M or S. Transmission bandwidths of MBS and SBS S are represented with B_M and B_S , respectively and transmission power of MBS and SBS S at time t is indicated by $P_{tx,M}^t$ and $P_{tx,S}^t$, respectively. Power spectral density of the noise is denoted by N_0 .

- $R_{jj'S}^t$ is the rate at time t and is formulated as in [67]:

$$R_{jj'S}^t = B_{jj'S} * \log \left(1 + \frac{P_{t,UE}^t * \theta_{jj'S}^t}{N_0 * B_{jj'S} + P_{j,Iul}^t} \right) \quad (5.6)$$

where transmission bandwidth of V2X communication is represented by $B_{jj'S}$.

- Data rates that VUE j demands in DL and in UL at time t are $Q_{dl,j}^t$ and $Q_{ul,j}^t$, respectively.
- $\beta_{dl,Mj}^t$ and $\beta_{dl,Sj}^t$ denote the channel utilizations from MBS and SBS S to VUE

j in DL at time t respectively, where it is defined as the ratio of the demanded data rate to the data rate that can be supported over the channel. $\beta_{dl,Mj}^t$ and $\beta_{dl,Sj}^t$ represent the channel utilizations from MBS and SBS S to VUE j at time t in DL, respectively, and formulated as $\beta_{dl,ij}^t = \frac{Q_{dl,j}^t}{R_{dl,ij}^t}$, where i is M or S as in [41]. On the other hand, $\beta_{ul,Mj}^t$ and $\beta_{ul,Sj}^t$ denote the channel utilizations from MBS and SBS S to VUE j in UL at time t, respectively and formulated as $\beta_{ul,ij}^t = \frac{Q_{ul,j}^t}{R_{ul,ij}^t}$ where i is M or S. $\beta_{jj'S}^t$ is the channel utilization of VUE j and VUE j' in SBS S coverage and is demonstrated as $\beta_{jj'S}^t = \frac{Q_{ul,j}^t}{R_{jj'S}^t}$.

- Power consumption of MBS, P_M^t , at time t encompasses dynamic power consumption $P_{Dyna,M}^t$ at time t and static power consumption P_{Static} [42]. Rectifier, air conditioner and backhaul link power consumption values are included in P_{Static} [44]. $P_{Dyna,M}^t$ is denoted as $F^t * P_l$, where $F^t = \frac{\sum_{j=1}^{N_b} \beta_{d,Mj}^t + \beta_{ul,Mj}^t}{N_{RFcM}}$ is the load factor. Power consumption of power amplifier, the transceiver, the digital signal processing unit is included in the term P_l .
- P_S is the power consumption of SBS S for all traffic load. Microprocessor P_{mp} , FPGA P_{FPGA} , transceiver $P_{tx,S}$ and power amplifier $P_{amp,S}$ power consumption values are contained in P_S as in [42].
- $P_{d,fhl}^t$ represents the power consumption on FH link in DL at time t and is linearly dependent with data rate of VUE j in DL, $Q_{dl,j}^t$ [46], whereas $P_{u,fhl}^t$ demonstrates the power consumption on FH link in UL at time t and is linearly dependent with data rate of VUE j in UL, $Q_{ul,j}^t$.
- $P_{Rx,j}^t$ is the receive power consumption of a VUE j and is constant as in [108].
- Transmission power consumption of VUE j at time t, $P_{TX,j}^t$, includes power consumption of circuitry $P_{circuit}$, and power amplifier P_{amp}^t at time t [47].

5.3 Optimization Problem

VUE association, switching on/off the SBSs and VUE-VUE communication link formation are optimized jointly to minimize total network power consumption with the incorporation of dynamic power consumption of MBS, FH link power consumption, VUE power consumption subject to capacity, rate constraints. The optimization problem is formulated in Subsection 5.3.1.

5.3.1 Problem Formulation

$$\begin{aligned}
 \min \quad & \sum_{t=1}^T \left(P_{Static} + \sum_{j=1}^{N_b} (\beta_{dl,Mj}^t * P_l * x_{Mj}^t) + \sum_{S=1}^K P_S * T_S^t + \sum_{S=1}^K P_{fh} * \sum_{j=1}^{N_b} Q_{dl,j}^t * x_{Sj}^t \right. \\
 & + w_N * \left(\sum_{j=1}^{N_b} \left((P_{TX,j}^t + P_l) * \beta_{ul,Mj}^t \right) * y_{Mj}^t + \sum_{j=1}^{N_b} P_{TX,j}^t \sum_{s=1}^K \beta_{ul,Sj}^t * y_{Sj}^t \right) + \\
 & \left. \sum_{S=1}^K P_{fh} * \sum_{j=1}^{N_b} Q_{ul,j}^t * (y_{Sj}^t + z_{jj'S}^t) + w_D * \left(\sum_{j=1}^{N_b} \sum_{\substack{j'=1 \\ j \neq j'}}^{N_b} (P_{Rx,j}^t + P_{TX,j}^t) * z_{jj'S}^t \right) \right)
 \end{aligned} \tag{5.6-01}$$

$$\text{s.t.} \quad Q_{dl,j}^t * x_{Mj}^t \leq R_{dl,Mj}^t, \quad j \in \{1, N_b\}, \quad t \in \{1, T\} \tag{5.6-02}$$

$$\begin{aligned}
 & Q_{dl,j}^t * x_{Sj}^t \leq R_{dl,Sj}^t, \\
 & j \in \{1, N_b\}, \quad S \in \{1, K\}, \quad t \in \{1, T\}
 \end{aligned} \tag{5.6-03}$$

$$Q_{ul,j}^t * y_{Mj}^t \leq R_{ul,Mj}^t, \quad j \in \{1, N_b\}, \quad t \in \{1, T\} \tag{5.6-04}$$

$$\begin{aligned}
 & Q_{ul,j}^t * y_{Sj}^t \leq R_{ul,Sj}^t, \\
 & j \in \{1, N_b\}, \quad S \in \{1, K\}, \quad t \in \{1, T\}
 \end{aligned} \tag{5.6-05}$$

$$\begin{aligned}
 & Q_{ul,j}^t * z_{jj'S}^t \leq R_{u,jj'S}^t, \\
 & j \in \{1, N_b\}, \quad j' \in \{1, N_b\} \quad S \in \{1, K\}, \quad t \in \{1, T\}
 \end{aligned} \tag{5.6-06}$$

$$x_{Mj}^t + \sum_{S=1}^K x_{Sj}^t = 1, \quad j \in \{1, N_b\}, \quad t \in \{1, T\} \tag{5.6-07}$$

$$y_{Mj}^t + \sum_{S=1}^K y_{Sj}^t = 1, \quad j \in \{1, N_b\}, \quad t \in \{1, T\} \tag{5.6-08}$$

$$\sum_{S=1}^K \sum_{\substack{j=1 \\ j \neq j'}}^{N_b} z_{jj'S}^t \leq 2, \quad j' \in \{1, N_b\}, \quad S \in \{1, K\}, \quad t \in \{1, T\} \quad (5.6-09)$$

$$z_{jj'S}^t \leq y_{Sj}^t, \\ j \in \{1, N_b\}, \quad j' \in \{1, N_b\} \quad S \in \{1, K\}, \quad t \in \{1, T\} \quad (5.6-10)$$

$$d_{jj'}^t * z_{jj'S}^t \leq d_{th}, \\ j \in \{1, N_b\}, \quad j' \in \{1, N_b\} \quad S \in \{1, K\}, \quad t \in \{1, T\} \quad (5.6-11)$$

$$x_{Sj}^t \leq T_S^t, \quad j \in \{1, N_b\}, \quad S \in \{1, K\}, \quad t \in \{1, T\} \quad (5.6-12)$$

$$y_{Sj}^t \leq T_S^t, \quad j \in \{1, N_b\}, \quad S \in \{1, K\}, \quad t \in \{1, T\} \quad (5.6-13)$$

$$z_{jj'S}^t \leq T_S^t, \\ j \in \{1, N_b\}, \quad j' \in \{1, N_b\} \quad S \in \{1, K\}, \quad t \in \{1, T\} \quad (5.6-14)$$

$$\sum_{j=1}^{N_b} Q_{dl,j}^t * x_{Sj}^t + \sum_{j=1}^{N_b} Q_{ul,j}^t * y_{Sj}^t + \\ \sum_{\substack{j=1 \\ j \neq j'}}^{N_b} \sum_{\substack{j'=1 \\ j' \neq j}}^{N_b} Q_{ul,j}^t * z_{jj'S}^t \leq C_{fh,S}, \quad S \in \{1, K\}, \quad t \in \{1, T\} \quad (5.6-15)$$

$$\sum_{j=1}^{N_b} \beta_{dl,Sj}^t * x_{Sj}^t + \sum_{j=1}^{N_b} \beta_{ul,Sj}^t * y_{Sj}^t + \\ \sum_{\substack{j=1 \\ j \neq j'}}^{N_b} \sum_{\substack{j'=1 \\ j' \neq j}}^{N_b} \beta_{u,jj'S}^t * z_{jj'S}^t \leq N_{RFc,S}, \quad S \in \{1, K\}, \quad t \in \{1, T\} \quad (5.6-16)$$

$$\sum_{j=1}^{N_b} \beta_{dl,Mj}^t * x_{Mj}^t + \sum_{j=1}^{N_b} \beta_{ul,Mj}^t * y_{Mj}^t \leq N_{RFc,M}, \quad t \in \{1, T\} \quad (5.6-17)$$

$$\text{Vs.} \quad x_{Mj}^t, y_{Mj}^t, x_{Sj}^t, y_{Sj}^t, T_S^t, z_{jj'S}^t \in \{0, 1\} \quad (5.6-18)$$

where K is the number of SBSs, N_b is the number of VUEs and T is the total time period. The decision variables of the problem are T_S^t , which is a binary variable taking value 1 when SBS S turns on in case of VUE association in UL or in DL at time t and 0 otherwise; x_{Mj}^t and x_{Sj}^t , which are binary variables taking values 1 in

case of association of VUE j to MBS and to SBS S in DL at time t , respectively and 0 otherwise; y_{Mj}^t and y_{Sj}^t , which are binary variables taking values 1 in case of association of VUE j to MBS and SBS S in UL at time t , respectively and 0 otherwise and $z_{jj'S}^t$, which is a binary variable taking value 1 when a VUE-VUE communication link is formed between VUE j and VUE j' within the coverage of SBS S at time t and 0 otherwise.

As demonstrated in the objective function, optimization problem aims to minimize the total system power consumption. Weights (w_D) and (w_N) emphasizes the contribution of VUE and network power consumption on the total system power consumption. Data rate of VUE j in DL should be less than or equal to the achievable rate from MBS and SBS S to VUE j , as shown in Constraints (5.6-02) and (5.6-03). Data rate of VUE j in UL should be less than or equal to the achievable rate from MBS and SBS S to VUE j , as ensured in constraints (5.6-04) and (5.6-05). Data rate of VUE j in SL should be less than or equal to the achievable rate at VUE j within coverage of SBS S , as stated in constraint (5.6-06). Constraints (5.6-07) and (5.6-08) assure that VUE j at time t can only be assigned to MBS or to SBS in DL and in UL, respectively. VUE j can be associated with two VUEs in the coverage region of SBS S at time t as ensured by the constraint (5.6-09). Constraint (5.6-10) represents VUE j has a connection to SBS S if a VUE-VUE link is formed between VUE j and VUE j' , if the distance between VUE j and VUE j' at time t is not greater than the distance threshold value, d_{th} , as implied by the constraint (5.6-11). d_{th} is the specified distance value to fulfill QoE requirements of VUE j . Moreover, constraints (5.6-12), (5.6-13) and (5.6-14) show that SBS S is turned on at time t if there exists an assigned VUE in DL, in UL and a VUE-VUE communication link in SL in between VUE j and VUE j' within coverage of SBS S , respectively. Total data transmitted on FH links in UL, DL and in SL at time t can not be greater than the FH link capacity as implied by the constraint (5.6-15). Maximum number of VUEs, which are handled at the same time by SBS S and MBS in UL, DL and in SL can not be greater than $N_{RFe,S}$ or $N_{RFe,M}$ as indicated by the constraints (5.6-16) and (5.6-17), respectively.

5.3.2 NP-Hardness

Theorem 4. *The minimization problem formulated in Section 5.3 is an NP-Complete SSCFLP [34], which is a special case of CFLP.*

Proof. We reduce NP-Complete SSCFLP [34] proposed in Section 5.3 to set cover problem [48]. Given a set of j VUEs, i BSs, the set cover problem aims to minimize the cost weighted average distance between VUE and the nearest of the selected BSs.

Let us define a problem instance, where we analyze HO problem at a specific time instance t . Analysis of SSCFLP at a specific time instance t corresponds to VUE association problem at a time instance t . First, we assume that the transmission of VUEs are handled by more than one BS in DL and UL or by one VUE in SL, which relaxes variables $x_{Mj}^t, y_{Mj}^t, x_{Sj}^t, y_{Sj}^t, z_{jj'}^t, z_{j'j}^t$ and T_S to be continuous. In this case, our optimization problem is reduced to CFLP [49].

The CFLP is NP-Complete as a generalization of the NP-complete set cover problem [48], where $N_{Rfc,M} = +\infty, N_{Rfc,S} = +\infty$ and $C_{fh} = +\infty$. Therefore, the SSCFLP studied in this paper is NP-Complete. $\square$

5.4 Solution Methodology

We propose a polynomial time heuristic algorithm to solve *SSCFLP*. The objective of our proposed heuristic algorithm is to minimize total power consumption by improving the output of the primal heuristic composed of LP-Relaxation and rounding process with the help of repeated use of two heuristic algorithms, heuristic for assignment problem and heuristic for re-allocation of UEs. In our heuristic, as a result of LP relaxation and rounding, we attain a set of assigned UE-BS pairs, unassigned UEs and off BSs as the input to the proceeding heuristic algorithms. This reduces the complexity of the algorithm, enables comprehensive and fast search for the minimum and allows the algorithm perform close to optimal.

The flowchart of the proposed heuristic is given in Fig. 5.2. The algorithm starts with the initialization of Cnt^t, Cnt_{max} , the LV at time t (LV^t), the RV at time t

(RV^t) , present time slot (t) and period (T). Cnt^t counts how many times a VUE-BS pair is split into unassigned VUEs and turned off BS, Cnt_{max} is the maximum number of counter, LV^t is the power consumption value obtained from the heuristic algorithm for assignment or re-allocation, MV is the power consumption value of the proposed heuristic algorithm and RV^t is the sum of power consumption value obtained from LP relaxation and rounding and the power consumption value of assigning unassigned VUEs to random on BSs. T is the total time period.

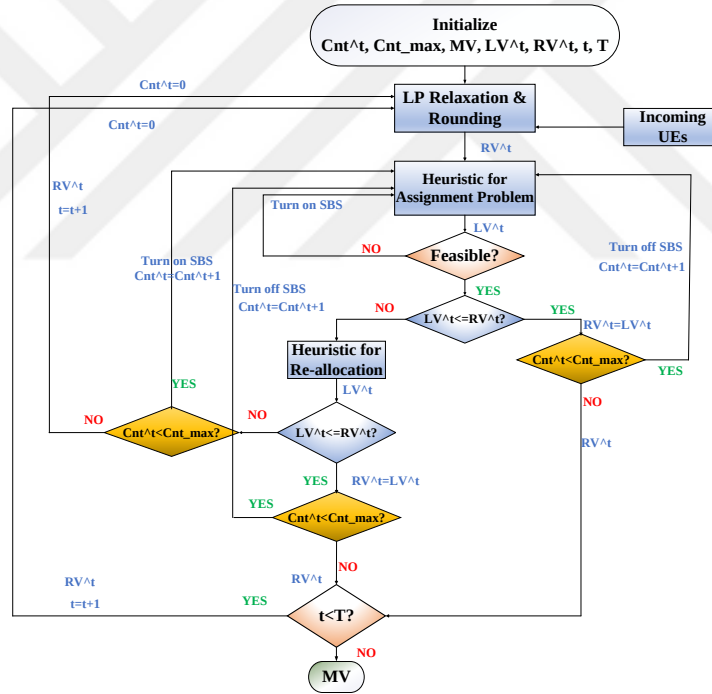


Figure 5.2: General Structure of the Proposed Algorithm

First, at time t , LP Relaxation of the binary integer problem in Equation (5.6-01) is solved, and RV^t is set to value of LP relaxation and rounding. After rounding process, we obtain a set of assigned VUE-BS pairs, VUE-VUE pairs unassigned VUEs and off BSs. Then, the set is the input to the heuristic for assignment problem to assign unassigned VUEs to on BSs or to VUEs. If the on BSs or VUEs are not able to provide service to unassigned VUEs, then the solution is infeasible. An off BS is turned on randomly and heuristic for assignment problem is run again. Otherwise,

LV^t is set to the power consumption of the output of the heuristic for assignment problem. If the power consumption value obtained from the heuristic for assignment problem is less than RV^t , then our heuristic turns off an on BS, randomly. The VUEs assigned to the turned off BS become unassigned and heuristic for assignment problem is run again to check if power consumption can be further decreased by turning off an on BS as long as Cnt^t is less than Cnt_{max} .

If the heuristic for assignment problem does not provide decrease in power consumption, our proposed heuristic checks if the VUEs of the assigned VUE-BS or VUE-VUE pairs can be re-allocated to further minimize total power consumption by using the heuristic for re-allocation of VUEs. If VUE re-allocation further decreases total power consumption, a BS is turned off randomly, the VUEs assigned to the turned off BS become unassigned and heuristic for assignment problem is run again to check if power consumption can be further decreased as long as Cnt^t is less than Cnt_{max} . Otherwise, a BS is turned on randomly and heuristic for assignment problem is run again to check if power consumption can be further decreased as long as Cnt^t is less than Cnt_{max} . This process repeats until time slot t is greater than equal to the total period T .

5.5 Performance Evaluations

In this section, we assess the performance of proposed heuristic algorithm at different distance thresholds for adaptive and maximum VUE TX power compared to the previously proposed algorithm, TS-EOS [100]. In TS-EOS, energy efficiency is maximized by considering two-stage optimization problem. In the first stage, the distance between each VUE to BSs and other VUEs are calculated. In case when the distances between the VUEs are greater than the distance threshold, VUEs gets assigned to BSs both in UL and DL. Otherwise, VUEs perform VUE-VUE communication. Additionally, to preserve power, VUEs can form VR links, where a VUE relays the information of another VUE to the BS. In the second stage, in case when VUE-BS or VUE-VR-BS links are formed, transmit power of BS is regulated with respect to the SNR and

distance values of the corresponding VUE-BS links, adaptively.

Network topology consists of 4 SBSs and 20 VUEs. Locations of SBSs are random and have a distance of 10 m among each other whereas the locations of VUEs are also random occupying of 5-15 meters between each other. IBM CPLEX Optimization Studio with MathWorks MATLAB is utilized to perform simulations. Communication links are considered to be in LoS, NLoS, or in outage. Path loss at time t is formulated as $\psi_{ij}^t = PL(d_0) + 10 * \eta_j * \log_{10} \left(\frac{d_{du,ij}^t}{d_0} \right) + X_{\sigma_j}^t$, where ψ_{ij} can be replaced with α_{ij} in DL, θ_{ij} in UL and $\theta_{jj'}$ in SL for VUE-VUE communication. $PL(d_0)$ is the free space path loss in dB at a reference distance d_0 , η_j is the path loss exponent, $d_{du,ij}^t$ is the distance between BS i and VUE j at time t , $d_{jj'S}^t$ is the distance between VUE j and VUE j' at time t within coverage of SBS S and $X_{\sigma_j}^t$ represents the shadow fading factor at time t , which is a zero mean Gaussian random variable with σ_j^2 variance.

The parameters of the model used in the simulations are $\eta_j=1.9$ and $\sigma_j=1.1$ for LoS and $\eta_j=4.5$ and $\sigma_j=10$ for NLoS, $\sigma_j=8.9$ for MBS, $PL(d_0)=30$ dB, $N_0=-134$ dBm/MHz, $B_M=20$ MHz (for 2.4 Ghz carrier frequency) , $B_S=800$ MHz (for 28 Ghz carrier frequency) , $B_{jj'}=20$ MHz (for 5.860 GHz PC5), $P_{t,MBS}=43$ dBm, $P_{t,SBS}=33$ dBm, $P_{t,VUE}=23$ dBm, antenna heights of MBS, SBS and VUE are highlighted in [37], $w_D=1$ and $w_N=1$, $C_{fh}=4.45$ Gbps, $N_{rf,M}=8$, $N_{rf,S}=4$, $N_{rf,UE}=1$, $P_{fh}=0.1$ W/Mbps, $\vec{V}=50$ km/h, $Q_{dl,j}^t$ and $Q_{ul,j}^t$ are uniformly distributed between (10-300) Mbps and (5-75) Mbps and power consumption values of MBS and SBS are summarized in [42].

Fig. 5.3 demonstrates the comparison between the power consumption values of optimal algorithm, proposed heuristic algorithm and TS-EOS for adaptive and maximum VUE transmit powers with respect to distance threshold values. Up to a particular distance threshold value, the system power consumption decreases for all algorithms. However, system power consumption increases for all algorithms as the distance threshold increases. Our proposed heuristic algorithm outperforms TS-EOS in terms of the power consumption since the proposed heuristic enables VUEs to select network assisted or VUE-VUE transmission mode and selection of VUE-VUE

transmission mode helps to decrease the system power consumption.

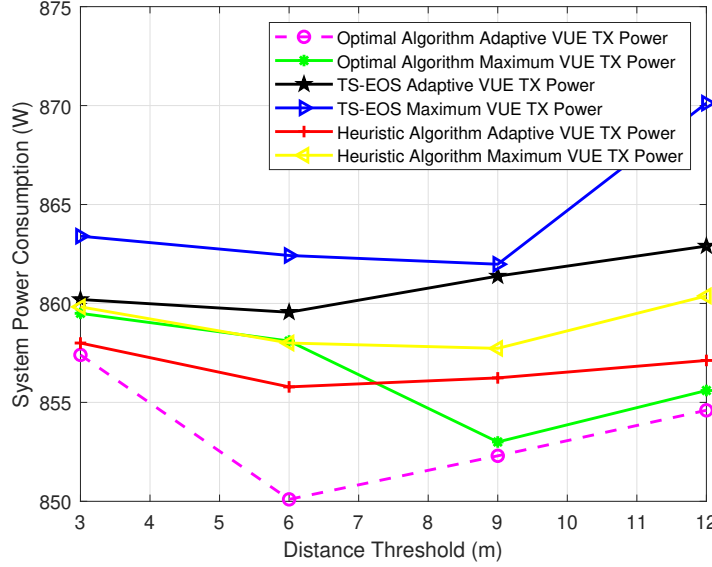


Figure 5.3: Power consumption vs. Distance Threshold

The VUE association with adaptive TX power is illustrated in Fig. 5.4. The VUEs select VUE-SBS association for all algorithms and there does not exist any VUE-VUE communication links for 3m because VUEs are located five-to-fifteen meters apart from each other. Therefore, the VUEs select VUE-SBS association for all algorithms. Then, the number of VUE-VUE and SBS-VR-VUE links increases compared to the number of VUE-BS association links for optimal and proposed heuristic algorithms and TS-EOS. For this reason, the power consumption decreases. Further, system power consumption increases as the distance threshold increases, since there exist increase in number of VUE-BS association links for both optimal and proposed heuristic algorithm and VUE-BS and BS-VR-VUE association links for TS-EOS. Since the aim is to minimize the system power consumption, our proposed heuristic outperforms TS-EOS by forming energy efficient VUE-VUE communication links.

For increasing threshold values, the effect of maximum VUE transmit power on system power consumption is demonstrated in Fig.5.5. VUE-VUE communication

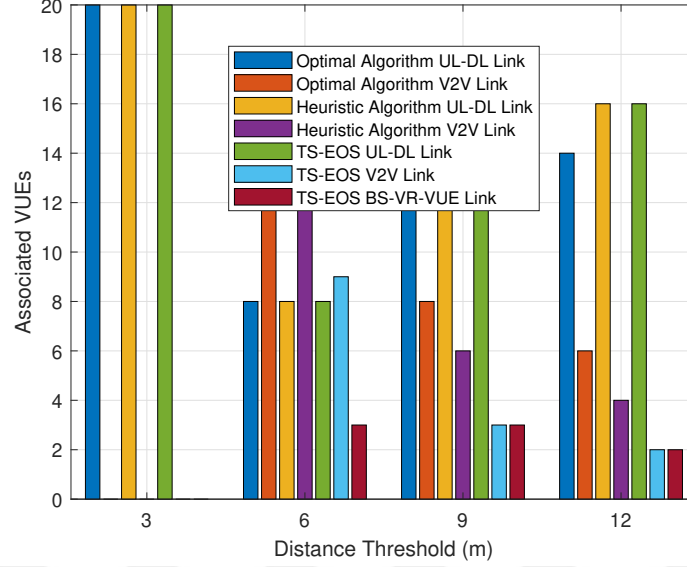


Figure 5.4: VUE association with Adaptive VUE transmit power vs distance threshold

links are not formed due to the distance constraint, where the minimum distance of any two VUE is larger than the specified distance threshold value. Next, up to a particular value, the number of VUE-BS pairs and VUE-SBS and SBS-VR-VUE pairs decrease in the case of optimal and proposed heuristic algorithms and TS-EOS, respectively, as a result of increase in the number of VUE-VUE communication links. For increasing distance threshold values, VUE-BS pairs increase for optimal and heuristic algorithm and VUE-BS and BS-VR-VUE pairs also increase for TS-EOS. Transmission with maximum VUE transmit power has a greater distance threshold value than the transmission with adaptive VUE transmit power since high transmit power can compensate the destructive effects of shadowing and small scale fading for all algorithms and achieve required QoE. The formation energy efficient VUE-VUE communication links in our proposed algorithm enable the system consume less power than the TS-EOS algorithm, where the majority of the communication links consist of VUE-BS and BS-VR-VUE communication links.

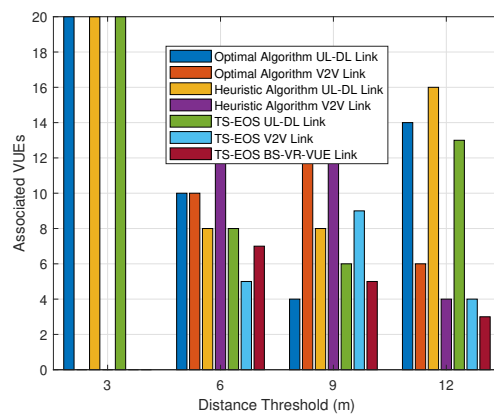


Figure 5.5: VUE association with Maximum VUE transmit power vs distance threshold

Chapter 6

CONCLUSIONS

In the thesis, it is shown that HCRAN is a promising candidate to alleviate energy and reliability constraints of 5G paradigm to certain extent and to build next-generation services. The analysis and studies in this thesis help realization of 5G Heterogeneous Cloud Radio Access Networks. The thesis also points out open research issues and how UE association, Multi-Connectivity, HO and CV2X communication can be implemented in 5G Heterogeneous Cloud Radio Access Networks. In conclusion, the following topics have been investigated.

- Extensive review of minimization of power consumption techniques in HetNets, CRAN and 5G HCRAN.
- UL/DL Decoupled UE-BS Association Method.
- New Methodologies for an energy-efficient system.
- Extensive review of MC in 5G.
- Investigation of MC and its contribution to robustness of 5G systems.
- Extensive review of HO policies in HetNets, CRAN and 5G HCRAN.
- New HO execution policy, which is based on energy efficiency.
- Extensive review of CV2X networks in the context of power consumption.
- Design of power efficient transmission mode selection interface.

Chapter 2: Uplink/Downlink Decoupled Energy Efficient User Association in Heterogeneous Cloud Radio Access Networks

In this chapter, we present a holistic framework for energy efficient UE association incorporating UL/DL decoupling and the dynamic on/off scheme for SBSs and realistic power consumption models, including the static and the dynamic power consumption of MBS, the static power consumption of SBS, power consumption of the FH links as a function of data rate and the power consumption of UEs in UL. We formulate the optimization problem as a SSCFLP. We propose a heuristic algorithm that minimizes the total power consumption by improving the output of the primal heuristic composed of LP-Relaxation and rounding process with the help of repeated use of two heuristic algorithms, heuristic for modified matching and heuristic for re-allocation of UEs. As a result of LP relaxation and rounding, we obtain a set of assigned UE-BS pairs, unassigned UEs and off BSs as the input to the proceeding heuristic algorithms in contrast to RMA and PMA, that take all UEs as unassigned UEs and all BSs as off BSs as input. We demonstrate the superiority of the SRRA to previously proposed solution methods in terms of closeness to the optimality for different networks topologies and data rate requirements via extensive simulations. We also demonstrate that for decoupled UL/DL UE association scheme with SBSs operating on mmWave frequencies providing high bandwidth, high data rate demanding UEs get associated with SBSs in UL and DL, whereas low data rate demanding UEs get associated with SBSs in UL and MBS in DL.

Chapter 3: Multi-Connectivity based Uplink/Downlink decoupled Energy Efficient User Association in 5G Heterogenous CRAN

In this chapter, MC based UL/DL decoupled energy efficient UE association problem in HCRAN is formulated for the first time in the literature. We demonstrate the problem to be NP-hard. We propose polynomial time heuristic algorithm, MCUAA, based on $LPR - R$ and GAP heuristic. We analyze the

power consumption, time complexity and achievable rate of MCUAA and verify its superiority compared to existing methods. For future work, our objective is to deepen in MC based UL/DL decoupled energy efficient UE association and consider other metrics such as HO rate and age of information.

Chapter 4: Minimization of the number of Handovers in Multi-Connectivity based Energy Constrained UL/DL Decoupled HCRAN

In this chapter, we provide a holistic framework for the minimization of HO number in HCRAN by using an energy constrained HO execution policy to overcome the limitations of RSS based and velocity based HO policies for the first time in literature. The framework incorporates realistic power consumption models encompassing transmissions in the BBU-Cloud and signaling overhead, which are crucial points in analyzing the benefits of MC, UL/DL decoupled UE association and transmission with effective rate. We formulate the problem as a BILP. However, the formulated problem is proven to be NP-Hard and cannot be solved in polynomial time. Therefore, we propose a heuristic algorithm that minimizes the number of HOs by improving the output of the LP-Relaxation and rounding process with the utilization of GAP heuristics and HO execution policy. On the contrary to previously proposed RSS [73] or on Velocity [77] based algorithms, ECHO algorithm executes HO based on checking if the difference of the energy consumption in consecutive time-slots is below a pre-defined energy consumption value. Extensive simulations demonstrate the supremacy of our proposed algorithm over existing methods in terms of closeness to the optimal for different networks and various data rate requirements. We show that number of cooperating BSs increase to decrease the number of HOs for increasing predefined energy consumption value since ECHO allows the network to consume more ϵ power. Furthermore, we demonstrate that as the number of UEs increases, the number of HOs and the number of cooperating BSs increase. Moreover, we demonstrate that for increasing number of small BSs the number of HOs decreases whereas the signaling overhead and number of cooperating

BSs increase. Last, we show that ECHO algorithm is more prone to error than previously proposed heuristic algorithms.

Chapter 5: Power Efficient Transmission Mode Selection for Cellular Vehicle to Everything Communications

- In this chapter, energy efficient VUE association problem in C-V2X networks is considered. Simulation results demonstrate that selection of VUE-VUE transmission decreases the power consumption of the network in comparison to VUE-BS transmission mode at different distance threshold values. Our objective for future study is to include the effect of increasing number of VUEs and HOMO mechanism into vehicular networks with the purpose of reducing the number of handovers for energy conservation.

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