2021

Energy and throughput efficient strategies for heterogeneous future communication networks

Haitham El-Mohamdy Khaled
Edith Cowan University

Energy and Throughput Efficient Strategies for Heterogeneous Future Communication Networks

This thesis is submitted for the degree of

Doctor of Philosophy (PhD)

Haitham El-Mohamdy Khaled

School of Engineering
Edith Cowan University

2021

Use of Thesis

is not included in this version of the thesis

Abstract

As a result of the proliferation of wireless-enabled user equipment and data-hungry applications, mobile data traffic has exponentially increased in recent years. This increase has not only forced mobile networks to compete on the scarce wireless spectrum but also to intensify their power consumption to serve an ever-increasing number of user devices. The Heterogeneous Network (HetNet) concept, where mixed types of low-power base stations coexist with large macro base stations, has emerged as a potential solution to address power consumption and spectrum scarcity challenges. However, as a consequence of their inflexible, constrained, and hardware-based configurations, HetNets have major limitations in adapting to fluctuating traffic patterns. Moreover, for large mobile networks, the number of low-power base stations (BSs) may increase dramatically leading to sever power consumption. This can easily overwhelm the benefits of the HetNet concept.

This thesis exploits the adaptive nature of Software-defined Radio (SDR) technology to design novel and optimal communication strategies. These strategies have been designed to leverage the spectrum-based cell zooming technique, the long-term evolution licensed assisted access (LTE-LAA) concept, and green energy, in order to introduce a novel communication framework that endeavors to minimize overall network on-grid power consumption and to maximize aggregated throughput, which brings significant benefits for both network operators and their customers. The proposed strategies take into consideration user data demands, BS loads, BS power consumption, and available spectrum to model the research questions as optimization problems.

In addition, this thesis leverages the opportunistic nature of the cognitive radio (CR) technique and the adaptive nature of the SDR to introduce a CR-based communication strategy. This proposed CR-based strategy alleviates the power consumption of the CR technique and enhances its security measures according to the confidentiality level of the data being sent. Furthermore, the introduced strategy takes into account user-related factors, such as user battery levels and user data types, and network-related factors, such as the number of unutilized bands and vulnerability level, and then models the research question as a constrained optimization problem.

Considering the time complexity of the optimum solutions for the above-mentioned strategies, heuristic solutions were proposed and examined against existing solutions. The obtained results show that the proposed strategies can save energy consumption up to 18%, increase user throughput up to 23%, and achieve better spectrum utilization. Therefore, the proposed strategies offer substantial benefits for both network operators and users.

Keywords

Cognitive radio, Heterogeneous networks (HetNets), Software defined radio, Next generation wireless networks, cognitive radio security issues, Green communication, LTE-LAA, Traffic steering, User association, Cell zooming, Spectrum-based cell zooming.

Declaration

is not included in this version of the thesis

Dedication

This thesis is dedicated to my loving parents, who have embraced enormous challenges and sacrifices to make my life better.

Acknowledgements

First and foremost, I would like to express my sincere gratitude to Allah for giving me patience and letting me through the roller-coaster ride of PhD.

Immeasurable appreciation and deepest gratitude for the help and support are extended to my principal supervisor A/Prof. Iftekhar Ahmad. As an international student coming from a different country to Australia, I am extremely grateful for all the support and pieces of advice that he has offered me through my journey. As a researcher, he has taught me how to carry out research and how to write world-class research papers. Words are not enough to express my appreciation and deepest gratitude to him.

I would like to thankfully acknowledge the contributions of my co-supervisor Professor Daryoush Habibi. I really appreciate his insightful opinions, observations, and valuable suggestions on addressing the key points of the research work. My special thanks to Dr. Quoc Viet Phung for his technical advice and recommendations. I am also grateful to Edith Cowan University (ECU) for providing me state-of-the-art research facilities and prestigious ECU-HDR Scholarship.

I owe a lot to my parents for their unconditional love, sacrifices, and patience. I believe, their inspirations and prayers have been a boost for me to conquer the difficult stages of the PhD journey. They inspired and enforced me to continue the PhD journey, when I was losing trust on myself. I am sincerely grateful to my wife, Doaa, for her endless support, patience, and enormous sacrifices to be my side. I am indebted to my daughter, Malika, who has missed me a lot in her school events, school parents meeting, birthday parties, and many other occasions, because I was busy working on my research.

Last but not least, I acknowledge the contribution of my motherland, Egypt, for providing me world-class education and making me eligible to achieve a prestigious scholarship in Australia.

List of Publications Arising From This Thesis

- H. Khaled, I. Ahmad, D. Habibi, and Q. V. Phung, “A Green Traffic Steering Solution for Next Generation Communication Networks,” *IEEE Transactions on Cognitive Communications and Networking,* Early Access, 2020. doi: 10.1109/TCCN.2020.2987799.

- H. Khaled, I. Ahmad, D. Habibi, and Q. V. Phung, “A Secure and Energy-Aware Approach For Cognitive Radio Communications,” *IEEE Open Journal of the Communications Society,* Vol. 1, P900-915, 2020.

- H. Khaled, I. Ahmad, D. Habibi, and Q. V. Phung, “An Energy-aware Cognitive Radio-Based Communication Approach for Next Generation Wireless Networks,” *IEEE 21st International Conference on High Performance Computing and Communications.*, IEEE, 2019, pp. 1817-1824, 2019.

- H. Khaled, I. Ahmad, D. Habibi, and Q. V. Phung, “Enhancing Throughput and Energy Efficiency in Heterogeneous Networks for Next-Generation Communication Systems,” *IEEE Transactions on communications* (Under Review).

Contents

List of Figures

List of Tables

List Of Symbols

$\mathcal{J}$	The set of users.
$\mathcal{I}$	The set of Base Stations (BSs).
ε_0	The median number of small cell BSs per unit area.
$\mathcal{L}_0$	A list of idle/unused bands in the licensed spectrum.
$\mathcal{L}_1$	A list of idle/unused bands in the unlicensed spectrums.
$\mathcal{L}_2$	A list of the nearby macro-connected users.
$\mathcal{L}_3$	A list of the optimum user-BS association.
P_{ij}	The transmission power of the BS i towards the user j.
g_{ij}	The gain of the channel between a BS i to a user j.
σ^2	The noise power.
$SINR_{ij}$	The signal to noise plus interference ratio between BS i & user j.
γ	The channel attenuation factor.
m	The modulation order.
P_e^b	The bit-error probability.
w	The codeword width.
N_{ij}	The total number of assignable sub-carriers at BS i.
N_{symb}	The number of symbols.
R_w	The code rate.
Θ	The modulation order.
T_{fr}	The frame time duration.
λ	The arrival rate.
φ	The average traffic load density.
D_{ij}^{eff}	The effective data rate for a user.
η	The total throughput of a BS.
p_j^{st}	The static power.
p_j^{dy}	The dynamic power.
ψ_j	A linear coefficient.
p_r	The minimal detectable BS power.
d	The measured distance.
G	The antenna gain.
f	The frequency.

$P_{j_{max}}$	The user's maximum affordable transmission power.
β	The trade-off coefficient.
ϱ^j	The application index.
R^{max}	The maximum achievable down-link data rate.
W	The Bandwidth.
E	The normalization factors power consumption.
B	The battery level.
D	The data size.
μ	The confidentiality level.
Φ_i	The probability of a security breach to occur at AP i.
ζ	The high-risk factor.
$\mathcal{A}$	The set of all interfering users.
$\mathfrak{S}$	The total benefit.
C_i	The base/standard price of AP i.
$\mathfrak{R}$	The number of idle bands to available secondary users.
γ	The initial back-off contention window size.
ω	The number of times that the back-off window can be extended.
P_j^{scb}	The power consumed to scan a single band.
P_j^{sw}	The power consumed to switch between bands.
α_{ij}	The probability that user j can detect a better band.
Δ_i	The mean number of SUs per idle band at AP.
P_j^{cr}	The total power consumed by user j to send data using the CR.

Chapter 1

Introduction

1.1 Overview

Wireless networks have become an integral part of our daily life, and due to rapid advances and developments in wireless technology, wireless-enabled user devices have become more affordable and powerful. Consequently, the number of these devices has increased dramatically in recent years, resulting in an increase in mobile data traffic around the globe. In 2018, Cisco reported that worldwide mobile data traffic has increased by 70% over the past three years, where 88% of that increase was generated by smart-phones [1]. In the same report, Cisco highlighted that in 2018, smart-phones represented almost half of the world's mobile wireless-enabled devices, up from 36% in 2015. However, due to the popularity and proliferation of wireless-enabled user equipment, this increase is gaining further momentum, with numbers anticipated to multiply exponentially in the coming years [1]. For instance, the number of wireless-enabled devices served by various wireless networks around the globe is predicted to reach 100 billion by 2030 with 10,000 times more mobile data traffic as compared to 2010 [2]. Based on Ericsson's mobility report, Ericsson expects that around 4 billion broadband subscriptions will be added globally to the mobile telecommunication market within the coming years [3]. In the same report, Ericsson predicts that by 2022 90% of mobile data traffic will come from smart-phones[3].

Moreover, new applications are being investigated by researchers and industry practitioners around the globe. These applications include the Internet of Things (IoT), Device to Device (D2D) communications, and Machine to Machine (M2M) communications, which will lead to a massive increase in the number of wireless-enabled devices, reaching up to tens of thousands connected devices in a single cell [4]. This type of increase not only demands mobile networks to expand their capacities, but also to intensify their power consumption to serve a rapidly-increasing number of user devices [5]. For mobile network operators, this capacity expansion and huge power consumption translates to a large operational expenditure ($OPEX$) to fulfill this explosively growing demand[6–8]. In this thesis, the implication of this unprecedented growth of traffic on the power consumption and spectrum capacity of communication networks is investigated. Additionally, the thesis proposes various approaches to alleviate the negative impact of the increase in power consumption and overall throughput.

1.1.1 Power Considerations

Mobile data traffic generated by the unprecedented-increasing number of user equipment and expanding networks' infrastructure, to accommodate the explosive demands, are all resulting in an increase in power consumption. Currently, for any network operator, energy consumption accounts for almost 30% of total operational costs [2]. Globally, the annual energy bill for mobile network operators has already exceeded US$10 billion [9]. Additionally, the total amount of power consumed by the telecommunication sector is forecast to reach 1710 terawatt-hours (TWh) by 2031, up from 600 TWh in 2011, which will result in unprecedented levels of CO_2 emissions from the sector [10]. The sector already produces around 1.4 billion tones of CO_2 per annum [11]. Moreover, for devices that are battery-constrained and have limited computational capacities, such as smart-phones and laptops, this explosive escalation in data traffic raises major concerns as these devices are not yet ready to process such massive amounts of data traffic. This leads to a consistent high-demand for more advanced devices and increases the disposal rate of current devices, including their batteries. The current annual rate of disposal has already surpassed 250 thousand [12]. These aspects do not only have a detrimental effect on the environment and human health [2][13], but also increase the OPEX to unmatched levels [14].

As a result of this, the energy efficiency aspect is considered as a key-pillar when it comes to resource management and network planning of any communication system. Hence, researchers, network operators, and manufacturers are seeking high performing communication solutions that are energy-efficient, cost-efficient, and environmentally friendly [2] [15]. Various initiatives have already been undertaken to develop solutions, such as Optimizing Power Efficiency in Mobile Radio Networks (OPERA-NET), Green Radio, Energy Aware Radio and Network Technologies (EARTH), and Towards Real Energy-efficient Network Design (TREND) [15],[16]. Nevertheless, driven by the huge demand, developing and designing more energy-efficient and cost-effective solutions is still one of the main focuses of the communication sector. Another major focus of the communication sector is the spectrum capacity. In particular, there is much attention on how to accommodate an ever-increasing number of wireless-enabled devices and their tremendous traffic with limited spectrum capacity. This concern is covered in the following section.

1.1.2 Spectrum Capacity Considerations

Whilst the number of wireless-enabled devices is increasing at a formidable rate, their data-hungry applications, alongside emerging technologies and their requirement for greater data rate and bandwidth, are also extensively evolving and growing in a consistent manner [17]. In addition to this enormous volume, mobile data traffic is unevenly distributed across time and space [18]. This drastic variation in traffic results in a rigid dilemma in terms of planning the infrastructure of a network; where either the existing capacity is insufficient to fulfill peak traffic requirements or overabundant average traffic demands. Additionally, mobile data has become more random and diverse, driven by various types of emerging applications. For instance, social media, gaming, multimedia downloads, and augmented reality, all of which demand various QoS requirements compared to conventional voice service [19]. Moreover, traditional mobile networks have been built on a core infrastructure that is typically optimized to provide services that are moderate in volume and delay-sensitive services, such as voice. Hence, various delay-insensitive high-volume services, such as emerging data-hungry applications, are very cost-ineffective [19].

Radio spectrum is a precious and limited resource. Due to existing radio spectrum policies, most available radio spectrum has already been allocated to specific licensed providers. This is known as the spectrum-scarcity problem [20]. Accordingly, for a mobile network operator, enormous traffic volume with a diverse nature is regarded as overwhelming traffic that can easily cause network congestion, degradation of throughput and quality of service (QoS), which accordingly intensifies the spectrum scarcity problem [21]. This introduces a challenge that demands an urgent need for spectrum-efficient communication solutions. As a consequence, major communication organizations, such as Federal Communications Commission (FCC), Defense Advanced Research Projects Agency (DARPA), along with researchers around the globe, have been working on solutions to alleviate the spectrum scarcity problem and utilize available wireless spectrum in a more reliable and efficient manner [17]. Nevertheless, driven by the anticipation of a tremendous volume of traffic, developing and designing more throughput-efficient and cost-effective solutions is another main focus of the communication sector. One of these is the heterogeneous network. Such a solution is considered as a realistic and integral solution that is expected to be energy-efficient, throughput-efficient, and cost-efficient. More details about this solution are discussed in the following sections.

1.1.3 Heterogeneous Network as a Solution

Owing to the exponential data traffic growth, in particular over the last five years, and the fact that licensed-spectrum is a scarce resource, current mobile network infrastructures are becoming progressively dense and chaotic [22]. Furthermore, next-generation mobile networks are anticipated to serve one million wireless-enabled devices per square kilometer [23] with a very rigorous latency, ms-level end-to-end latency, and all-time reliability as mandatory requirements [24]. Accordingly, the need for innovative communication techniques and revamping current communication networks, using newly designed approaches, has formidably intensified. In order to meet the demand for such unprecedented growth in traffic and the number of connections, the concept of heterogeneous networks (HetNets) has emerged as a promising solution that can tackle many of these challenges.

HetNets possess great potential in addressing spectrum scarcity and power consumption challenges in next-generation networks[25]. In HetNets, mixed types of base stations

(BSs) (e.g. femto, pico, and micro BS), known as small cell BSs, coexist with traditional large macro base stations (MBS) to alleviate overall power consumption and spectrum demands. These base stations are different in terms of their maximum coverage area and transmission power. This allows HetNets to boost their capacity by employing the frequency-reuse concept intensively within contiguous cells and to alleviate the spectrum scarcity problem [26]. Additionally, due to to their small coverage areas, small cell BSs (SCBSs) require less power than traditional BSs [4]. The benefits of this approach can be realized by both network operators and users. From the user perspective, this kind of network brings infrastructure closer to users, thereby improving link robustness and quality. From the operator perspective, and considering user distribution, SCBSs are usually installed in areas that have high user densities to offer better coverage with less power consumption and reduced latency. Driven by the great potential of HetNets, various techniques have been developed to further enhance HetNet capacity as covered in the following section.

1.1.4 HetNets' Capacity Enhancement Techniques

For capacity enhancement, the long-term evolution-licensed assisted access (LTE-LAA) is a promising solution that expands LTE to unlicensed bands to greatly boost HetNet capacities and deliver high throughput. In LTE-LAA, as shown in Fig. 1.1, if a user P1 is operating in a licensed band and needs more bandwidth, when all the licensed bands are fully utilized, the base station can utilize free channels from an unlicensed band and allocates the free channels to the user P1 to accommodate his/her additional needs [27–30]. The LTE-LAA technique was approved as a part of the 3rd Generation Partnership Project (3GPP) Release 13 [31].

Another promising solution, which is designed to address the spectrum scarcity problem, is Cognitive Radio (CR) [32][33]. The CR technique is motivated by the fact that most often the licensed spectrum is underutilized by its primary users [17] resulting in idle (i.e unused) holes in the spectrum. If these idle holes can be opportunistically used by other users (i.e., secondary users) then the overall spectrum usage can be improved. Federal Communications Commission (FCC) has already approved an approach that allows cognitive-devices to sense available spectral medium and transmit upon detecting

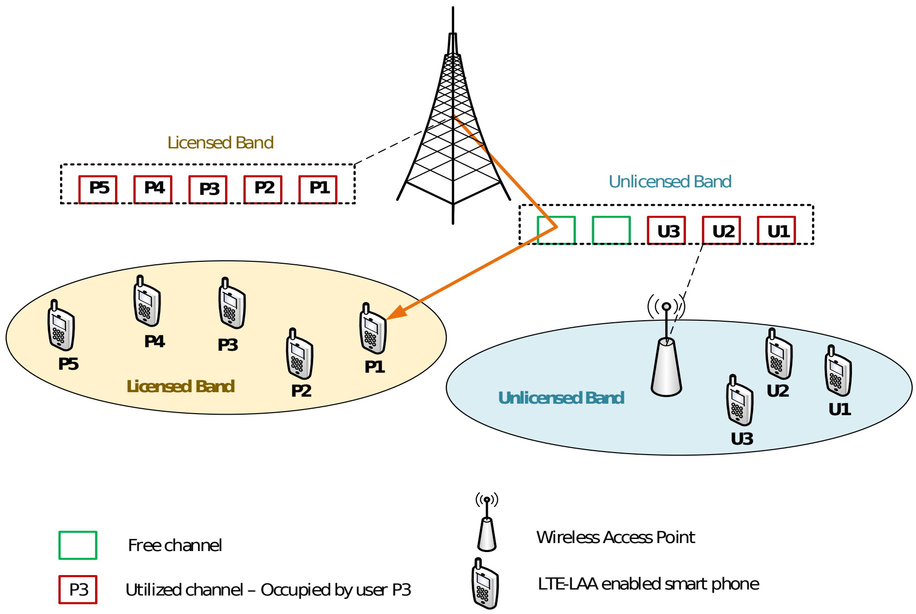


Fig. 1.1: Demonstrative figure for the LTE-LAA Technology

unused channels [34]. It is worth noting that in CR-enabled networks, two groups of users are allowed to coexist [35]. The primary users (PUs) group has the license/right to use the licensed bands. The secondary users (SUs) are allowed to access PU bands in PU absence to avoid interference [35].

For the above-mentioned capacity enhancement techniques (i.e. LTE-LAA and CR), software-defined radio (SDR) technology is the enabling tool. SDR technology enables the transmitter/receiver to dynamically adjust their operating parameters such as frequency bands and transmission power to establish a communication link [36] [37]. Hence, SDR makes the prospects/benefits of both techniques more realizable than ever before.

All the above-mentioned enhancement techniques and solutions are beneficial and offer great potential to fulfill the ever-increasing demand of users. However, the integration between these techniques and solutions must be done carefully to ensure that the overall communication system is working in an efficient manner. Hence, the significance and motivation of this thesis become apparent, as discussed in the following section.

1.2 Significance and Motivation

For HetNets, although a small cell base station (SCBS) consumes less power than a macro base station (MBS), the number of SCBSs in a large mobile network can be much higher than the number of MBSs. As a result, the total power consumption of a network with a large number of SCBSs is likely to be high [38]. This is a matter of concern because in mobile networks, as shown in Fig. 1.2, base stations already account for 68% of total network power consumption. Additionally, from user perspective, the use of SDR technology, which is the enabling technology for LTE-LAA and CR, involves field-programmable gate arrays (FPGAs), which consumes significantly more power (up to four times) compared to an application-specific integrated circuit (ASIC) design [39] [40]. This raises major concerns for battery-constrained devices such as smart phones and laptops, where excessive power consumption can easily overwhelm the benefits offered by both techniques. Furthermore, the opportunistic and open nature of the CR technique can lead to major security concerns about transmitted data. Hence, new approaches that consider the battery levels of user portable devices and endeavor to maximize any BS-related power saving would be significantly beneficial for users, network operators, and the environment.

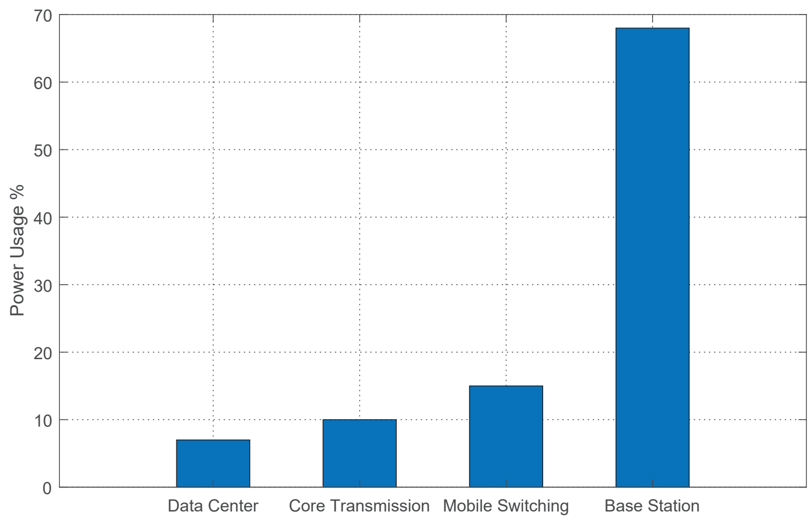


Fig. 1.2: The power consumption distribution in a mobile network

In addition, as a consequence of their inflexible, constrained, and hardware-based configurations, HetNets have major limitations in adapting to fluctuating traffic patterns [41]. For instance, due to non-uniform user distribution, some SCBSs with bounded capacities may become overloaded, while others become lightly loaded which results in a critical resource management problems. Moreover, due to rigid coupling in control-plane decision-making between contiguous base stations, the ability to control high-denity networks that utilize the frequency reuse concept, like HetNets, becomes a complex task. This coupling reveals itself in a couple of ways. Firstly, due to small cell coverage, load fluctuates rapidly owing to users' mobility. Therefore, resource allocation, cell association, and handovers must be maintained at each BS in concert with contiguous BSs to minimize signal interference, increase network capacity and balance traffic loads [42]. Secondly, the extensive frequency reuse and broadcast nature of wireless communication results in users of one base station experiencing considerable interference from surrounding BSs. This degrades HetNets usable capacity [42].

Furthermore, extending LTE-LAA to the unlicensed band present two major challenges. Firstly, how to ensure an interference-free coexistence between LTE-LAA enabled devices and WiFi-enabled devices, which are the major consumers of unlicensed bands [43]. Secondly, how to maintain a fair channel-occupation ratio between the two types of users (LTE-LAA and WiFi) to maintain their throughput levels, taking into consideration that WiFi technology employs a contention-based channel access mechanism and LTE-LAA employs an orthogonal frequency-division multiple access (OFDMA) channel access mechanism [43]. Therefore, smart allocation and management of HetNet resources are crucial for achieving power savings and simultaneously fulfilling rapidly increasing traffic requirements.

Driven by these authentic factors, this thesis investigates and presents communication strategies exploring novel, energy-efficient, and throughput-efficient resource management. More specifically, these strategies investigate the exploitation of long-term evolution-licensed assisted access technology, cognitive radio technology, renewable energy, and their associated trade-offs.

1.3 Aims of the Thesis

The aim of this research is to develop energy-and-throughput efficient communication approaches, that are reliable and sustainable for next-generation wireless networks. Moreover, the research aims to explore trade-offs between power consumption and overall throughput. Specifically, the main aims of this research are:

- Developing a novel SDR-based LTE-LAA architecture for HetNets with an optimum resource management-and-allocation solution for this architecture. The main goal of this architecture is to decrease energy consumption and increase overall throughput.
- Designing a green traffic-steering approach that leverages the spectrum-based cell zooming technique, the LTE-LAA concept, and SDR technology to efficiently steer users across a network. This approach reduces the overall network's on-grid power consumption and increases the aggregated throughput of all users.
- Proposing an energy and security-aware communication approach that exploits CR techniques and finds an optimal base station for user association. This technique minimizes energy consumption and maximizes the benefits of CR-enabled users in terms of throughput and data security.

1.4 Research Contributions

This research work contributes to the enhancement of various communication techniques and approaches for next-generation networks. Furthermore, it optimizes not only the users association process, but also the resources (i.e. spectrum and power) management and allocation, in a reliable and sustainable manner. The main contributions of this work are:

- The research work demonstrates that using the LTE-LAA approach to extend mobile networks to the unlicensed band has the potential to alleviate energy consumption and considerably enhance network throughput, if it is utilized along with an efficient user steering strategy. The key idea is to find the most suitable BS in terms of the number of subcarriers, traffic load, and the available amount of green energy, to optimally pick and steer data-hungry users to it, using the spectrum-based steering technique. Simulation analysis illustrates that the proposed approach not only mitigates energy consumption, but also boosts user throughput. This offers substantial benefits to both users and network operators.

- This study shows that the CR technique is not suitable for every user and for every situation. However, a restrictive CR-based communication approach brings significant benefits for both network operators and users. The novel idea of this work is to carefully restrict CR techniques in communication to shortlisted SUs. These chosen SUs are optimally chosen, according to their traffic type, data size, data-security requirement and to BS idle spectrum bands, to maximize total benefits of shortlisted SUs and minimize their energy and vulnerability costs. Numerical analysis demonstrates that the proposed technique can significantly increase both user throughput and operator spectrum utilization, in an energy-efficient and secure manner. Hence, the proposed approach offers considerable benefits to both users and network operators.

- This thesis presents a resource management scheme for HetNet architecture. This scheme utilizes the LTE-LAA technique and SDR technology to dynamically adapt to rapid traffic fluctuations. The hypothesis is that, owing to user movement, BS loads are not the same and vary over time and according to the BS location. Hence, the goal of the resource management scheme is to utilize the flexibility of SDR-based architecture to associate users to the most suitable BS that fulfills their requirements while decreasing overall network energy consumption and increasing overall throughput. This research study formulates the resource management problem as a constrained optimization problem and provides solutions to the problem. The obtained results, from the proposed approach, show not only a reduction in total energy consumption and an increase in users' total throughput, but also a high spectrum utilization compared to other approaches. Accordingly, the proposed scheme offers considerable benefits to both users and network operators.

1.5 Thesis Outline

This thesis is structured as follows:

- **Chapter 1** introduces an explicit overview of power consumption and throughput related issues of HetNets. Additionally, it provides information about the significance of this research work, its main goals, and its contributions along with the thesis outline.

- **Chapter 2** provides a comprehensive review of the most recent communication strategies in HetNets. It provides a concise description of the role of LTE-LAA, SDR, and cognitive radio in mobile networks and illustrates their associated technical challenges. The spectrum-based cell zooming technique, the green aspects, and security-related concerns of relevant cognitive radio approaches are also covered here. Additionally, this chapter discusses how this research work covers the gaps in prior research works and presents the main research questions for this research work.

- **Chapter 3** shows that through careful design and management of an SDR-based LTE-LAA system, a higher level of adaptability can be achieved in HetNets, which contributes to higher throughput and lower energy consumption. The research challenge of achieving higher throughput and lower energy consumption is formulated as a constrained optimization problem. Considering the time complexity of the optimization problem, a heuristic solution is proposed in this chapter. The research work of this chapter is currently under review in *IEEE Transactions on communications.*

- **Chapter 4** introduces a new traffic steering technique for energy conservation in next generation communication networks. By leveraging spectrum-based cell zooming techniques, the long-term evolution licensed assisted access (LTE-LAA) concept, and software defined radio technology, the chapter introduces a green traffic-steering framework that endeavors to minimize overall network on-grid power consumption and maximize aggregated throughput. Considering the time complexity of the optimum solution, a heuristic solution is proposed in this chapter that provide sub-optimal solution. The research work of this chapter has been reviewed and published in *IEEE Transactions on Cognitive Communications and Networking,* Early Access, 2020. doi: 10.1109/TCCN.2020.2987799.

- **Chapter 5** presents an energy-and-security-aware CR-based communication approach that alleviates the power consumption of the CR technique and enhances its security measures according to the confidentiality level of the data being sent. Furthermore, the proposed approach takes into account user-related factors, such as the users battery level and users data type, and network-related factors, such as the number of unutilized bands and vulnerability level and then models the research question as a constrained optimization problem. Considering the time complexity of the optimum solution, a heuristic solution is also proposed in this chapter that provides a sub-optimal solution. The research work of this chapter has been reviewed and published in *IEEE Open Journal of the Communications Society,* Vol. 1, P900-915, 2020.

- **Chapter 6** briefly reviews the concluding remarks and highlights the overall contribution of this research. Additionally, it introduces the recommended future research areas.

Chapter 2

Background and Literature Review

2.1 Introduction

The goal of this chapter is to present a background of the HetNet concept and to introduce a comprehensive overview of recent research advances in HetNets that focus on energy and throughput related challenges. Subsequently, based on the extensive and explicit information in the existing literature, the research questions are formulated.

This chapter's contribution can be summarized as follows;

- The chapter presents an explicit overview of the HetNet concept and it categorizes its main technical challenges as inflexibility of its infrastructure, licensed-spectrum scarcity problem, and user-BS association strategies. A concise elaboration on these challenges and their impact on the overall power consumption and throughput is presented in Section 2.2.
- An extensive analysis of recent research works that aim to enhance HetNets' energy-efficiency and throughput-efficiency is also introduced in Section 2.2. Additionally, in the same section, various communication approaches/techniques are comprehensively discussed and analysed.
- Lastly, based on the above-mentioned analysis, the research gabs are identified and the research question are formulated in Section 2.3

2.2 An Overview of HetNets

Heterogeneous networks (HetNets) has been regarded as a promising technology for next-generation networks that can alleviate the excessive power consumption issue and tackle the spectrum scarcity problem [25, 44–46]. In HetNets, macro cells are overlaid with smaller cells to improve the spectrum efficiency, users throughput, and quality of service (QoS) [45]. The deployment of various types of small cells could be visualized as a multi-tier HetNet, as shown in Fig. 2.1. These various small cells can be categorized into three main categories: Femto-cells, Pico-cells, and Micro-cells.

The Femto-cell is considered the smallest cell with a radius that ranges from 15 to 30 meters and consumes around 100 mWatt in transmission [47]. As shown in Fig. 2.1, it is regularly used indoor, and is backhauled using a broadband connection. The Pico-cell has a larger radius, up to 100 meters, and its power consumption ranges from 0.25 to 2 Watts [48]. It is usually used to cover a large indoor environment, such as airports and shopping malls. However, it can be used to enhance an existing outdoor cellular coverage, that has Macro-cells and Micro-cells [48]. The Micro-cell's coverage area has a larger radius than Pico, up to 2 km and transmission power around 10 watts [48].

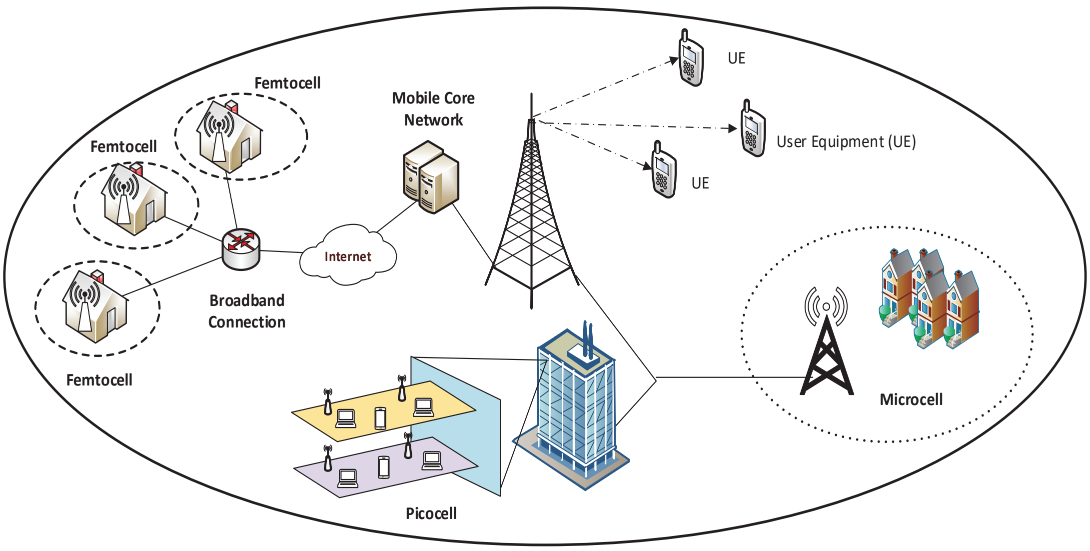


Fig. 2.1: HetNet Architecture

The paradigm of using mixed types of cells in HetNets allows to intensively use the frequency-reuse technique within nearby cells to boost the overall network capacity. Additionally, from the users' perspective, this paradigm brings the infrastructure closer to the user, thereby improving link robustness, throughput, and quality. Although such a paradigm is already utilized in existing networks, the next-generation HetNets will have a higher density of these small cells [45]. This densification, along with the explosive increase in the number of users and the amount of generated data, leads to stressful challenges for next-generation HetNets. These challenges manifest themselves in three main points as follows:

2.2.1 HetNets' Inflexible Infrastructure

The formidable growth in mobile data traffic and the fact that licensed-spectrum is a scarce resource result in current mobile network infrastructures becoming progressively dense and chaotic. In order to meet the demand for such unprecedented growth in traffic, next-generation networks rely on the concept of heterogeneous networks. However, owing to the current fixed-spectrum fragmentation and allocation policy, it is still a challenge for HetNets to meet the dramatic increase in mobile data traffic. Accordingly, recently, the HetNet has been a popular research topic, where the literature has offered plentiful techniques to ameliorate its performance.

Authors in [49–53] conducted in-depth research on HetNet backhauling architecture to maximize its capacity and minimize its power consumption by introducing different backhauling solutions. The authors in [54], investigated the utilization of millimeter wave band in backhaul and access networks. They intensively analyzed various bands, including 73 GHz, 60 GHz, 38 GHz, and 28 GHz, to improve the small-cell capacity. Dehos and his co-authors, in [55], evaluated the millimeter wave feasibility for both backhaul and access infrastructure taking into consideration the V and E bands. In [56], the authors presented a novel HetNet backhaul infrastructure that utilizes millimeter wave and orthogonal frequency division multiple access with passive optical networks (OFDMA-PON).

In addition to the limitation caused by the fixed-spectrum fragmentation and allocation policy, HetNets have major limitations in adapting to fluctuating traffic patterns because of their inflexible, constrained, and hardware-based configurations [41]. For instance, due to non-uniform user distribution, some SCBSs with bounded capacities may become overloaded, while others become lightly loaded which results in a severe resource management problem. These limitations/inflexibility in adaptation result in users of one base station (BS) experiencing a considerable lack of enough resources and interference from surrounding BSs. This degrades HetNets' performance and usable capacity [42]. Software-defined radio (SDR) technology, which can dynamically update operating parameters, including frequency bands, can be very useful in this context [57]. Hence, SDR technology has attracted numerous researchers to adopt it in their research.

In [58, 59], the authors presented a comprehensive overview of the SDR concept including the challenges and the potential benefits of adopting it in cellular networks. The authors in [60] proposed an SDR-based networking architecture called SoftAir. The main target of the proposed architecture was to manage the allocated licensed-spectrum in a more resource-efficient manner by using different traffic-engineering solutions. In, [42], a SDR-based centralized control plane, named SoftRAN, for a cellular network has been developed by the authors. SoftRAN deals with all base stations in a specific coverage area as a big virtual BS comprising of a single central controller. The aim behind this proposal was to enhance network manageability and profitability.

The authors in [61] introduced a green-energy aware users-associating scheme that utilizes the SDR technology to distribute and adapt the associating algorithm according to traffic load. The authors' ultimate target was to alleviate the total power consumption and alleviate loads on the backhaul network. The authors in [62] proposed a mobility-based user-associating scheme that can be used in cooperative communication. Further, in [63], the authors have proposed a platform based on SDR, named 5G-EmPOWER. The proposed platform was assessed by the authors in terms of mobility management and load balancing. Additionally, in [64], the authors have presented a novel SDN-based system, SODALITE, that can integrate with current 4G architectures and mitigate the cost and management complexity for small cells dense deployments

Table 2.1 introduces a summary of other existing research studies and their the key contributions in enhancing the HetNets infrastructure performance and adaptability/flexibility.

Table 2.1: The literature review summary for Infrastructure improvement in HetNets

Research Area	Authors	Key Focus	Research Outcome
Next generation Wireless Networks	P Pirinen [65]. F Boccardi[66].	Wireless evolution toward 5G networks.	Current status of 5G implementation and identification of major research directions.
	Zhang et al. [67]	Energy efficient research and design for future wireless networks.	Research progresses of 4G and 5G communications and potential challenges and impacts of fundamental green tradeoffs.
	Jaber et al. [68]	5G backhaul challenges.	Analysis of existing backhaul solutions and a new 5G backhaul vision.
	Mowla et al. [69]	Energy-efficient small cell networks (SCNs)	Energy-efficient backhauling solutions for 5G HetNets.
Software Defined Radio For Wireless Networks	M Dardaillon [70]. T Chen[71].	SDR development toward 5G networks.	Current status of SDR implementation and identification of major research directions.
	M Yang [72]. W Xia[73].	Software-defined networks enhancements.	Current status of SDR implementation and identification of major research challenges.
	H Kobo [74].	Software-defined wireless networks.	Current evolution status in SDR-based wireless networks implementation and identification of design major challenges.
	L Peizhe [75].	exploiting the Game Theory and SDR for better power consumption.	a novel game-theoretic and energy efficient algorithm that can be used along with the SDR to achieve better energy efficiency.
	G Anuga [76].	SDR-based internet of things communication challenges.	comprehensive survey on 5G networks for the internet of things and their communication challenges.
	A Nauman [77].	SDR-based internet of things	comprehensive survey on Multimedia internet of things and their communication challenges.
	S Al-Rubaye [78].	leveraging Inseparability for accessing unlicensed band via utilizing SDR.	a software-based utility architecture that can use an SDN controller to enhance resource provisioning and management to capture the aggregation of data flows between utility components.

Continued on next page

Continued from previous page			
Research Area	Authors	Key Focus	Research Outcome
Software Defined Radio For Wireless Networks	H Lue [79].	under-water SDR-based wireless sensor networks	Informative survey on different kind of SDR-based architectures and technologies based that are based on SDR.
	Z Ding [80].	Interference mitigation in wireless networks.	Energy-efficient Routing Algorithm with Interference Mitigation for Software-Defined Wireless Sensor Networks.
	H Isaac Kobo [81].	Control systems in wireless sensor networks.	Fragmentation-Based Distributed Control System for Software-Defined Wireless Sensor Networks.
	I Haque [82].	Frameworks for Wireless Networks.	Introduction of SDSense which is a Flexible and agile SDN-Based Framework for wireless networks
	J Xie [83].	exploiting Machine Learning in SDR.	a comprehensive survey on the challenges and research issues related to different Machine Learning techniques when it comes to the SDR technology.
	Y Zhao [84]	Networking applications.	a comprehensive survey on various networking applications that apply the software defined networking concept along with the Machine Learning.
	R C.A Alves [85]	SDR-based sensor networks	The introduction of "The cost of software-defining things" concept and presentation of a scalability study of Software-Defined sensor networks.
	M Husain [86]	Smart grid communications.	offering a comprehensive survey on software-defined-networks-based smart grid communication.
	N Marriwala [87]	Error Control Coding.	Error Control coding for software defined radios using soft computing.
	A Capponi [88]	Mobile Crowd-Sensing systems.	Introduced a comprehensive survey on the challenges, solutions, and opportunities for the SDR-based Mobile crowd-sensing systems.

Almost all of the above-mentioned research works focused on utilizing different technologies (mmWave bands, FTTB, FTTN, VDSL2, SDR ..etc) with different techniques to relax backhaul traffic, reduce cost and delay, increase coverage area, enhance spectrum-efficiency and reduce backhaul power consumption. However, nearly all of the above-mentioned works were based on wireless network designs that are profoundly constrained by the pre-configured hardware and built on closed, inflexible, and non-adaptable architecture. Such designs typically impose serious challenges to networks to adjust to the uneven, variable, and increasingly growing traffic-patters and lead to degraded performance and less user throughput.

This thesis has proposed a SDR-based and LTE-LAA-enabled architecture for next-generation communication networks that offers more flexibility and a higher level of adaptability. In the proposed architecture, the SDR technology has been used to introduce open-access/shared SDR-based BSs that support LTE-LAA and can serve users from different operators. Such an architecture increases the overall throughput and minimize the transmission power consumption and end-to-end delay, which are stringent requirements of 5G/6G networks. Accordingly, its benefits can be realised by both operators and users.

2.2.2 Licensed-spectrum Scarcity Problem

Since most of the usable licensed-spectrum is of a limited physical extent and new licensed bands are extremely expensive and rare, this limited resource is regulated and governed by trusted agencies. Hence, most of the available radio bands are exclusively allocated to specific user/company/service-provider/operator and unlicensed users are not allowed to access these bands. Nevertheless, with the explosive growth in the number of wireless-enabled devices and wireless applications, the radio spectrum is facing enormous demands and this leads to a severe spectrum scarcity problem. Another contributing factor to the spectrum scarcity problem is rooted in the traditional policy of static spectrum allocation, where only licensed users are allowed to utilize their designated spectrum. This often results in under-utilization of radio spectrum bands as reported in [89].

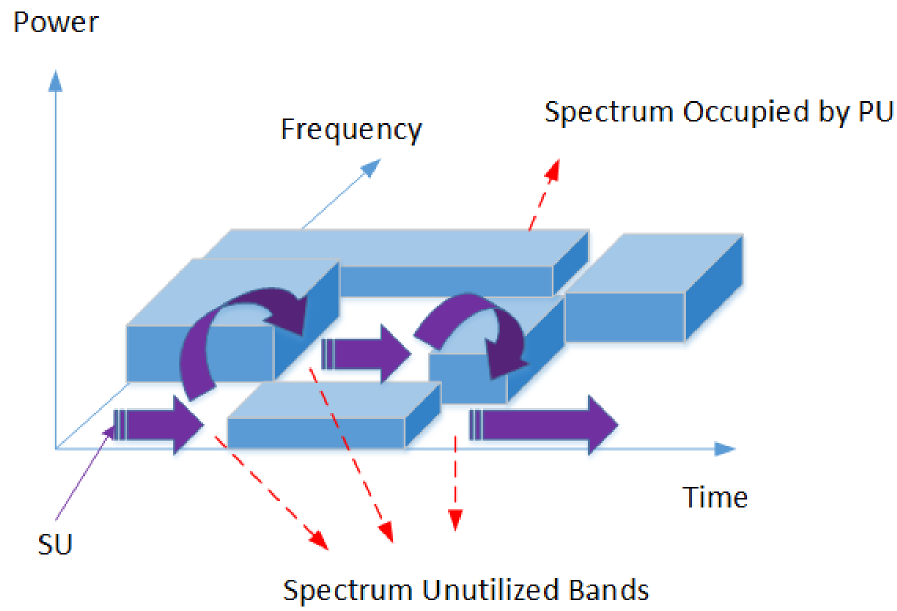


Fig. 2.2: Demonstration of the Cognitive Radio technique

To overcome the spectrum scarcity problem, various studies have investigated multiple options. One of these options is the CR technique, where unlicensed users are allowed to opportunistically access unutilized licensed bands. In the CR approach, as shown in Fig 2.2, an unlicensed user, named secondary user (SU), exploits the primary user's (PU) unutilized bands to send his data. However, the SU must refrain from using those bands whenever the PU becomes available to avoid any possible interference. Using such a technique enables agile and flexible access to the radio spectrum and can resolve the spectrum-scarcity problem and maximize spectrum efficiency.

Another option is the LTE-LAA technology, where more carriers are added, as shown in Fig.2.3, by extending the sub-carriers frequency range to the unlicensed bands [29].

In the literature, various CR and LTE-LAA techniques have been extensively adopted and studied to reach the optimum performance. In [90], secondary users (SUs) have been categorized by the authors based on their required quality of service, and by utilizing an auction-based model, where the authors increased the spectrum efficiency of their network. The authors in [91], presented multiple cooperation policies between SUs and primary users (PUs). These policies are based on Markov decisions and aimed to reduce

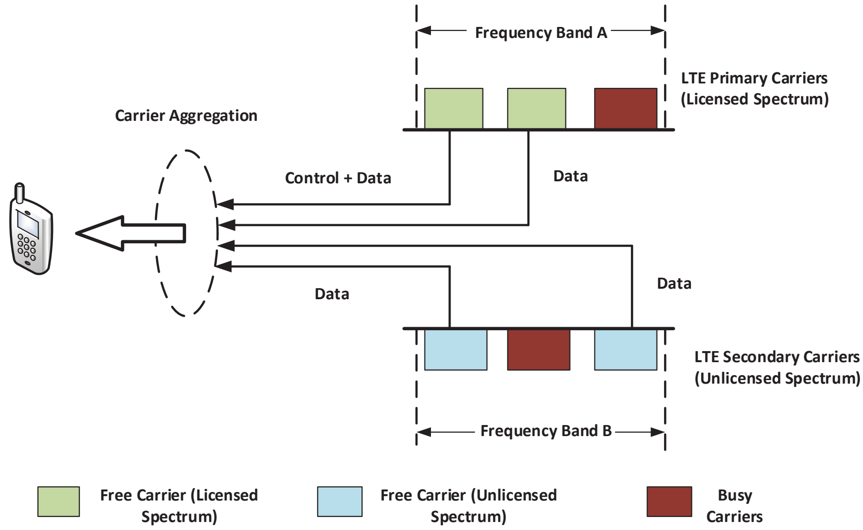


Fig. 2.3: Carrier aggregation in LTE-LAA

SUs' blocking probability for better throughput and spectrum efficiency. In [92], three sub-carriers selection approaches were introduced by the authors to boost SUs' signal to interference and noise ratio (SINR) to maximize their data throughput.

In [93], the authors have proposed techniques and algorithms to predict the idle bands of the spectrum. These techniques and algorithms are utilized by SUs to access the idle frequency bands and transmit the data. Authors in [94] have presented a repeated-game-based strategy, that allows CR-enabled devices to increase their throughput and decrease the probability of collisions with other CR-enabled devices that are contending on the idle bands of a spectrum. The authors in [95] have introduced a novel cooperative spectrum-sensing technique, based on an optimal energy-detection technique and can reduce the probability of detecting fake idle frequency bands in a spectrum. In [96], the authors have presented a comprehensive review for main and indispensable spectrum-sensing techniques and media access strategies used in cognitive radio.

Energy efficiency in CR has also been covered widely in the literature. For instance, the work in [97] has presented an energy-harvesting-based CR technique that trades-off both energy efficiency and spectrum efficiency to achieve high benefit from the CR technology. Leveraging CR, the authors in [98] presented a cooperation mechanism between secondary base stations (SBSs) and primary BSs (PBSs) to reduce power consumption of both BSs and to increase spectrum efficiency. The authors in [35] presented an overview of various energy-efficient techniques that are used in spectrum sensing to locate idle frequency bands in a spectrum. In [99], the authors have utilized green-energy to the CR to boost the energy efficiency and reduce the overall power consumption.

While the above-mentioned research studies have presented useful mechanisms and techniques to increase the energy efficiency of CR processes and networks, these studies have not considered the security aspect in their communication method, and assumed that all CR-enabled devices (i.e. SUs) are equipped with large power resource, where it is affordable for all of them to participate in the CR process. However, this consideration is not accurate as wireless communication networks serve different mobile users with different data traffic needs, limited-power resources, and different types of traffic (i.e. confidential or not). Accordingly, the affordability is different from one user to another.

This thesis has introduced an energy-and-security-aware CR-based communication technique that alleviates the power consumption of the CR technique and enhances its security measures according to the confidentiality level of the data being sent. Furthermore, the proposed approach has taken into account user-related factors, such as users battery levels and users data types, and network-related factors, such as the number of unutilized bands and vulnerability level. Such a technique increases the overall throughput and minimize the transmission power consumption and end-to-end delay, which are stringent requirements of 5G/6G networks.

For the LTE-LAA, the authors in [89, 100, 101] introduced comprehensive surveys of various optimum deployment scenarios. The authors analyzed Wi-Fi coexistence-related issues and how to overcome these issues to reach optimum performance for the LTE-LAA-based systems. The authors in [29], proposed a novel Markov chain-based model that can handle the LTE-LAA frame variation and enhance the performance evaluation for the LTE-LAA systems.

The authors in [102] studied and analyzed the performance of various 3GPP LTE-LAA releases. Additionally, it proposed some enhancements that can increase the throughput of these releases. Table 2.2 introduces a summary of other existing research studies and their the key contributions in alleviating the licensed-spectrum scarcity problem by using different techniques.

Table 2.2: The literature review summary for solving the licensed-spectrum Scarcity Problem.

Research Area	Authors	Key Focus	Research Outcome
Cognitive Radio For Next-Generation Networks	Beibei Wang [103] [104]	Advances in Cognitive Radio networks.	Current status of the cognitive radio advances and technologies.
	T. Yucek and H. Asdlan [105]	Spectrum Sensing algorithms for cognitive radio.	Current status of the algorithms for sensing spectrum in the cognitive radio networks.
	T C Clancy. [106]	Interference management in Cognitive radio.	Spectrum shaping methodology for interference management in CR networks .
	E Hossain. [107]	Future trends for Cognitive Radio.	Existing techniques for Cognitive radio and their future trends in addition to their challenges.
	J M Chapin . [108]	Market challenges for cognitive radio.	Overview of the market challenges and success path for the cognitive radio and dynamic spectrum access technologies.
	A He. [109].	Energy Consumption in Cognitive radio	How can we minimize the energy consumption in cellular networks using the cognitive radio.
	HY Lateef. [110]	Energy-aware 5G HetNets	CR-enabled energy efficient deployment strategies for 5G.
	Y Pei. [111] AT Hoang [112] [113] G Gr [114]	Energy-Efficient Cognitive radio.	Energy efficient design of sequential channel sensing in cognitive radio networks.
	DJ Kadhim. [115] R Min [116]	Power Efficiency in Cognitive radio.	Power efficiency maximization methodology utilizing the cognitive radio networks.
	M Pirmoradian. [117]	Energy consumption in cooperative Radio networks	An analytical evaluation of energy consumption in cognitive radio .
	MC Oto. [118]	Energy Efficiency optimization in CR.	optimum packet size for CR sensor networks.
	Y Liu. [119]	CR green networks .	Power efficient spectrum discovery methodology for CR green networks.

Continued on next page

Continued from previous page			
Research Area	Authors	Key Focus	Research Outcome
LTE-LAA For Next-Generation Networks	M Pirmoradian. [120]	Energy Efficiency in cognitive radio .	Adaptive power control scheme for energy efficient cognitive radio networks.
	E Bedeer. [121] Y Wang [122]	Energy-aware Cognitive radio systems.	current status of the Energy-aware cognitive radio systems and their features.
	B Ismaeil [123].	Extending LTE to the unlicensed band in the Device-to-Device communications.	Comparison of different LTE-LAA-enabled Device-to-Device architectures including pros and cons.
	A Mukherhee [124].	LTE-LAA improvements	additional enhancements beyond LTE Release 13 for better LTE-LAA performance.
	V Maglogiannis [125].	Neural Networks	Enhancing the convolutional Neural networks performance by utilizing the LTE-LAA.
	U Challita [126].	LTE Resource Management.	a Deep-Learning-based proactive resource management scheme for the LTE-LAA networks that increases the spectrum utilization.
	L Li [127].	LAA Networks adaptability.	Adaptive energy detection technique that increases the accessibility of the unlicensed bands.
	C Zhang [128].	Deep Learning in LTE-LAA-enabled networks.	Comprehensive survey on various deep learning techniques that can be utilzied in the LTE-LAA networks to increase their overall performance.
	W Wu [129].	Protocol designs and resource allocation.	novel LTE-LAA protocol design the enhances the resource allocation process for better throughput.
	J Jeon [130].	LTE in the Unlicensed spectrum.	a comprehensive evaluation for various scenarios where LTE systems are extended to the unlicensed spectrum.
	Y Li [131].	LTE-LAA modeling.	Modeling and analyzing the coexistence of Wi-Fi and LTE in unlicensed spectrum.
	H Zhang [132].	Mobile network resource management.	A multi-leader multi-follower Stackelberg game for resource management in LTE Unlicensed.

While the above-mentioned LTE-LAA-related research studies have presented useful mechanisms and techniques. Owing to the inflexible hardware-based design and the fact that the licensed spectrum is a scarce resource, all of these works have worked on maximizing the efficiency of the allocated licensed spectrum not to maximize the user's achievable data rate. Furthermore, driven by their closed hardware-based design, most of the above authors have not considered the option of sharing BSs and radio resources with other operators to maximize the overall network throughput and reduce the overall running cost and energy consumption.

This thesis has exploited SDR technology, LTE-LAA concept, and green-energy to develop a green traffic-steering framework. This framework has utilized the spectrum-based cell zooming technique to steer users across multiple BSs from various networks toward the optimum BSs, which have abundant unlicensed carriers and abundant renewable energy, to minimize overall network on-grid power consumption and maximize aggregated throughput, which are stringent requirements of 5G/6G requirements.

2.2.3 User-BS Association Strategies

In networks that have multi-dimensional heterogeneity with reference to diverse cells' area, power sources (on-grid and green), divergent operating bands (unlicensed and licensed), and various traffic densities with different quality of service (QoS) requirements, one critical and primary problem is how efficiently can diverse network resources be utilized while providing high QoS to customers. In other words, although HetNets provide valuable opportunities to employ the advantages of particular resources or technologies for various services, they likewise result in numerous technical challenges to enhance network utilization and user experience owing to their extraordinarily dynamic environment and multi-dimensional heterogeneity.

In this regard, user-BS association, also known as traffic steering, strategies play a key role. According to the association strategy, users are distributed/steered in an optimal manner across various network units and bands with a view to fulfill a certain goal. These strategies enable network operators to manage and control their highly dynamic traffic loads across different access entities to maximize their network's resources utilization. For instance, as shown in Fig. 2.4, using user-BS association strategies, network operators can direct traffic from a lightly loaded on-grid cell to its neighboring off-grid (green-powered) cells and turn off the on-grid cell to save more power [133]. Hence, traffic steering exploits, in a more productive manner, network multi-dimensional heterogeneity.

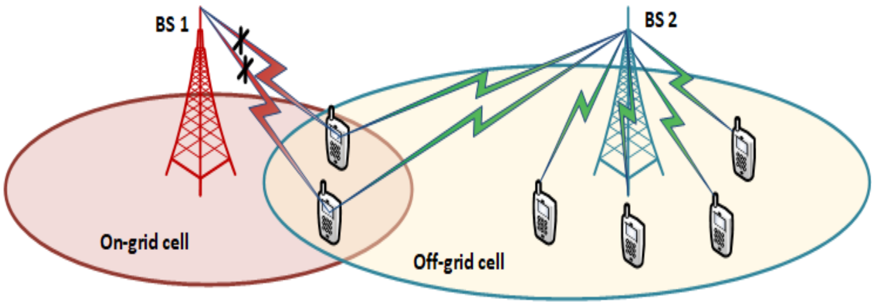


Fig. 2.4: Demonstration of the user-BS association concept.

As a result, in the literature, various user-BS association strategies have been introduced. For example, authors in [134] presented a user-cell association scheme in which users select BSs that accommodate their data demands with better QoS. In [135], authors formulated the user-cell association problem as a utility maximization problem and developed a user association algorithm to solve it and to maximize network utility (i.e. throughput or data rate). A congestion game-based traffic balancing model was introduced in [136] in which a user is considered as the player and the decision of user association is the action. Furthermore, in [137], authors presented a game-theory based solution that utilizes a generic algorithm to associate users with BSs that have optimum allocatable resources. An extensive overview of various traffic balancing techniques in HetNets has been offered by the authors in [138].

Traffic load balancing in HetNets can be considered the ultimate goal of a user-BS association strategy and this has also been a topic of interest in many recent research works. Numerous algorithms have been proposed to achieve efficient traffic load balancing in HetNets and optimize network resources. Authors in [139] modeled the problem of balancing traffic loads as a maximization optimization problem. Additionally, they presented a users-association algorithm based on the decomposition of primal-dual. In [140], Aryafar and co-authors modeled the problem of balancing traffic loads as a congestion game where decisions of the association are the actions and customers are players.

In [141], authors presented flexible cell-breathing techniques that can be utilized in HetNets to transfer loads from over-loaded BSs to lightly-loaded adjacent BSs. These techniques have been developed to achieve energy efficiency along with load balancing. Comprehensive surveys have been done by the authors of [142, 143] on available techniques for traffic load balancing and BSs biasing in the HetNets to enhance HetNets energy-efficiency and performance.

Table 2.3 introduces a summary of other existing research studies and their the key contributions in developing highly efficient user-BS association strategies for HetNets.

Table 2.3: The literature review summary for user-BS association strategies.

Research Area	Authors	Key Focus	Research Outcome
User association Strategies For Next Generation Networks	D Liu. [144].	User association in 5G networks.	A comprehensive survey on various user-BS approaches and strategies for teh next generation networks.
	Y Wang. [145].	HetNet download rate and user association.	A joint caching placement and user association technique that minimizes the user's download delay.
	T Van Chien. [146].	Power Allocation in HetNets.	Joint power allocation and user association optimization for Massive MIMO systems.
	X Ge. [147].	Load balancing in HetNets.	Joint user association and user scheduling scheme for load balancing in HetNets.
	L Qi [148].	Fog Radio Access Networks.	Advanced user association in Non-Orthogonal multiple access-based Fog Radio Access networks.
	M Attiah [149].	mmWave and spectrum sharing	a comprehensive survey on mmWave user association mechanisms and spectrum.
	X Sun [150].	Drone assisted Mobile networks.	Jointly optimized 3D drone mounted base station deployment and user association in drone assisted Mobile Access Networks.
	F Cheng [151].	Dual-UAV Enabled wireless networks.	Learning-based user association for Dual-UAV enabled wireless networks with D2D connections.
	T Ha Ly Dinh [152].	Beamforming in 5G Fog Radio Access networks.	Energy-efficient user association and beamforming for 5G Fog Radio Access networks.

Almost all of the above-mentioned studies have focused on either magnifying the data rate, reducing overall power consumption, or adapting to network dynamics. However, from the network operator's point of view, all of these are crucial components that influence network manageability and operational expenditure ($OPEX$). Hence, by simply optimizing one metric, mobile operators cannot minimize their ($OPEX$) effectively or achieve consistent reliability.

2.3 Research Questions

As discussed in the previous section, HetNets have attracted the attention of researchers and industry professionals. HetNets can enhance cellular networks' performance by boosting their capacity via useful technologies such as LTE-LAA, CR, and SDR. The major focus of most of the existing research works was either the energy aspects, overall throughput, or spectrum efficiency of the HetNets. However, from the user and operator's point of view, all of these are crucial components and must not be overlooked. Accordingly, and based on the research findings that were discussed and detailed in the previous section, This thesis tackles the following research questions:

- How to develop a flexible SDR-based architecture for next-generation HetNets where users, irrespective of their operators, can utilize the LTE-LAA technique to dynamically benefit from available radio resources?
- How to exploit the spectrum-based traffic steering technique and renewable energy for the above-mentioned architecture to maximize its overall throughput and minimize its on-grid power consumption?
- In the same architecture, from user prospective, how to establish an energy-and-security-aware CR-based communication approach that alleviates the power consumption of the CR technique and enhances its security measures, while considering user-related factors, such as the users battery level and users data type, and network-related factors, such as vulnerability level and spectrum utilization?

2.4 Concluding Remarks

This chapter has presented a comprehensive survey of the most recent research studies that are focusing on HetNets and how to boost their performance. Additionally, it has summarized the prime contributions of those research studies and has discussed the research gaps in these studies. Moreover, the chapter has identified the key technologies/techniques (i.e. CR, LTE-LAA, SDR, and steering techniques) that hold enormous potential for improving the performance of next generation networks. Finally, based on these techniques/technologies research gaps, the chapter has identified and presented the research questions for the thesis. The following chapters introduce various SDR-based LTE-LAA approaches for next-generation communication networks that enhance the throughput and energy efficiency.

Chapter 3

An SDR-based Architecture for Next-Generation HetNets

Chapter 3 is not included in this version of the thesis.

Chapter 4

A Green Traffic Steering Solution for Next Generation HetNets

4.1 Introduction

In Chapter 3, a flexible SDR-based LTE-LAA HetNet architecture was proposed. The proposed architecture utilized the LTE-LAA along with SDR technology to maximize the throughput and minimize the overall power consumption of the network in HetNets. In this chapter, the green energy item is added to alleviate even further the on-grid power consumption. To maximize the benefit of both the green energy and the LTE-LAA, a green traffic steering solution is proposed in this chapter. The proposed steering solution is mainly used to steer users to BSs with an abundant green-energy supply and number of subcarriers.

In the proposed approach, the carrier aggregation via the SDR-based LTE-LAA technique allows operators to extend their usable frequency ranges to other available bands and provide users with more carriers for higher throughput. On the other hand, the available renewable energy is utilized to process the BSs load to ease the pressure on the grid and minimizes on-grid power. Moreover, in the proposed approach, the SDR technology allows users to be steered to nearby BSs, not only to their vendor's BS, which saves more power for BSs that have edge-users to serve.

Considering all the above-mentioned factors, the research question becomes how to steer traffic/users to available BSs so that maximum throughput and minimum BSs' power consumption can be achieved.

The major contributions of this work can be summarized as follows:

- This is the first work to utilize the spectrum-based cell zooming technique, green energy, the SDR, and the LTE-LAA concept all together to provide a green traffic-steering approach to maximize throughput and minimize energy consumption in an LTE-LAA network. The proposed cell zooming approach takes into account idle spectrum resources (licensed and unlicensed), application types and available green energy in various cells.
- The traffic steering problem is formulated as a constrained multi-objective optimization problem and provided optimum solutions. The objective is to minimize power consumption and maximize throughput. Due to the computational complexity of the optimization problem, an algorithm-based heuristic that achieves sub-optimum solutions has been developed and introduced in this chapter. This chapter also benchmarks the proposed solution against other existing solutions. The obtained results are promising.

4.2 The Proposed SDR-based LTE-LAA Green Architecture and its Resource Management Scheme

This section introduces a description of our spectrum-based traffic steering system model for a SDR-enabled heterogeneous network with hybrid energy supplies and unlicensed bands (i.e, LTE-LAA). This description consists of the network model, energy model, SDR-based BS communication model, and traffic model.

In this study, the prime aim is to minimize the network's on-grid power consumption along with maximizing overall network throughput. In order to achieve this goal, the number of SCBSs that need on-grid power to serve their users is minimized by steering their users to other SCBSs with abundant renewable energy using the spectrum-based

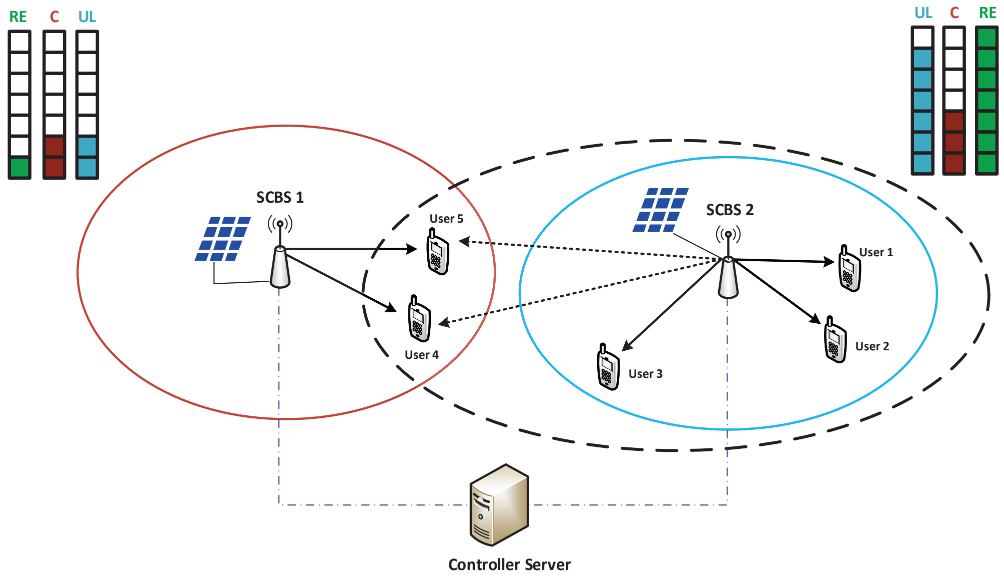


Fig. 4.1: A scenario for the proposed spectrum-based traffic offloading.

cell zooming technique. However, steering the users should occur towards BSs that can provide a higher number of carriers (i.e. throughput) for users to meet their traffic demands.

To illustrate even further, take the example shown in Fig. 4.1. The SCBS 1 has 1 unit of renewable energy (RE) and the power demand is 2 units to serve its users. Accordingly, the SCBS 1 needs to consume on-grid power to meet its demand and serve its users. Contrastingly, the SCBS 2 has 7 units of renewable energy and needs 3 units only to serve its users. Additionally, in terms of load capacity (C), SCBS 2 can still afford three more users and it has abundant carriers in the unlicensed band (UL) compared to SCBS 1. Hence, by exploiting LTE-LAA technology, it can offer more carriers (i.e. throughput) for its users. Thus, the controller server, which is updated with these details periodically, steers SCBS 1 users to SCBS 2 by using the spectrum-based cell zooming technique and switch SCBS 1 into sleep mode. This saves on-grid power consumption and provides users with a higher data rate which translates into higher throughput.

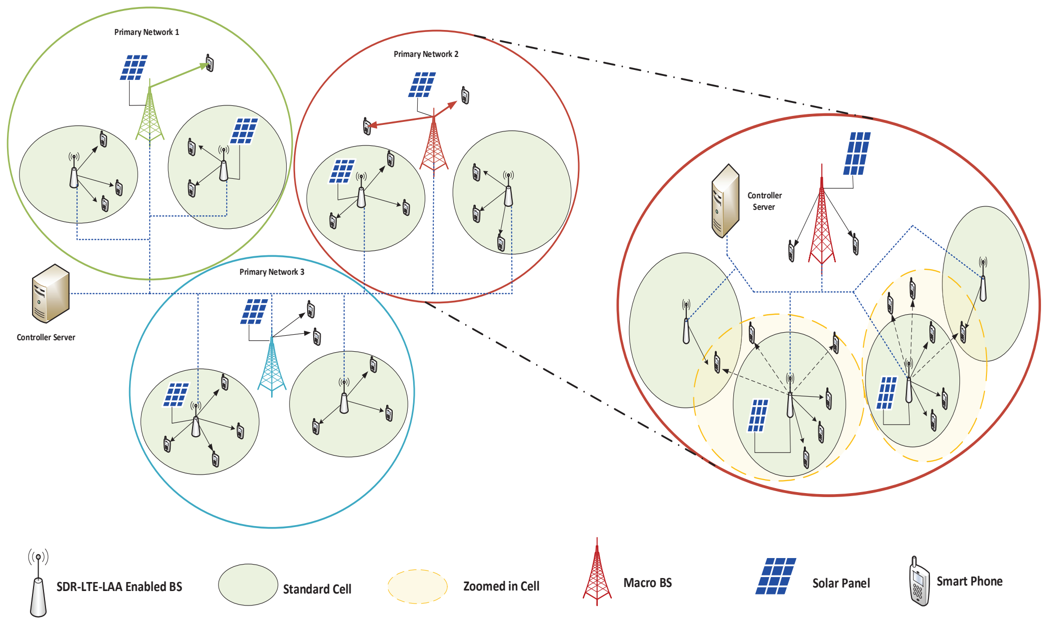


Fig. 4.2: The spectrum-based cell zooming system model with a controller server that is responsible for steering users load, via the spectrum-based cell zooming, between solar-powered Macro BSs and SDR-enabled small cells in the area to achieve the optimum performance.

4.2.1 Network Model

The network architecture of the proposed spectrum-based traffic steering system model is displayed in Fig. 4.2. The system is comprised of 3 macro base stations, multiple SDR-enabled small cell BSs (SCBSs), a controller sever, and a number of end users. The users' set is denote as $\mathcal{J} = \{J_1, J_2, J_3, \ldots, J_N\}$ indexed by j, and BSs' set is denoted as $\mathcal{I} = \mathcal{I}_1 \cup \mathcal{I}_2$ indexed by i, where $\mathcal{I}_1 = \{1, 2, 3 \ldots, m\}$ represents the set of Macro BSs and $\mathcal{I}_2 = \{1, 2, 3 \ldots, M\}$ represents the set of small cell BSs. In the proposed system model, the small cell BSs are SDR-enabled and support spectrum-based cell zooming and the LTE-LAA technique where the carrier aggregation concept is utilized to combine LTE carriers from both unlicensed and licensed spectrum [27]. In the system model, each MBS belongs to a different service provider.

The distribution of the small cell BSs around MBSs is in alignment with spatial Poisson Point Process (PPP) and at a density of ε_0, where ε_0 is the small cell BSs median number per unit area [154, 155]. Hence, the introduced system model presents a two-tier heterogeneous network where the SDR-enabled small cells are overlaid by the MBS.

4.2.2 Application Categories

Next-generation wireless networks are expected to serve a mixture of users with a diverse range of applications. Some of the applications (e.g., critical mission applications) can be adversely affected by traffic steering. In order to accommodate the application diversity, the proposed approach considers the following applications [170, 171]:

- **Category one:** this includes critical mission applications that are very time-sensitive and cannot afford any delay or error during transmission that might be caused during the steering process.
- **Category two:** this includes strictly inelastic applications, where no extra resources are required beyond a certain amount of data rate. For instance, a phone needs a certain minimum data rate to translate a telephone call over a network. Consequently, no additional data rate is used/required beyond this data rate. Hence, no extra radio resources are required.
- **Category three:** this includes strictly elastic applications, where these applications are not time-critical such as internet browsing, social networking, and email applications. These applications have no minimum data rate. However, additional resources given by the network give users a better quality of experience (QoE).
- **Category four:** this includes applications that have a minimum data rate and are based on video streaming, such as YouTube and video streaming applications. Unlike voice calls, an additional data rate provides greater enhancement and quality for these applications. For instance, instead of watching a poor quality movie, the user can stream the same movie with HD quality.

In this study, the users' applications are categorized using the application index ϱ^j. ϱ^j takes any value from 0 to 1 (i.e. $0 < \varrho^j \leq 1$), where 0 represents the critical mission applications (i.e., category 1) and 1 represents applications in category four.

4.2.3 Traffic-Steering and Sub-Carriers Aggregation Framework

This section provides a detailed description of how the proposed traffic-steering framework utilizes the SDR and aggregates sub-carriers from both licensed and unlicensed spectrums.

In the proposed traffic-steering framework, the SCBSs sweep the spectral environment regularly to generate and update three lists ($\mathcal{L}_0$, $\mathcal{L}_1$, and $\mathcal{L}_2$). $\mathcal{L}_0$ consists of idle/unused bands in the licensed spectrum. $\mathcal{L}_1$ consists of idle/unused bands in unlicensed spectrums in their area of coverage. $\mathcal{L}_2$ contains a list of channels occupied by their nearby users. Subsequently, SCBSs forward these lists along with their green energy reserves, user application categories, and traffic loads to the controller server, which is connected to all BSs through high-speed fiber cables as shown in Fig. 4.2.

Using $\mathcal{L}_0$, the controller server can estimate the total minimum throughput that each BS can provide. Using $\mathcal{L}_1$, the server can calculate the additional throughput that each BS can provide to its users through the unlicensed bands. $\mathcal{L}_2$ represents the potential traffic that can be steered toward the small cell BSs, using the spectrum-based cell zooming technique. Consequently, based on these details, the controller server steers users towards the SCBSs that have abundant green energy and a high number of unlicensed subcarriers, to minimize on-grid power consumption and provide higher throughput to users.

The controller server exploits $\mathcal{L}_0$ and $\mathcal{L}_1$ to accommodate user demands and conducts carrier aggregation (CA) for the LTE-LAA technique. According to the LTE-LAA standard [172], control information and signals are sent through the licensed band (i.e. through the radio resources in $\mathcal{L}_0$) and data flows through the unlicensed band (i.e. through the radio resources in $\mathcal{L}_1$). Hence, to maintain users' connectivity to the SCBS, the controller server allocates at least a single radio resource (i.e. carrier) from $\mathcal{L}_0$. However, when the controller server assigns radio resources (i.e. carriers) to users from $\mathcal{L}_1$, it attempts to optimize the utilization of available resources depending on the category of users' applications and user demands. Accordingly, the number of aggregated carriers that the controller server allocates to each user, from $\mathcal{L}_1$, differs from one user to another depending on the application index ϱ^j, which reflects the application category of user j.

In this context, SDR technology plays a key role in providing SCBSs with the ability and capability to regularly adjust their transmission parameters to be able to swap radio resources between their users to accommodate user needs. It is worth noting that the inter-cell interference is mitigated by the controller server when allocating subcarriers to BSs, via accurate frequency planning, where the server has a comprehensive knowledge of users and BSs locations.

Finally, based on the above-mentioned framework and received data from small cell BSs, the controller server can determine the best user-BS association combination that minimizes overall power consumption and maximizes overall network throughput. Accordingly, it generates Π that contains the optimum user-BS association matrix along with the number of users' allocated carriers and notifies the SDR-enabled BSs to act accordingly.

4.2.4 SDR-Based Base Stations Communication Model

The power of transmission for the BS i towards user j at location x is denoted as P_{ij}, and the channel gain between both of them as $g_{ij}(x)$. In general, antenna gain, shadowing, and path loss are included in $g_{ij}(x)$. σ^2 denotes the noise power. $\mathcal{B}_i$ represents the BSs' set that interfere with ith BS's transmission. $\mathcal{B}_z(x)$ is the average interference value detected by the user at location x from zth BS [173, 174]. Consequently, the signal to interference plus noise ratio (SINR) can be expressed as:

$$SINR_{ij}(x) = \frac{P_{ij} \cdot g_{ij}(x)}{\sum_{k \in \mathcal{B}_i} \mathcal{B}_z(x) + \sigma^2} \tag{4.1}$$

This study utilizes the highest throughput channel-state approach, in which the modulation and coding scheme (MCS) is adjustable according to the channel attenuation factor γ [156]. This approach guarantees the highest throughput by adapting the MCS in accordance with the SINR [157]. Consequently, the maximum achievable down-link data rate from the BS i toward user j at location x, based on channel condition, can be expressed as:

$$R_{ij}^{max}(x) = \frac{N_{ij}(x) \cdot R_w \cdot log_2(\Theta)}{T_{fr}} \tag{4.2}$$

where $N_{ij}(x)$ is expressed as:

$$N_{ij}(x) = (N_{ij}^{l}(x) + \varrho^{j} N_{ij}^{u}(x)) \cdot N_{symb} \cdot P_{fr}(x) \tag{4.3}$$

where $N_{ij}^{l}(x)$ and $N_{ij}^{u}(x)$ represents the total number of allocated licensed and unlicensed sub-carriers at location x, respectively, to the user j. ϱ^{j} represents the application category of user j. $\varrho^{j} N_{ij}^{u}(x)$ represents that portion of unlicensed sub-carriers allocated to user j based on his application category. N_{symb} is the total number of symbols, R_w denotes the code rate of the used MCS, Θ represents the modulation order, $P_{fr}(x)$ denotes the probability of receiving an error-free data block at location x, and the frame time duration is represented by T_{fr}.

Consequently, and according to Shannon theorem, when user j at location x is assigned to BS i, the allocated bandwidth can be calculated as follows;

$$W_{ij}(x) = \frac{R_{ij}^{max}(x)}{log_2(1 + SINR_{ij}(x))} \tag{4.4}$$

4.2.5 Traffic Model

Each user's traffic, from location x, is assumed to arrive at the BS i with an arrival rate of $\lambda_j(x)$ and in line with a Poisson Process. The traffic flow lengths have an average value of l_j. Accordingly, user j creates an average traffic density in BS i equals to

$$\delta_{ij}(x) = \lambda_j(x) \cdot \rho_i(x) \cdot X_{ij}(x) \tag{4.5}$$

where $\rho_(x)_i$ represents the service rate that BS i provides at location x and is expressed as:

$$\rho_i(x) = \frac{R_{ij}^{max}(x)}{l_j} \tag{4.6}$$

where X_{ij} is a binary decision-variable and takes a value as follows

$$X_{ij}(x) = \begin{cases} 1 & \text{if user } j \text{ is connected to BS } i \\ 0 & \text{otherwise} \end{cases} \tag{4.7}$$

By consolidating all traffic densities for all users who are connected to BS i and distributed across a coverage area of $\mathcal{A}$, the BS's traffic load density can be calculated. Hence, it can be expressed as

$$\Gamma_i = \int_{x \in \mathcal{A}} \delta_i(x)\, dx \tag{4.8}$$

The BS recognizes a sharing queue of type an M/G/1 process because the arrival rate of users' traffic λ_j is in accordance to the Poisson Process (PP) and traffic load service time for each user imitate the general distribution [164].

In such a sharing queue, the average service time for user j at location x can be calculated as [160]:

$$T_{ij}(x) = \frac{l_j}{R_{ij}^{max}(x) \cdot (1 - \Gamma_i)} \tag{4.9}$$

However, the throughput for each user is expressed as [159]:

$$R_{ij}^t(x) = R_{ij}^{max}(x) \cdot (1 - \Gamma_i) \tag{4.10}$$

where R_{ij}^t is the throughput of user j when it is connected to BS i. Accordingly, BS i's total throughput is calculated as:

$$\eta_i = \sum_{j \in J} R_{ij}^t(x) \tag{4.11}$$

4.2.6 Energy Model

In the spectrum-based cell zooming technique, utilizing SDR technology, BSs change their pilots' signal frequency every τ seconds to zoom in/out upon the controller server instruction over a period of time that consists of T updates. The controller server associates user j at location x to the BS i by requesting the BS to use its SDR capabilities to change their pilots signal strength which can be expressed, as per Friis transmission formula, as follows:

$$P_{ij}^{t}(x) = \frac{P_{ij}^{r}(x) \cdot (4 \cdot \pi \cdot d(x) \cdot F_{k,n}^{o})^2}{G_t \cdot G_r \cdot c^2} \tag{4.12}$$

where G_t, G_r, and c are the BS transmitter antenna gain, user equipment (UE) receiver antenna gain, and speed of light respectively. Distance between the BS and location x is $d(x)$. $F_{k,n}^{o}$ denotes the pilots signal's frequency at kth update. Let the pilot signal's power at kth update $\vec{P_k} = (p_{k,1}, p_{k,2}, p_{k,3} ... p_{k,M})$ correspond to pilot signal frequencies $\vec{F_k} = (f_{k,1}, f_{k,2}, f_{k,3} ... f_{i,M})$. Accordingly, the users-BSs assignment matrix at the kth update is determined by $\vec{P_k}$ as follows;

$$X_k(i,j) = \begin{cases} 1 & \text{if user } j \text{ is connected to BS } i \\ 0 & \text{otherwise} \end{cases} \tag{4.13}$$

Then, the power consumption of BS i at kth update can be formulated as

$$P_{k,i} = \sum_{j=1}^{N} X_k(j,i) \cdot P_{ij}^{t} + P_{k,i}^{fix} \cdot Y_{k,i} \tag{4.14}$$

where the BS's power consumption contains two parts: the dynamic power consumption presented by the first term and the static one $P_{k,i}^{fix}$ represents the amount of power that is required to maintain the BS active with no traffic being processed. $Y_{k,i}$ equals to 1 if at least one user is assigned to the BS i at kth update and 0 otherwise. Hence, it can be formulated as follows

$$Y_{k,i} = \begin{cases} 1 & \sum_{j=1}^{N} X_k(j,i) > 0 \\ 0 & \text{otherwise} \end{cases} \tag{4.15}$$

Assuming that the solar power stored amount at BS i at kth update is $S_{k,i}$. This amount depends on the amount of generated and consumed power in the previous update. Hence, $S_{k,i}$ can be expressed as

$$S_{k,i} = \begin{cases} S_{k-1,i} - P_{k-1,i} + \gamma & S_{k-1,i} \geq P_{k-1,i} \\ S_{k-1,i} + \gamma & \text{otherwise} \end{cases} \tag{4.16}$$

where γ is the solar power generated from the solar cell. By assuming $P_{0,i}$ as the initial value of solar power and the generation rate does not change over the duration T, then $P_i^{on-grid}$ can be expressed as

$$P_{k,i}^{on-grid} = \begin{cases} 0 & S_{k,i} \geq P_{k,i} \\ P_{k,i} & \text{otherwise} \end{cases} \tag{4.17}$$

4.2.7 Problem Formulation

As shown in Fig. 4.2, the BSs are equipped with hybrid power supplies (i.e., solar panels and public grid supplies). As a result of the spatial and temporal dynamics of solar energy generation between various BSs and the location of BSs, some BSs' power demands can be met by their renewable energy and others have to rely on the on-grid power supplies to process their traffic loads. Accordingly, to fully exploit the available renewable energy, users should always be steered to the BSs with abundant renewable energy. Hence, the BS i's on-grid power consumption can be formulated as:

$$P_{k,i}^{on-grid} = max(P_{k,i} - P_{k,i}^{r}, 0) \tag{4.18}$$

where P_i is the total power consumption, $P_i^{on-grid}$ and p_i^r represent the BS i's on-grid power consumption and solar energy generation rate, respectively.

In deciding user-BS associations, the steering scheme aims to achieve two key targets. Firstly, decreasing BSs' on-grid power consumption. Secondly, to boost the total throughput of the network. For the power part, users can be steered in a way that maximizes the utilization of BSs' available solar energy. For the throughput part, driven by the concept of carrier aggregation and the LTE-LAA technology, small cell BSs can allocate more sub-carriers, from the licensed and unlicensed spectrum, to users to boost their throughput and hence boost networks' overall throughput. Therefore, users should be steered to the BSs that have more sub-carriers.

Considering both of the above-mentioned targets, the steering decisions are based on the total throughput and total on-grid power consumption and hence can be formulated as a network utility as follows:

$$z = a \cdot \frac{1}{D} \cdot \sum_{k \in T} \sum_{i \in I} \sum_{j \in J} R_{ij}^{tk} - b \cdot \frac{1}{E} \cdot \sum_{k \in T} \sum_{i \in I} p_{k,i}^{on-grid} \tag{4.19}$$

where D and E are the normalization factors for throughput and power consumption, respectively. D represents the maximum achievable network throughput of the system as depicted in Fig.4.2. E represents the maximum total on-grid power consumption of the network. The first term in equation (4.19) represents the normalized network throughput and the second term represents the normalized on-grid power consumption. In the objective function, the coefficient associated with the normalized network throughput is represented by a while b represents the coefficient for the normalized on-grid power consumption. These coefficients are provided/adjusted by the network operator according to their operational requirements. A higher value of a allows users to be associated with SCBSs with more available carriers whereas a higher value of b allows users to be associated with SCBSs with abundant green energy.

Accordingly, the steering objective function z is written as follows:

$$\text{maximize } z \tag{4.20}$$

subject to

$$\sum_{i=1}^{I} X_{ij} \leq 1, \qquad \forall j \in \mathcal{J} \tag{4.21a}$$

$$\sum_{i=1}^{I} P_i^r \geq P_i^{th}, \qquad \forall i \in \mathcal{I} \tag{4.21b}$$

$$P_{k,i} \leq P_{i_{max}}, \qquad \forall k \in \mathcal{T}; \forall i \in \mathcal{I} \tag{4.21c}$$

$$X_{ij} \cdot SINR_{ij} \geq SINR_{ijmin}, \qquad \forall j \in \mathcal{J} \tag{4.21d}$$

$$\sum_{j=1}^{J} R_{ij}^t \leq \eta_i \qquad \forall i \in \mathcal{I} \tag{4.21e}$$

$$0 < \varrho^j \leq 1 \qquad \forall j \in \mathcal{J} \tag{4.21f}$$

$$0 < \sum_{j=1}^{J} \varrho^j \cdot N_{ij}^u \leq \Upsilon^i \qquad \forall i \in \mathcal{I} \tag{4.21g}$$

where,

- Eq. (4.21a) ensures that a user can only be allocated to only one BS.
- Eq. (4.21b) ensures that only BSs who have available solar energy amount over a specific threshold should be allowed to receive the steered users and process their traffic loads.
- Eq. (4.21c) expresses that, at any time k, BS transmit power needed to steer any user must not exceed the maximum transmission power, $P_{i_{max}}$, that BS i can afford based on its available power supplies to maintain stable communication.
- Eq. (4.21d) ensures that SINR recognized by each user is higher than a threshold, $SINR_{ij_{min}}$, for better seamless communication between users and BS.
- Eq. (4.21e) ensures that total traffic loads at BS i is less than or equal to the total BS capacity (η_i).
- Eq. (4.21f) ensures that users with critical mission applications are excluded from the steering procedures.
- Eq. (4.21g) ensures that the number of allocated unlicensed-carriers to a user does not exceed the available unlicensed carriers at each BS.

Here,

$$X = \begin{pmatrix} X_{1,1} & X_{1,2} & X_{1,3} & \dots & X_{1,M} \\ X_{2,1} & X_{2,2} & X_{2,3} & \dots & X_{2,M} \\ X_{3,1} & X_{3,2} & X_{3,3} & \dots & X_{3,M} \\ \vdots & \vdots & \vdots & \ddots & \\ X_{N,1} & X_{N,2} & X_{N,3} & \dots\dots & X_{N,M} \end{pmatrix} \tag{4.22}$$

The above-mentioned optimization problem was solved using the IBM CPLEX software. The proposed approach is detailed in **Algorithm 1**. Driven by the time complexity to solve the problem of optimization, eq.4.19, in real-time, particularly for networks that cover great areas with an enormous number of BS and users, the following section prove that it is an NP-hard problem and propose a heuristic solution.

lemma: Optimization problem number (4.19) can be considered as NP hard problem

Proof: Assuming that two BSs are located at a specific point and the capacity of each BS is infinity with SINR threshold equal to zero. Thus, all users can be steered to any of them without violating any constraint. Additionally, if solar energy generation rate is the same for each of them, let's assume it equals to G, and the required network power to process the traffic equals to the solar energy, then the problem can be expressed as:

$$min \sum_{i=1}^{2} max(P_i - G, 0) \tag{4.23}$$

subject to

$$\sum_{i=1}^{2} P_i = 2G \tag{4.24}$$

Hence, the optimal solution for the above-mentioned optimization problem, which minimizes the power consummation of the on-grid type, is to allocate loads into both of the BSs equally. In other words, it becomes a partition problem, which is considered as an NP-hard problem [164]. Accordingly, this optimization problem is an NP-Hard one.

4.2.8 Heuristic Solution

In order to alleviate the computational complexity of the optimal solution, this section presents a heuristic-based algorithm. The proposed algorithm considers both on-grid power consumption and overall network throughput. Accordingly, the user's utility can be formulated as follows:

$$z_{ij} = a \cdot \frac{1}{D} \cdot R_{ij}^{t} - b \cdot \frac{1}{E} \cdot p_{ki}^{on-grid} \tag{4.25}$$

The controller sever, which has an overview regarding all BSs and their status in terms of traffic loads, solar energy generation rate, and available size of unlicensed/licensed spectrum, executes Algorithm 4 in order to steer the traffic loads to BSs with high renewable energy generation rate and more unlicensed/licensed spectrum availability to be able to maximize the overall network throughput and minimize network on-grid power consumption.

As shown in **Algorithm 4**, the proposed algorithm begins with a preliminary users-BSs association matrix, a flag F equals to zero, and all users are set to be members of a group $j^{'}$ named unmarked. Subsequently, the proposed algorithm iteratively adapts the association matrix to reduce the network's consumption of the on-grid power via steering traffic loads to BSs with abundant solar energy and higher available bandwidth (i.e. BS with a high number of licensed and unlicensed sub-carriers).

During each iteration, the proposed algorithm locates the BS with the highest on-grid power consumption i^{*}. Thereafter, the algorithm finds, within BS i^{*}, the unmarked user that requires the highest transmission power to be serviced j^{*} and steer the user to a new BS that can serve the user using less on-grid power and yet increase the overall network utility. In case a BS is found, the algorithm allocates the user to that BS and starts the new iteration. Alternatively, it marks the user and starts the new iteration until all users are marked and then it terminates.

Algorithm 5 tries to locate the best BS for user j^{*}. Thus, the algorithm finds the BSs that surround user j^{*}, and sort them in descending order in terms of their utility. Thereafter, the algorithm checks them in order. If a BS is found, the user is allocated to it and the algorithm updates the matrix. The last step is to mark the BS to avoid the computational complexity problem.

Algorithm 6 checks the suitability of the new BS. Hence, the algorithm checks if the total on-grid power consumption, after connecting the user to the new BS, is less than the current one or not. If yes, is the overall new network utility is higher than the current one or not. If yes, then the BS is a suitable one. Otherwise, the algorithm locates the unmarked users in the new BS and checks if they can be re-allocated to another BS to alleviate the traffic load in this BS. Hence, there is a better chance for the user j^{*} to be assigned to the BS.

Algorithm 4 SDR-based approach

1: **Initialise** a preliminary users-BSs association matrix
2: **Set** $J^{'} = \{j|j \in J\}$; unmark all users
3: **Set** $F = 0$;
4: **while** $J^{'} \neq \phi$ **do**
5:     Find $i^{*} = argmax_{i \in I}(P_i - G_i)$;BS with max $P^{on-grid}$;
6:     In this BS, find user $j^{*} = argmax_{j \in J, i^{*} \in I}(P_{ij})$;
7:     $(\hat{\Pi}, F) =$ *find_better_bs* (j^{*}, Π, z_t);
8:     **if** $F == 1$ **then**
9:         $\Pi = \hat{\Pi}$;
10:         Jump to step 5;
11:     **else**
12:         Move user to final group x;
13:         **if** $J^{'} \neq \emptyset$ **then**
14:             Jump to step 5;
15:         **else**
16:             Terminate
17:         **end if**
18:     **end if**
19: **end while**
20: **return** Π

Algorithm 5 $(\hat{\Pi}, F) =$ *check_better_bs* (j^{*}, Π, z_t)

1: Set $z_{min} = z_t$;
2: Set F=0
3: Find $I_{j^{*}}$ for user j^{*} where $I_{j^{*}} = \{i|z_{ij} > z_{min}, i \in I^{'}\}$
4: Sort $I_{j^{*}}$ in descending order
5: **for** i = 1: $I_{j^{*}}$ **do**
6:     $(\bar{\Pi}, F) =$ *suitability_check* (i^{*}, Π, z_t);
7:     **if** F==1 **then**
8:         Allocate j^{*} to i^{*}
9:         $\hat{\Pi} = \bar{\Pi}$
10:     **end if**
11:     Mark BS
12: **end for**

Algorithm 6 $(\hat{\Pi}, F) =$ *suitability_check* (i^*, Π, z_t);

Set F=0
if $P^{grid}_{new} < P^{grid}_{current}$ **then**
  if $z^{new}_t > z^{current}_t$ **then**
    $\hat{\Pi} = \Pi$
  end if
else
  Find $J_i = \{j | z_{ij} < z_{min}, i \in I^{'}\}$
  for n= $1 : J_i$ **do**
    if $\varphi_i - \varepsilon_{in} < \varphi_{max}$ **then**
      find_better_bs (j^*, Π, z_t)
    end if
    if F=1 **then**
      $\hat{\Pi} = \bar{\Pi}$
    end if
  end for
end if

4.2.9 Computational Complexity Analysis

This section investigates the computational complexity of the proposed heuristic. In **Algorithm 4**, the algorithm starts with a preliminary users-BSs association, a flag F equals to zero, and all users are set to be members of a group $j^{'}$ named unmarked. Then, the algorithm finds the BS with the highest $P^{on-grid}$ from the M BSs, and in this BS i^*, the algorithm needs to find the user j^*, from N/M users connected to this BS, that requires max transmission power to be serviced. Hence, computational complexity, up to this stage, is $O(M + (N/M))$. Consequently, using **Algorithm 5** and **Algorithm 6**, this user is steered to a new BS that can serve him using less on-grid power and yet increases the overall network utility to meet the objective function.

As mentioned previously, **Algorithm 5** tries to locate the best BS for user j^*, and the algorithm has one finding procedure, one sorting procedure, and one for-loop procedure. However, it uses other procedures in **Algorithm 6** to check the suitability of the new BS. **Algorithm 6** has one finding procedure and one for solution. Hence, the computational complexity of both **Algorithm 5** and **Algorithm 6** can be expressed as $O(2M + MlogM)$ and $O(N^2)$, respectively.

Finally, assuming that the heuristic searches all users and BSs in the worst case scenario, the complexity of the whole heuristic can be expressed as $O(N^3M^2Log(N+M))$, where M represents the BSs number and N represents the users number. Accordingly, our heuristic algorithm is the type of pesudo polynomial time algorithm.

4.3 Simulation Results and Discussion

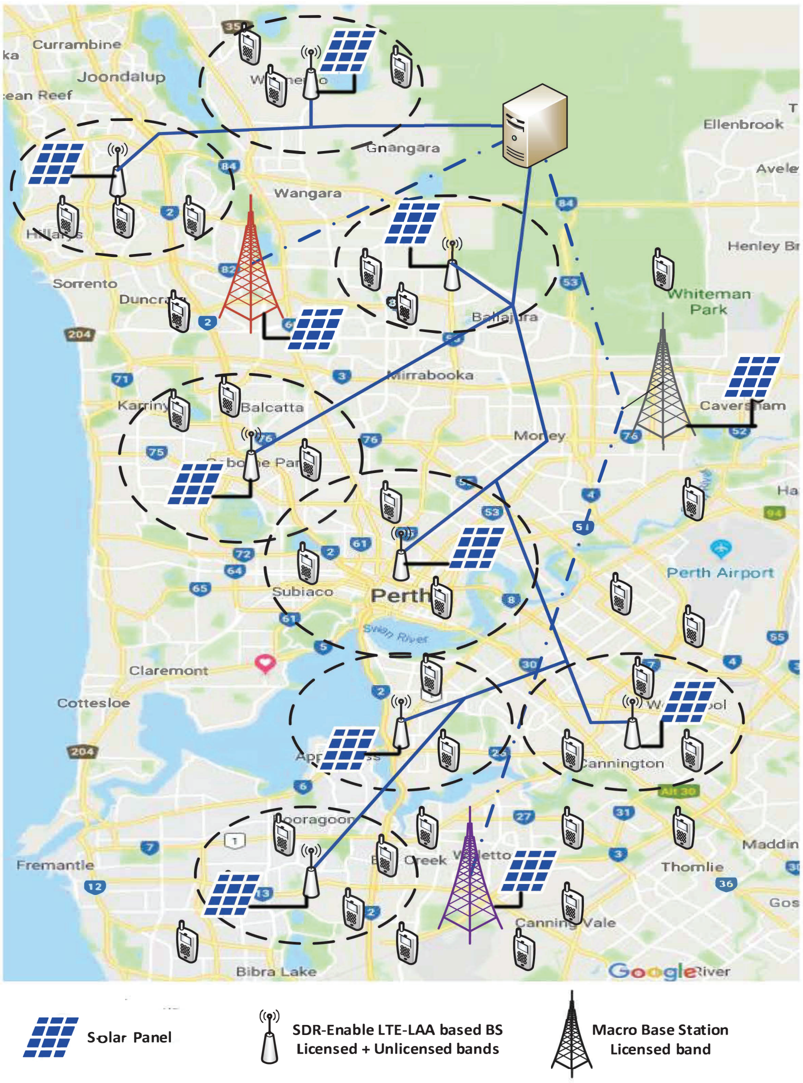


Fig. 4.3: Hypothetical SDR-based system deployment - Perth, Western Australia.

Table 4.1: Parameters used in the simulation of the proposed green traffic steering solution.

Parameter's name	Value
Frequency of the Carrier [163]	1900 MHz
Bandwidth of the Channel [163]	10 MHz
Transmission Power of Macro BS [163]	20 W
Transmission Power of SCBS [164]	5 W
Static Power of Macro BS [164]	500 W
Static Power of SCBS [164]	80 W
Number of Licensed Carriers per SCBS [164]	5:10
Number of Unlicensed Carriers per SCBS[165]	10:25
Application Categories [165]	1:4
Max generation rate of solar energy [165]	174 W/mˆ2
MBS solar panel size [165]	4.6 mˆ2
SCBS solar panel size [167]	0.7 : 2.8 mˆ2
Average flow length [167]	200 KB
Path Loss Model [167]	COST 231 Walfish-Ikegami
Allocation of The Spectrum	Partitioned [167]
Transmitter Gain [167]	1 dB
Receiver Sensitivity [167]	-97 dBm
Noise Power Level [167]	-104 dBm

To benchmark the proposed approach, a hypothetical deployment was implemented, shown in Fig. 4.3, which shows the system model in the business district area of Perth. The hypothetical deployment was implemented in Matlab R2015b with the simulation parameters listed in Table 4.1. Comparisons were made between the proposed approach and best SINR user-BS association approach, named as Best-SINR [161], and also with load aware users-BS association approach proposed in [162]. In the best SINR approach, users are allocated to the BSs with the strongest SINR. In the load-aware approach, users are allocated to lightly loaded BSs.

As shown in Fig. 4.3, the simulation model consists of 3 macro BSs and 8 SDR-enabled BSs. The macro BSs have a radius of 1000m and SDR-enabled BSs have a radius of 200m[69]. In the simulation model, all SDR-enabled BSs (i.e., small cells) have a circular shape coverage, and are uniformly distributed across the coverage area. All BSs allocate/distribute the resource blocks of a component carrier (CC) equally across CC's users [167, 175]. The users' arrival was presumed to follow the Poisson Process [164]. Additionally, the COST 231 Walfisch Ikegami [176] was adopted as the propagation model with 5 dB shadowing fading and 9 dB Raleigh fading [177]. Moreover, it was presumed a standard condition for the weather with a temperature of 24 °C and an air mass of 1.5 [177].

In the simulation, the green-energy generation rate depended on the size of BSs' solar panels, listed in Table 4.1. Furthermore, all BSs were assumed to be equipped with a Radio Remote Head (RRH) unit attached to their antenna via fiber optic link to produce zero feeder loss. The controller server had a comprehensive knowledge of users and BS locations and is responsible for allocating subcarriers to cells via adequate frequency planning to mitigate the inter-cell interference challenge [4, 60, 164]. Thus, the interference between all BSs and the inter-cell interference were well controlled/managed by the controller server. In the simulation, the coefficients associated with the network throughput and power consumption in the objective function of the optimization model were set as one (i.e, unbiased).

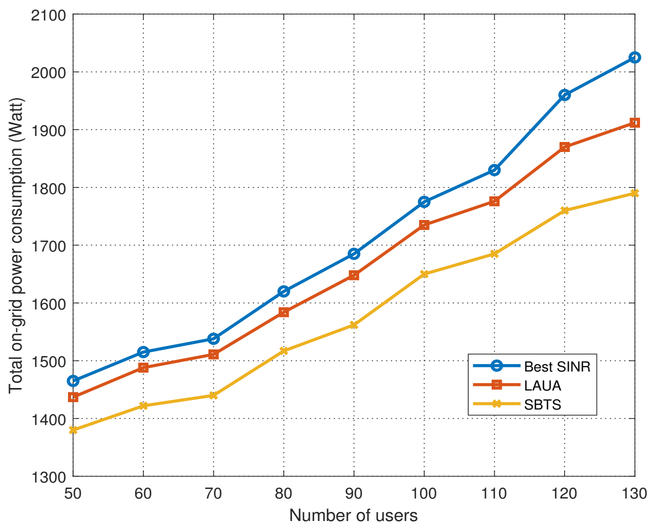


Fig. 4.4: On-grid power consumption.

Fig. 4.4 shows a comparison between the proposed approach SBTS and the other approaches (i.e. LAUA and Best SINR) in terms of total network on-grid power consumption and user numbers influence on it. The vertical axis in Fig. 4.4 shows the

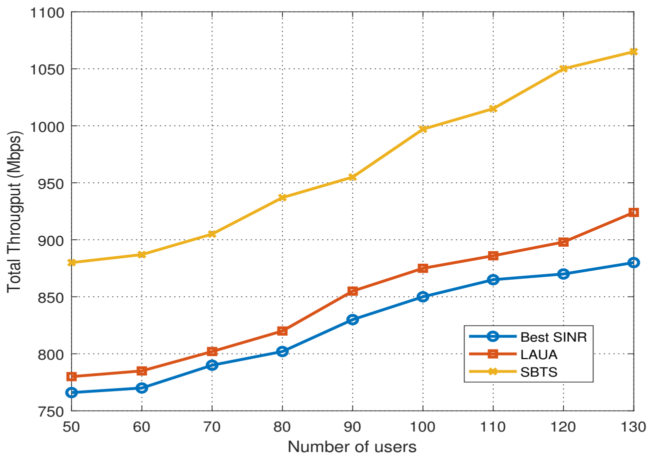


Fig. 4.5: Total network throughput.

instantaneous power consumption that is required to accommodate the varying number of corresponding users presented along the X-axis. Based on the results shown in Fig. 4.4, it is evident that the proposed approach required less on-grid power compared to the other two approaches. This occurs because, as the number of users grows, the proposed approach always aims to alleviate on-grid power consumption by steering users from overloaded BSs toward BSs that have abundant solar energy to optimize the usage of existing green-energy resources. However, unlike the proposed approach, the Best SINR approach and the LAUA approach associate users to BSs that have pilot signals with the best SINR, irrespective of the amount of green-energy available at these BSs. This results in a situation where some BSs become overloaded with users, where green-energy alone cannot power these BSs, hence more on-grid power is required.

Fig. 4.5 compares the total network throughput of the three different approaches (i.e. the proposed approach, Best SINR, LAUA) with a different number of users. From Fig. 4.5, it is evident that the proposed approach presents a higher total network throughput. Due to the utilization of carrier aggregation concept, the SDR-LTE-LAA-enabled BSs can allocate sub-carriers to users from both licensed and unlicensed bands (i.e., more resource blocks). As a result, the proposed approach steers users towards BSs that have a higher number of sub-carriers in order to optimize the usage of available sub-carrier resources in the network. This leads to more resource blocks allocation per user and this maximizes user throughput. However, in the other two approaches, users are either allocated to the BS that has the highest SINR or to those that are lightly loaded, irrespective of the available number of sub-carriers. This leads to some BSs becoming congested with users which degrades user throughputs at these BSs.

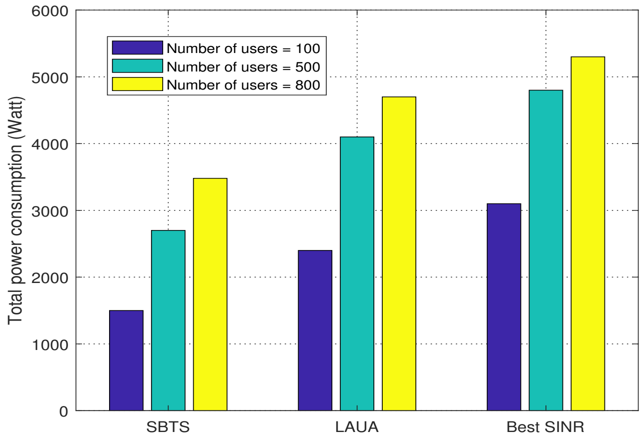


Fig. 4.6: Total power consumption.

Fig. 4.6 compares the total power consumption in the three approaches accounting for a different number of users. It is apparent, in the figure, that the proposed approach consumes less power, compared to the other approaches, whilst serving the same number of users. In other words, from Fig. 4.6, it is evident that the proposed approach is more energy-efficient than the other approaches. This power reduction happens because the proposed approach, in meeting its objective function (i.e. Eq 4.19), tends to steer users towards SDR-LTE-LAA enabled BSs which consume less power, compared to Macro BSs. It also provides higher throughput owing to the LTE-LAA technology. Thus, in the proposed approach, the majority of users are served by low-power SDR-LTE-LAA enabled BSs. On the other hand, the other approaches tend to allocate users to BSs with the highest SINR, which in many cases are Macro BSs. This results in more users being served by high-power Macro BSs. Hence, less total power is consumed in our approach.

Fig. 4.7 shows the total on-grid power consumption under different green energy generation rates. The figure also compares on-grid power consumption in the case where users are assigned to BSs based on the best SINR approach, load of the BS, and the proposed approach. From Fig. 4.7, it is evident that, for all approaches, increasing green energy generation rate decreases on-grid power consumption because BSs can now rely

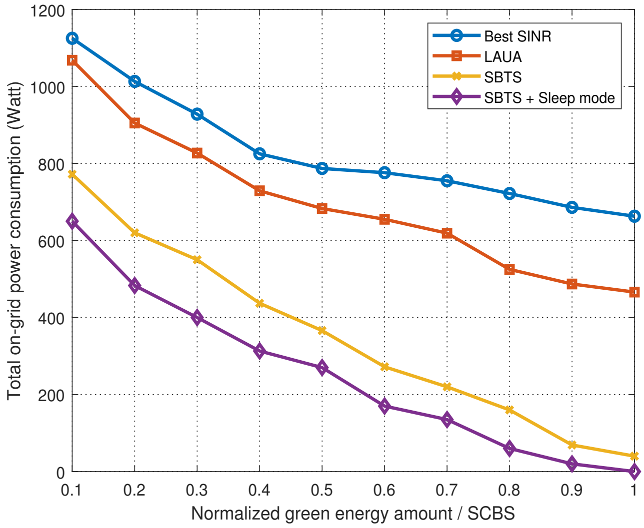


Fig. 4.7: Total on-grid power consumption with different green energy rate.

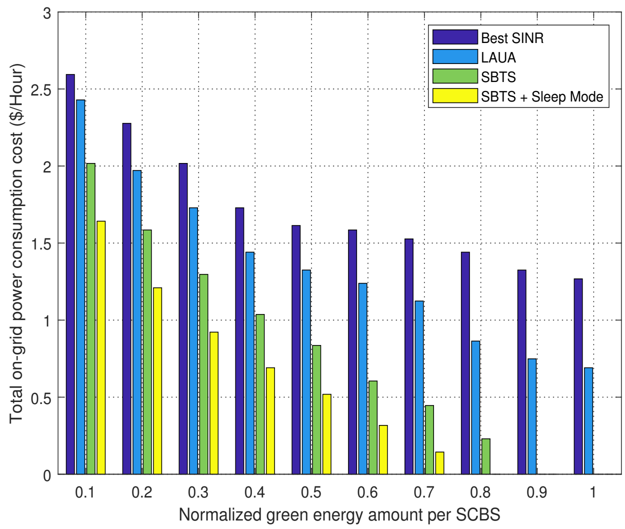


Fig. 4.8: Total on-grid power consumption costs with different green energy rate.

more on green energy to process their traffic loads. However, unlike the best SINR and load aware approach, the proposed approach offers lower on-grid power consumption, as it steers users in a way that can balance user loads between BSs according to BSs' available green energy amounts. This leads to less on-grid power consumption. Moreover, in case of utilizing the sleep mode, in which BSs without any loads are put into sleep

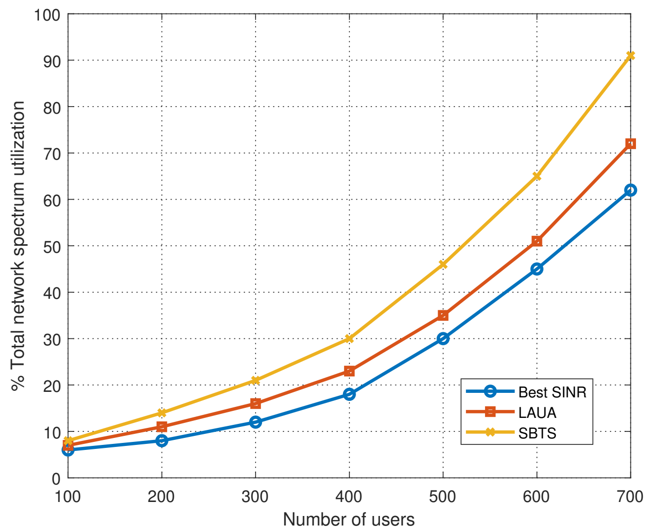


Fig. 4.9: Overall network's allocated-spectrum utilization.

mode, the amount of on-grid power will be even lower.

Fig. 4.8 illustrates the total on-grid power consumption costs per hour under different green energy generation rates and compares the cost values of the three different approaches. It is worth noting that the 1 kilowatt-hour (kWh) cost is 28.8229 cent, as per Perth's electricity company, Synergy [178]. As shown in Fig. 4.8, the proposed approach costs less compared to the other two approaches as the proposed approach tends to steer users towards the SCBSs with a larger amount of green energy to minimize on-grid power consumption. However, the other two approaches tend to allocate users to BSs with the strongest SINR or their traffic load, irrespective of the BSs' green energy available amounts. This proves that the proposed approach can reduce the operators' $OPEX$ by alleviating the network's on-grid power.

Fig. 4.9 presents a comparison of the overall utilization of the network's allocated spectrum with a different number of users. From Fig. 4.9, it is evident that the proposed approach increases the utilization of the network's allocated spectrum. Due to the utilization of the proposed traffic steering technique, users are offloaded to those BSs with unused spectrums and abundant green energy available. This balances the users' loads between BSs and increases the overall utilization of the network's spectrum. Unlike the proposed approach, other approaches (i.e. load-aware and best SINR) allocate users to the BS that have either a lighter load or best SINR. This results in some BSs becoming overloaded and other BSs having no loads at all. This has severe implications on network spectrum utilization.

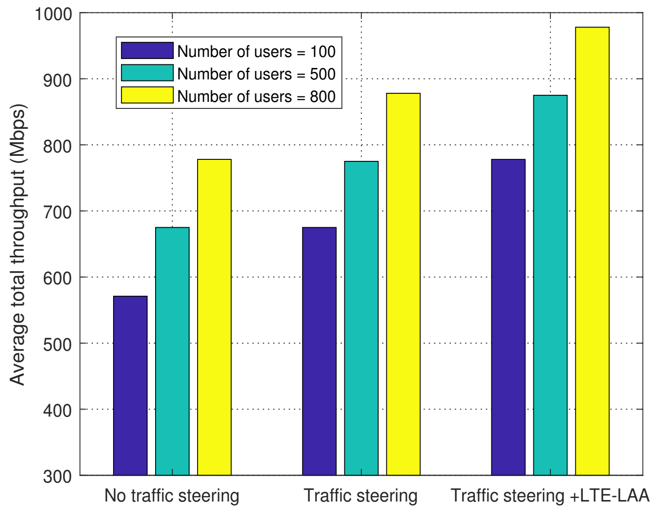


Fig. 4.10: Average overall network throughput.

In order to benchmark the benefit of utilizing the traffic steering concept and LTE-LAA technology, the average overall network throughput was measured for the network under different strategies: No traffic steering, with traffic steering, and with traffic steering plus LTE-LAA. Fig. 4.10 shows the obtained results for these scenarios with different numbers of users. Based on the results in Fig. 4.10, it is apparent that utilizing traffic steering along with LTE-LAA technology maximizes the overall network throughput. This is because the proposed traffic steering approach steers the users to BSs with a high number of available sub-carriers for higher throughput and the LTE-LAA adds even more carriers from the unlicensed band to increase user throughput even more by extending the sub-carriers frequency range to the unlicensed bands.

Fig. 4.11 displays the impact of unlicensed carriers' availability on the average power consumption per macro BS (MBS). Additionally, it shows this impact under a different number of small cell BS (SCBS) per Macro BS (i.e. 2, 4, 6). From Fig. 4.11, it is evident that increasing the number of sub-carriers in the unlicensed band at small cell BSs, has a genuine impact on power consumption per macro base station. High unlicensed band

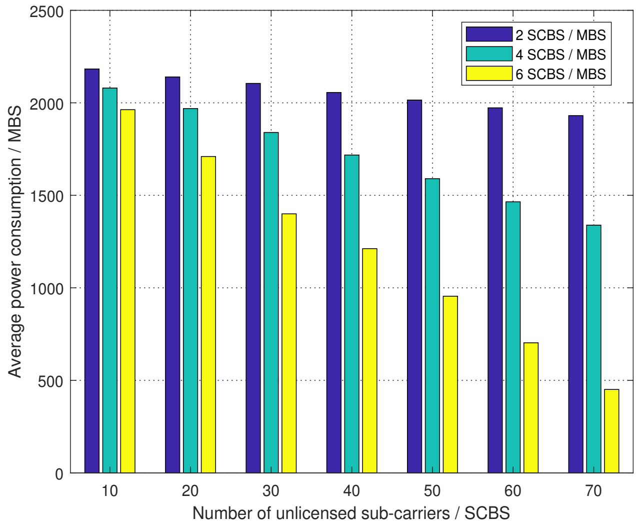


Fig. 4.11: The impact of unlicensed carriers availability on the macro BS's power consumption.

availability means more sub-carriers can be utilized in this band and hence more sub-carriers are allocatable to users. Thus, the proposed algorithm steers users toward these SCBSs instead of Macro BSs leading in less load at the MBS and consequently less power consumption. Further, as shown in Fig. 4.11, increasing the number of SCBSs, decreases the MB's power consumption. This occurs because increasing the number of SCBSs, increases the number of options that the proposed algorithm can steer users to owing to their LTE-LAA and SDR operability, SCBSs can provide users with a larger number of carriers. Thus, the proposed algorithm always tends to steer users away from the MBS and towards SCBSs. This alleviates, even more, the load on MBSs and saves their power.

Fig. 4.12 presents the impact of the number of small cell BSs per Macro BS on the utilization of the network's allocated-spectrum. Additionally, it presents a comparison of this impact under three different scenarios: no traffic steering, with traffic steering, and with traffic steering plus LTE-LAA. From Fig. 4.12, owing to the configuration flexibility of the SDR-enabled BSs, it is apparent that increasing the number of SDR-enabled BSs per macro BS increases the utilization of the allocated network spectrum. This occurs because the controller server can detect which bands are not used and re-allocate them to the SCBSs which adapt accordingly, using SDR technology. Moreover, Fig. 4.12

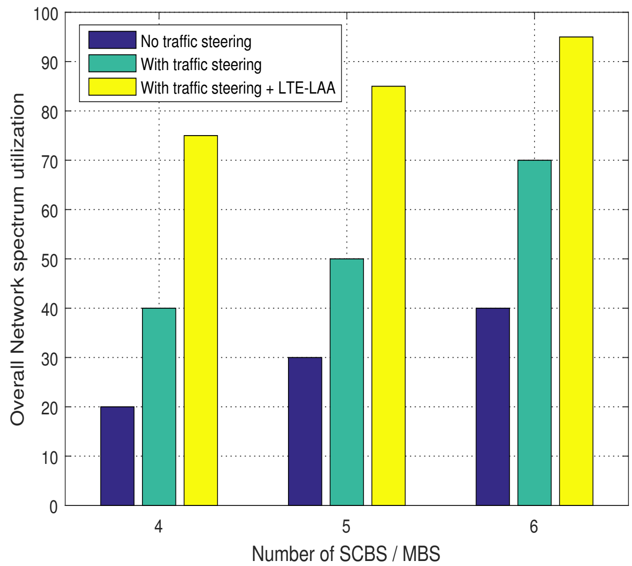


Fig. 4.12: The impact of number of SCBS per MBS on the network spectrum utilization.

shows that this utilization percentage increases by using the proposed traffic steering algorithm along with the LTE-LAA technology. the proposed traffic steering algorithm balances the user loads between BSs and the LTE-LAA technology allows BSs, using carriers aggregation concept, to exploit all idle bands in the allocated licensed spectrum along with the unlicensed spectrum.

Fig. 4.13 presents the impact of the number of small cell BSs per Macro BS on the saved amount of on-grid power per macro BS. Additionally, it presents a comparison of this impact in three different scenarios: no traffic steering, with traffic steering, and with traffic steering plus LTE-LAA. From Fig. 4.13, it is evident that increasing the number of SDR-enabled BSs per macro BS increases saved on-grid power per MBS. This happens because the controller server can detect which bands users are using while communicating with MBS and re-allocate them to the SCBSs, exploiting their SDR capabilities, and steers users, leaving MBSs, to these SCBSs which already consume less power than MBS. Hence, having more SCBSs means more users are steered to them and steered away from MBSs. Thus, more on-grid power is saved per MBS.

In addition, Fig. 4.13 shows a comparison of the impact on this amount of saved power in case of using the proposed traffic steering algorithm along with the LTE-LAA

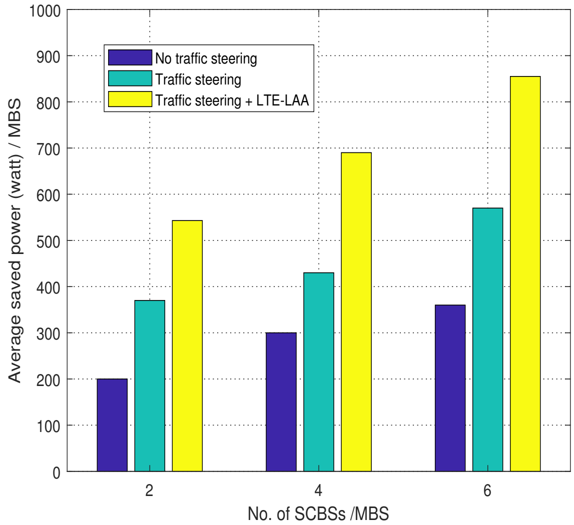


Fig. 4.13: The impact of number of SCBS per MBS on the saved on-grid power per Macro BS.

technology and in case of not using it. From Fig. 4.13, it is evident that the proposed traffic steering algorithm saves more power. This is because the proposed approach balances user loads between the BSs according to their solar energy amount and the LTE-LAA technology allows the BSs, using carriers aggregation concept, to exploit all idle bands in the allocated licensed spectrum along with the unlicensed spectrum.

In this study, the impact of changing users' application categories on total power consumption and total throughput was investigated. Fig. 4.14 and Fig. 4.15 show this impact, respectively. Additionally, while the total number of users is set at 100, the two figures compare this impact using the proposed approach and the other two approaches (i.e. LAUA and best SINR).

In the two figures, Fig. 4.14 and Fig. 4.15, Category 2 Apps represents inelastic applications (e.g., voice calls). Category 3 Apps represent applications that have no minimum data rate requirement, but higher data rates provide a better quality of experience for these applications, for example, internet browsing, social networking, and email applications. Category 4 Apps represent data-hungry applications that require a minimum data rate to ensure the quality of service (e.g., Youtube, Video streaming).

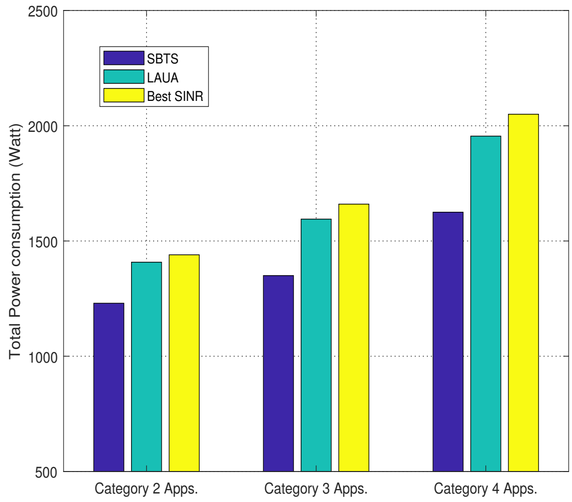


Fig. 4.14: Application categories impact on total power consumption.

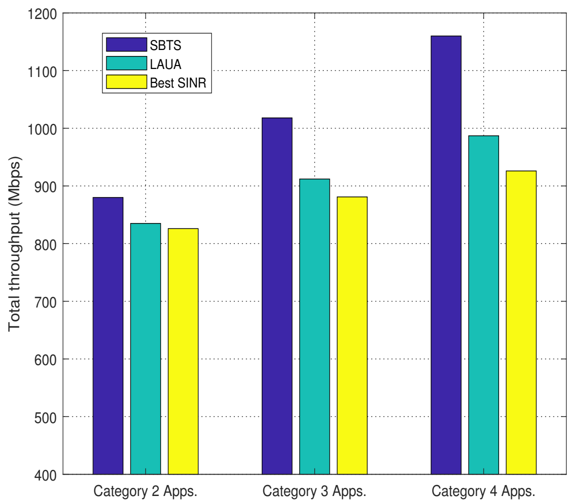


Fig. 4.15: Application categories impact on total throughput.

From Fig. 4.14, it is evident that the proposed approach consumes less power compared to these other approaches. This occurs because as the proposed approach steers users to SCBSs it can provide the optimum number of carriers according to user's application categories, whilst alleviating on-grid power consumption by steering users from overloaded BSs toward BSs that have abundant solar energy to optimize the usage of existing green-energy resources. Unlike the proposed approach, the Best SINR approach and the LAUA approach disregard the green-energy factor and simply steer users to BSs that have the best SINR, which leads to some BSs becoming overloaded with users and requiring more power to serve users.

From Fig. 4.15, it is evident that the proposed approach achieves higher throughput compared to the other approaches. This occurs in the proposed approach as the controller server tends to steer users to BSs that can offer more carriers to their users. However, unlike the proposed approach, the other approaches tend to steer users to BSs with higher SINR, irrespective of the number of available carriers at these stations. This results in less throughput compared to the proposed approach. In addition, it is noticeable from Fig. 4.15 that the proposed approach provides higher throughput for category 3 applications, compared to the other approaches. This is because the proposed approach, unlike the other approaches, provides a higher number of carriers for these typed of data-hungry applications.

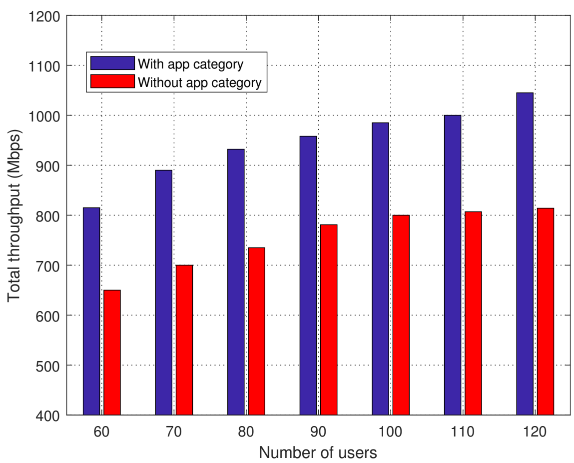
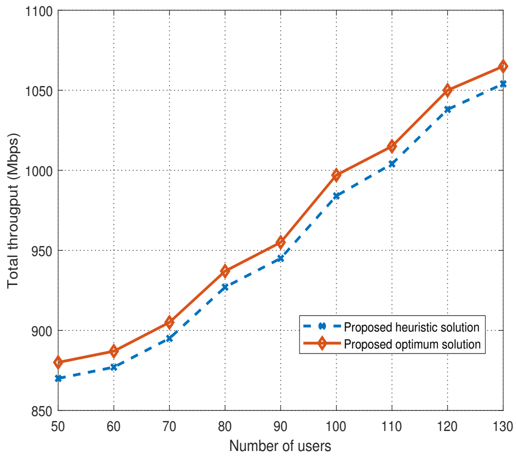
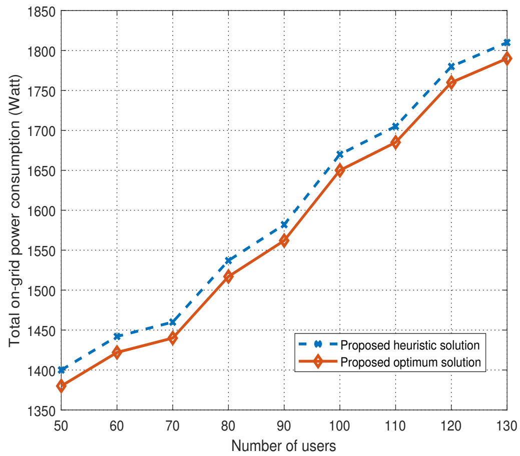


Fig. 4.16: Performance with and without considering different application categories data requirements

The performance of the proposed approach without considering the different application categories, as discussed in the sub-section 4.2.2, was also investigated. Fig. 4.16 shows that when the traffic steering process is influenced by the category an application belongs to, the total throughput of the system increases. This occurs because classifying applications into various categories in the proposed model tends to steer users requiring higher data rates to BSs that have a higher number of carriers, which ultimately leads to higher throughput.



(a) Throughput.



(b) On-grid Power Consumption.

Fig. 4.17: Heuristic simulation results: a) a data rate comparison between the optimum results and the proposed heuristic results b) a power consumption comparison between the optimum results and the proposed heuristic results.

Figures 4.17a and 4.17b present a comparison between the proposed heuristic and the ILP solution, generated using CPLEX, in terms of overall network throughput and total power consumption. The maximum achievable throughput with several numbers of users is presented in Fig. 4.5. Based on the results in Fig. 4.17a, it is apparent that the proposed heuristic provides marginally lower throughput than ILP with a difference within the range of 5% to 7% and accuracy up to 93%. Accordingly, it can be used to attain near-optimal results. Fig.4.17b illustrates the total power consumption with various number of users. Based on the results in Fig. 4.17b, it is notable that the proposed heuristic consumes slightly higher power than the ILP with a difference within the range of 4.5% to 8% and accuracy up to 92%. Hence, the proposed heuristic can be exploited to attain near-optimal results.

A summary of the research work findings is listed in Table 4.2. Moreover, it presents a comparison between the proposed approach and other approaches. As shown in Table 4.2, the proposed SDR-enabled and spectrum-based approach consumes lower power,

Table 4.2: Summary of the findings.

User-BS Association Strategy	Total On-grid Power Consumption (Watt)	Total Through-put (Mbps)	Allocated Spectrum Utilization (%)
Best SINR [161]	2025	870	61
LAUA [162]	1929	955	72
Proposed SDR-LTE-LAA	1725	1070	94

by up to 15%, compared with the other approaches. Furthermore, the proposed LTE-LAA-supported approach achieves higher throughput for users and, hence, for the whole network, by up to 23%.

Owing to the carrier aggregation concept and the proposed spectrum-based traffic steering mechanism, the proposed approach is able to aggregate more carriers, from different bands, and allocate them to users to achieve higher throughput. Following such a strategy increases the utilization of the allocated network spectrum and allows the SDR-enabled BSs, with the help of the controller server, to exploit idle bands of idle BSs. Accordingly, unlike the other approaches, Table 4.2 shows that the proposed approach has the highest spectrum utilization.

During the process of performance evaluation for the proposed approach, the impact of utilizing SDR and LTE-LAA technologies on overall system performance in terms of power consumption and total throughput was checked as well. As shown in Table 4.2 the utilization of unlicensed bans increases the total throughput and allows the proposed algorithm to steer users to the SCBSs, leaving Macro BSs, for higher throughput and less Macro BSs power consumption.

4.4 Concluding Remarks

This chapter, exploiting the spectrum-based cell zooming technique for traffic steering, has presented a flexible SDR-based architecture for HetNets. The proposed architecture has utilized green energy and LTE-LAA along with SDR technology to promptly adapt to ever-changing network dynamics to minimize the total grid power consumption and maximize user throughput. The relevant resource management problem has been formulated as a constrained optimization problem. The solution was found to surpass other current approaches by considerable margins. As illustrated in Table 4.2, the presented approach has consumed up to 15% less power. Additionally, it also has provided up to 23% higher throughput compared with the other approaches. Moreover, in terms of allocated spectrum utilization, the proposed approach has achieved higher utilization than others. Furthermore, the chapter has shown that the problem of optimization is an NP-hard, and to reduce the time complexity, a heuristic solution has been introduced that was found to achieve a good near-optimal solution.

Although adopting a heuristic approach offers a quick and low complex solution, it often is not able to provide the optimal solution. However, it can provide a sub-optimal solution. Such an approach has been adopted in various recent research studies as covered in the literature review chapter.

Although the proposed solution, in this chapter, has achieved higher spectrum utilization, better throughput, and less on-grid power consumption, it requires a high level of processing capacity and adaptability to process the huge number of variables and keep the whole network up and running in an efficient manner. These associated processes can be shifted towards the wireless-enabled device itself, using a different communication approach named Cognitive Radio (CR). The following chapter introduces a CR-based communication approach that lets the wireless-enabled device decides which BS would suitable for it based on multiple factors.

Chapter 5

A Secure and Energy-Aware Approach For Cognitive Radio Communications

5.1 Introduction

In the previous chapter, a green traffic solution for next generation HetNets was proposed. The main aim of the proposed solution was to steer users to the BSs that have an abundant supply of renewable energy and subcarriers to alleviate the on-grid power consumption and increase the overall throughput of the network and its spectrum utilization. This chapter introduces another communication approach that can alleviate the spectrum scarcity problem and also minimizes the BSs power consumption. This communication approach is based on what is named as the Cognitive Radio technique.

The cognitive radio (CR) technique has revealed a novel way of utilizing the precious radio spectrum via allowing unlicensed users (also called secondary users) to opportunistically access unutilized licensed bands. Using such a technique enables agile and flexible access to the radio spectrum and can resolve the spectrum-scarcity problem and maximize spectrum efficiency. However, two major impediments have been limiting the widespread adoption of CR technology. The SDR technology, which is the enabling technology for the CR technique, is power-hungry and this raises a major concern for

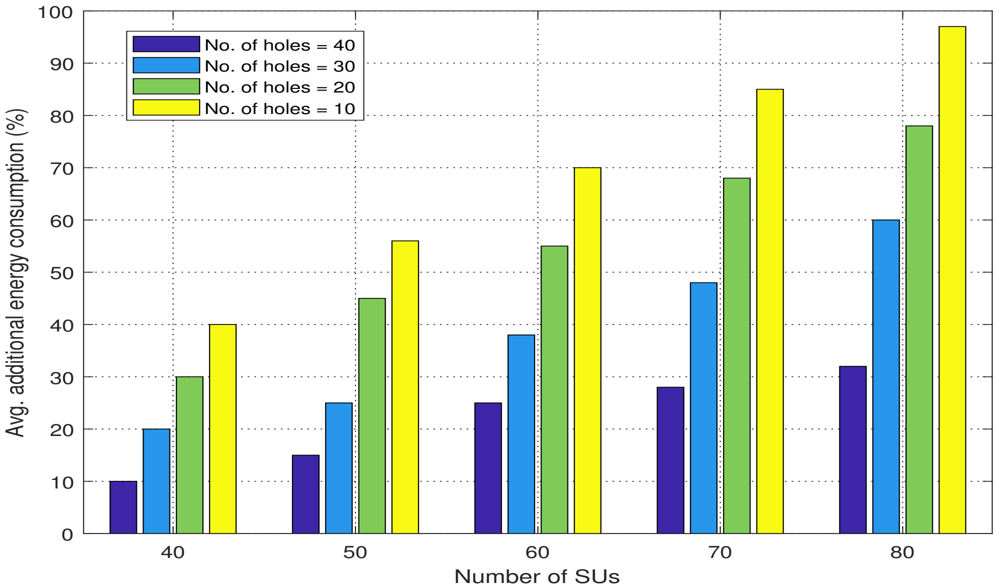


Fig. 5.1: The influence of increasing the number of contending SUs on total consumed power

battery-constrained devices. Secondly, the opportunistic and open nature of the CR can lead to major security concerns about the data being sent and how safe it is.

Accordingly, for battery-constrained devices such as laptops and smart phones, the costs associated with the additional power consumption and security risks of the cognitive radio technique can be overwhelming[133, 179, 180]. For instance, for a CR-enabled user (i.e. a SU) whose device's battery level is low and has non-critical data to send, the magnitude of the benefit that the CR technique offers can be easily overwhelmed by the cost associated with rapid battery depletion due to CR's power-hungry procedures. The same thing applies when a user has critical data to send and the CR technique picks a network that is vulnerable to security attacks.

Given the above-mentioned power and security related costs associated with the CR technique, not all SUs would benefit equally from the CR technique. Additionally, as shown in Fig. 5.1 and in literature [180–182], the more SUs compete for free/idle bands, the more power they would all consume to send their data. Consequently, the research question becomes- how to select/short-list secondary users to participate in the cognitive radio process so that their overall benefits can be maximized and corresponding costs in relation to power and security remain low.

This chapter addresses the above-mentioned challenge by introducing an energy-and-security-aware CR-based communication approach that alleviates the power consumption of the CR technique and enhances its security measures according to the confidentiality level of the data being sent. Furthermore, the proposed approach takes into account user-related factors, such as the users battery level and users data type, and network-related factors, such as the number of unutilized bands and vulnerability level to maximize the benefits of CR-enabled users.

The main idea is based on restricting the CR participation process to secondary users (SUs) who would achieve the highest benefit in return for their extra power consumption and security risks. By adopting such an approach, the number of SUs who would contend for unutilized/idle bands is kept at a reasonable level to maintain high benefits for all participants.

The major contributions of this work can be summarized as follows:

- This is the first CR-based communication approach that considers both reducing total power consumption and increasing the security of the CR-based transmission to increase the overall benefit of CR-enabled SUs while considering all the parameters listed in Table 5.1.

- The SUs association problem is formulated as a constrained multi-objective optimization problem. The objective is to minimize the cost and maximize the benefit. Due to the computational complexity of the optimization problem, an algorithm-based heuristic that achieves sub-optimum solutions has been developed and introduced in this chapter. The proposed solution was benchmarked against other existing solutions. The obtained results are promising.

Table 5.1: Key differences of our proposed approach

Parameters Considered	Authors in [91–96]	Authors in [183–188]	Authors in [35, 97–99]	Proposed approach
Number of SUs	-	-	-	✓
Traffic size	✓	-	✓	✓
Traffic type	-	✓	-	✓
Total Power consumption	✓	-	✓	✓
Total throughput Or blocking probability	✓	✓	-	✓
Safe transmission	-	✓	-	✓
SU's battery-level	-	-	-	✓

5.2 Proposed Secure-Green Cognitive Radio Model

This section offers a description of the system model, shown in Fig. 5.2, that is utilized in the energy and security-aware CR approach. This description covers the network model, communication model, benefit model, power model, and the vulnerability model.

The main aim of this work is to maximize the total benefit, in terms of total throughput of all users, while minimizing total costs, in terms of users' power consumption. To accomplish this, the number of SUs contending for free/idle bands in a spectrum should be restricted since increasing the amount/number of contention leads to higher average power consumption. The shortlisted SUs should be carefully/optimally chosen in order to maximize the benefit and minimize power costs without compromising data confidentiality.

To illustrate, even further, take an example of the secondary user 1 (SU1) in the three scenarios illustrated in Fig. 5.3. In all scenarios, SU1 has a full load of data (D), a very sensitive/confidential type of data (S), and the same number of free bands.

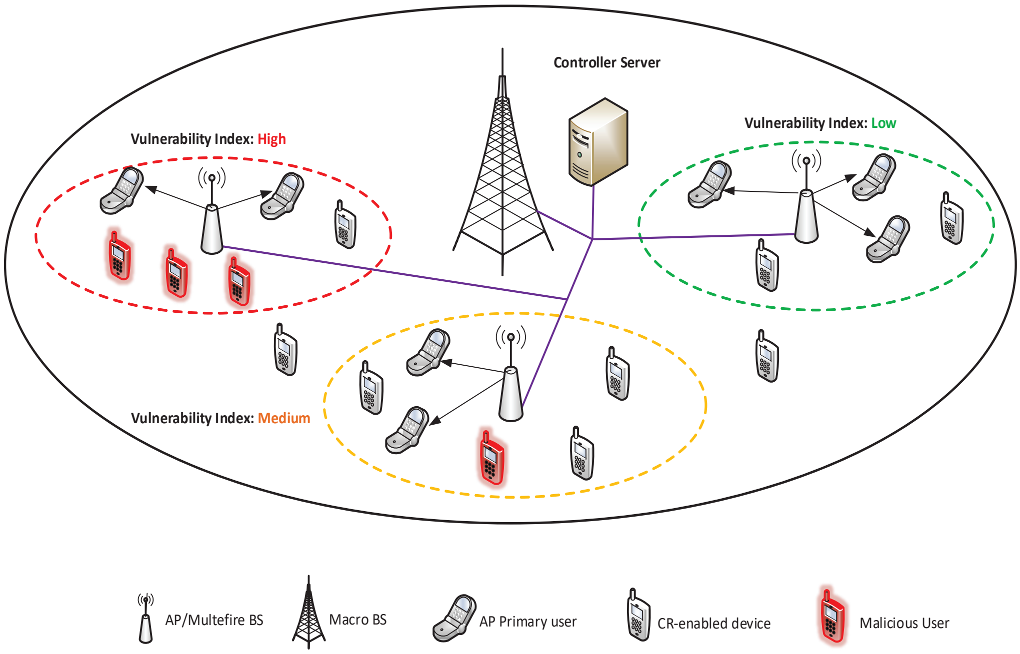


Fig. 5.2: System Model

However, the differences between the three scenarios are the battery level (BL) of SU1, the number of competing SUs, and the vulnerability level of the accessed spectrum. In scenario (a), SU1 is only competing with another single SU and SU1 has a decent battery level. Accordingly, for SU1, the cost required for the CR approach is considerably low because of the low contention level and the high level of battery affordability. Hence, in such a scenario, allowing SU1 to utilize the free bands, via the CR technique, can translate into higher benefits in terms of higher data rate and throughput.

Compared to scenario (a), the number of competing SUs in scenario (b) is much higher and the SU1's battery level is even lower. Hence, for the SU1 and compared to scenario (a), the required cost to participate in the CR technique is higher and the amount of benefit, in terms of higher data rate and throughput, is less than scenario (a). For scenario (c), SU1 has a critical battery level, a higher number of SUs competing on free bands, and some of these SUs are malicious users representing a high vulnerability level. Thus, compared to scenarios (a) and (b), SU1's cost is significantly higher in this scenario. Additionally, the amount of benefit is much less and is very vulnerable.

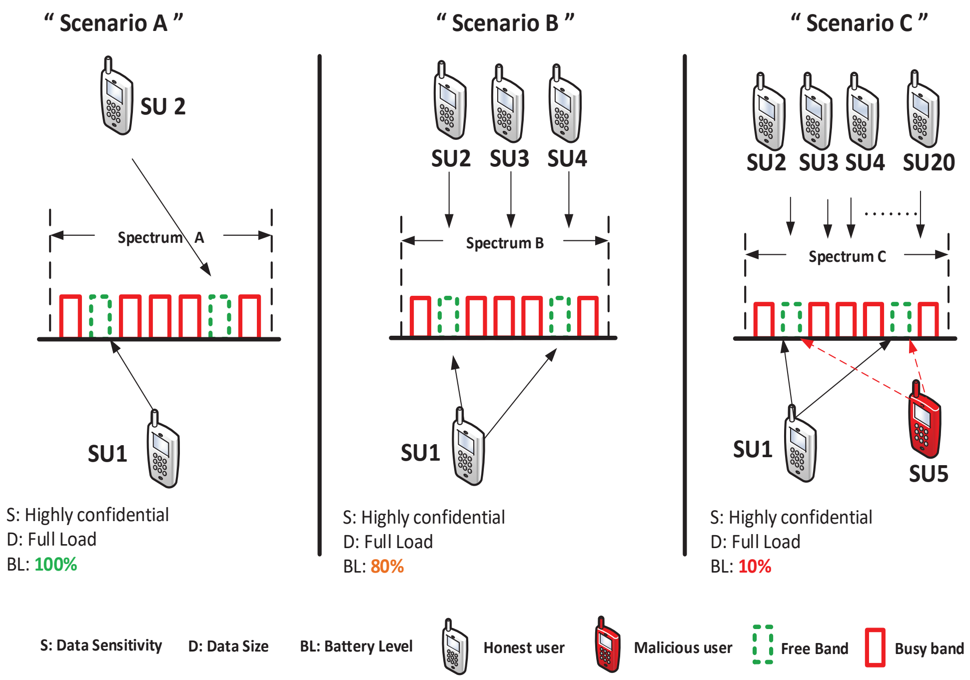


Fig. 5.3: Different Cognitive Radio Scenarios

Based on the above-mentioned scenarios, the CR technique is not for everyone and not for every situation. Hence, the proposed approach restricts the CR techniques in communication to shortlisted SUs. These chosen SUs are optimally chosen to maximize the total benefits of the shortlisted SUs and minimize their costs.

5.2.1 Network Model

The network model of the proposed approach is illustrated in Fig. 5.2. The system model is comprised of a macro base station, multiple access points with their primary users connected to them, a controller sever, and several end-users that are equipped with cognitive-radio-enabled (CR-enabled) devices and primarily connected to the macro BS (MBS). In the model, all the access points (APs) are operating in the unlicensed band (i.e 5 GHz). However, some of these APs use the IEEE 802.11 standard (WiFi technology) [189] which is the main incumbent technology in the unlicensed band[31, 190] and the rest of these APs are utilizing MultiFire technology which is a standalone Long-Term

Evolution (LTE) in the unlicensed band. The technical specifications of this radio access technique, named MultiFire, were finalized and published in mid of 2017 [191, 192].

Furthermore, as shown in Fig. 5.2, the controller sever is connected to the APs and the MBS. It regularly gathers information from the APs and MBS about their free/used bands, traffic loads, the number of connected users, and connection costs. Additionally, it collects from the users, through the MBS, their battery levels, data rate requirements, and confidentiality requirements. Subsequently, according to the obtained information and the APs' vulnerability indexes that the server has, the controller server selects/short-lists which users should participate in the CR procedures and which AP to be associated with. Consequently, the controller server informs the short-listed users, through the MBS, about the most suitable AP for them and instructs them to use their CR capabilities to access it.

Such a network model can practically exist/utilized where a mobile operator has a MBS that covers a users-dense area, such as a city business district (CBD) that has a mall, a train station, a library, and various multi-storey office buildings. This area already has various types of APs, from a security perspective, that also managed by the same mobile operator. The types of APs range from open access AP, similar to the WiFi APs in malls nowadays, through password-protected APs, to MultiFire APs that utilize high-security measures to protect their users.

Owing to the high number of users being served, increasing users' demand for extra data, and the limited licensed band, the MBS cannot meet all the users' demands. Hence, the MBS, with the controller server's support, select/short-list some of its connected users to access nearby APs by utilizing their CR abilities.

The process of pairing users with APs should consider the users' data confidentiality and APs vulnerability level and its impact on users' data. Additionally, it should consider the existing load if the APs, because, as previously explained, more users translates to higher power consumption, which is not appreciated for battery constrained devices. Accordingly, the users are shortlisted so that their overall CR benefits can be maximized and corresponding costs in relation to power and security remain low.

The users set is denoted as $\mathcal{J} = \{J_1, J_2, J_3, \ldots, J_N\}$ indexed by j. In the system model, the users' CR-enabled devices are all portable and wireless-enabled. The battery level of the jth user is represented by B_j where $0 < B_j \leq 1$ and 0 represents an empty battery and 1 means a fully charged battery. For user j, the data size and confidentiality are expressed as D_j and μ_j, respectively, and $0 \leq \mu_j \leq 1$ where 0 means the data is not confidential and can be shared and 1 means it is strictly confidential. Additionally, in the system model, the users' data sizes and confidentiality are not related or dependant on each other.

It worth highlighting that the users are utilizing the overlay CR access strategy, where SUs perform spectrum-sensing and send the data during the absence of the primary occupant/user. When the PU is active gain, the SU needs to refrain from using this band and find another band [17, 193, 194]. Such an access strategy requires no cooperation with the PU and offers flexible control and higher data rate compared to the underlay access strategy, in which both SU and primary user (PU) can use the same band at the same time, however, the interference caused by the SU must not exceed a tolerable threshold [195], which requires cooperation with the PU and high level of complexity to maintain the interference level with PU under a certain level [194, 195].

The APs' set is denoted as $\mathcal{I} = \{I_1, I_2, I_3 \ldots, I_M\}$ indexed by i and each AP has a number of free/idle bands that secondary users can utilize to send their data denoted by F_i and with a bandwidth of W_i. These access points are offering these bands for CR access for a monetary reward of C_{ij}.

5.2.2 Security and Risk Factor

The probability of a security breach (sniffing, spoofing, eavesdropping, .., etc) to occur at AP i is presented by the vulnerability index Φ_i where $0 < \Phi_i \leq 1$. 0 represents a 100% safe/non-vulnerable AP, which does not exist, and 1 represents an extremely vulnerable AP. The vulnerability here is presented by the probability of having malicious user/users within the AP coverage area that can make the AP prone to a security breach (sniffing, spoofing, eavesdropping, ..etc)[196]. Hence, the risk factor that is recognized by user j at AP i can be expressed as:

$$\zeta_{ij} = \frac{\mu_j}{\Phi_i} \tag{5.1}$$

accordingly, when user j has high confidential data and is accessing a very vulnerable AP i, the user will recognize a high value of ζ_{ij}, high-risk factor, and vice versa.

In the system model, since the MBS works only in the licensed band, serves only licensed users, authenticates its users by their valid subscriber identification module (SIM), and utilizes various encryption keys to secure its communication with its users [197], then its vulnerability index is the lowest. Subsequently, although the AP with MultiFire technology authenticates its users via their SIM cards, it works completely in the unlicensed band, which is a band that is accessible by an extremely wide range of users and technologies. This makes it more vulnerable to security attacks than the MBS. Hence, the AP with MultiFire technology has a slightly higher vulnerability level than MBS [192].

For the APs that use the IEEE 802.11 standard (WiFi technology) [189], they all work in the unlicensed band and they all allow any WiFi-enabled user, irrespective of their intention, to get connected. Some of these APs are password-protected where only users who know the predefined password can be granted access, and the rest are open (i.e. not password-protected) for the public use, such as the APs in train stations, airports, and malls.

Since the WiFi APs utilize a password-based security measure to control the users' accessibility, the WiFi APs' vulnerability level is much higher than the MultiFire AP and MBS. The reason for this is, as previously mentioned, the MultiFire AP and MBS utilize multiple extensive security measures including a hardware-based security measure (i.e. SIM cards) and extensive encryption to authenticate and secure their communications with their users [197]. However, in the case of WiFi APs, a limited software-based security measure (i.e. password) is utilized, which makes them much more prone to security breaches [31].

Accordingly, on the system model, the vulnerability index of the password-protected WiFi AP is much higher than MultiFire AP and MBS, and the vulnerability index of the public WiFi APs is even higher.

In order to quantify the suitability of a CR-enabled device/user j to access AP i with its battery status B_j, with a risk factor ζ_{ij}, we introduce another factor named the suitability factor that can be calculated as:

$$\daleth_{ij} = \frac{B_j}{\zeta_{ij}} \tag{5.2}$$

thus, for a device with a battery level B_j to be able to use its CR ability, he needs to pick an AP with low ζ_{ij} to increase its suitability for the CR process.

5.2.3 Communication Model

In this study, it is assumed that users' positions are fixed/static during an iteration. However, their positions may change in the next one. The transmission power of AP i is represented as P_i and the channel gain from AP i to user j as g_{ij}, which typically includes shadowing, path loss, antenna gain, and reflects the slow fading [169]. Furthermore, it is presumed that the channel gain is calculated at a large time scale, compared to the change of the channel, thus fast fading is not considered. Such an assumption has been adopted in previous works such as [98, 139, 169]. The noise power level is denoted as σ^2.

In addition, it was presumed that each user encounters a near static interference from interfering APs and other users. Although interference varies according to the network dynamics, it can be well controlled via various frequency domain techniques, time domain techniques, and power control techniques [169]. Accordingly, the interference could be modeled as a static value to simplify the analytical model [169]. Such an approach has been adopted in previous words such as [98, 169, 198].

Accordingly, let $\mathcal{B}_i$ denotes the set of all the interfering APs, whose transmissions interfere with the transmission of i^{th} AP with the user j across all bands. Similarly, $\mathcal{A}_j$ represents the set of all the interfering users whose transmissions interfere with the transmission of j^{th} user with the AP i across all bands. $\mathcal{B}_v^i$ and $\mathcal{A}_o^j$ are the average interference recognized by user j from v^{th} AP and o^{th} user, respectively [173].

Accordingly, the signal to interference plus noise ratio (SINR) of an AP i toward user j can be expressed as;

$$SINR_{ij} = \frac{P_j \cdot g_{ij}}{\sum_{v \in \mathcal{B}_i} \mathcal{B}_v^i + \sum_{o \in \mathcal{A}_j} \mathcal{A}_o^j + \sigma^2} \tag{5.3}$$

hence, the data rate R_{ij} of user j as AP i can be derived as a logarithmic function according to Shannon theorem as follows;

$$R_{ij} = F_{ij} \cdot W_i \cdot Log(1 + SINR_{ij}) \tag{5.4}$$

where F_{ij} and W_i represent the number of free/idle bands allocated to user j and the size of each band at ith AP, respectively. It worth highlighting that a user can use multiple bands, if his hardware is capable to do this. This has been used to add more flexibility to our mathematical model.

5.2.4 Benefit Model

To quantify the benefit of user j from using the CR technique to access the idle bands of AP i, the cost per bit at this AP is calculated, C_{ij}, and compared with the cost per bit at the macro BS, C_m. Hence, the amount of benefit that can be achieved by the user j is the difference between the two prices. Thus, the benefit/saving can be expressed as follows:

$$\mathfrak{S}_{ij} = R_{ij} \cdot (C_m - C_{ij}) \tag{5.5}$$

Owing to users' inconsistency of demands and activity patterns, each AP has variable demands and different amounts of available resources to offer during the day (e.g., peak vs off-peak hours). Hence, C_{ij} is not a standard fixed price for all APs, and it changes according to the APs' instantaneous-load level. The price/cost increases when the AP's load increases and vice versa. Such an approach protects the AP from being overwhelmed by the SUs request and being overloaded with SUs.

In this research work, a linear pricing model has been adopted, where the AP increases the price/cost of accessibility when the number of SUs associated with it increases and decreases the price when the number of SUs decreases. Hence, the pricing model identifies the price/cost for a service depending on its traffic demands and available supplies. Accordingly, C_{ij} can be expressed as[199]:

$$C_{ij} = \hat{a} \cdot \mathfrak{R}_{ij} + C_i \tag{5.6}$$

where C_i denotes the base/standard price of AP i, $\hat{a}$ represents the slop of the price/demand curve, and $\mathfrak{R}_{ij}$ denotes the ratio between the number of SUs associated with the AP, including user j and the number of free/idle bands at this AP. Hence, $\mathfrak{R}_{ij}$ can be calculated as follows:

$$\mathfrak{R}_{ij} = \frac{\hat{N}_{ij}}{F_i} \tag{5.7}$$

where $\hat{N}_{ij}$ presents the total number of SUs associated to SUs, including user j, and F_i denotes the total number of free/idle bands.

5.2.5 Power Model

For the user j, the total power consumed to send data using the CR technique includes the consumed power to scan the spectrum to search for idle bands, to switch between idle bands, and to transmit data through these bands. The power to send data can be expressed as [181, 200]:

$$P_j^{pkt} = P_j^{tr} + \frac{p_k}{1 - p_k} \cdot P_j^{co} + H(p_k) \cdot P_j^{bck} \tag{5.8}$$

where P_j^{pkt} is the consumed power to send a single packet by user j, P_j^{tr} represents the transmission power for the same user, p_k expresses probability for collision with k contending users, P_j^{co} denotes the power consumed by user j during collision, P_j^{bck} denotes the consumed power at back-off state, and $H(p_k)$ is the number of counted bands before the packet of data is actually sent. It presents the anticipated number of bands that need to be checked for availability before the packet is actually sent. $H(p_k)$ was derived and analyzed in [181, 201] as;

$$H(p_k) = \gamma \cdot \frac{(1 - p_k) - p_k \cdot (2 \cdot p_k)^{\omega}}{1 - 2p_k} - 1 \tag{5.9}$$

where γ represents the initial back-off contention window size in the AP that can be set by the AP and shared with the users and controller server to be able to process the proposed algorithm. ω represents the number of times that the back-off window can be extended before reaching the maximum. In this study, a scanning technique where the user j scans all the idle bands in AP i first and then selects the one for which the contention is lesser by a pre-determined threshold β was adopted. Accordingly, the total scanning power can be formulated as:

$$P_{ij}^{sc} = (F_i - 1) \cdot [P_j^{scb} + P_j^{sw}] + \rho_{ij} \cdot P_j^{sw} \tag{5.10}$$

where P_j^{scb} is the power consumed to scan a single band by user j. P_j^{sw} is the power consumed to switch between bands. This power is basically consumed by user j to change its SDR-based communication parameters to switch between bands. ρ_{ij} represents the probability that user j at AP i will switch from the existing band to another one and it is expressed as:

$$\rho_{ij} = \sum_{q=1}^{F_i} \alpha_{ij}(1 - \alpha_{ij})^{q-1} \tag{5.11}$$

where α_{ij} denotes the probability that user j can detect a better band, lesser contention, at AP i. α_{ij} can be derived as [40]:

$$\alpha_{ij} = F_x^i(k_i - \Delta_i) - \beta_j e^{-\beta_j(k_i - \Delta_i)} \tag{5.12}$$

where $F_x(\cdot)$ represents the cumulative distribution function of contending users at each band. k represents the number of users contending on bands and Δ_i represents the mean number of SUs per idle band at AP i.

Accordingly, the total power consumed by user j to send data using the CR technique P_j^{cr} through AP i can be formulated as:

$$P_{ij}^{cr} = (F_i - 1) \cdot [P_j^{scb} + P_j^{sw}] + \rho \cdot P_j^{sw} + P_{ij}^{tr} \tag{5.13}$$

where P_{ij}^{tr} is the consumed power by user j while sending data through AP i and can be calculated as:

$$P_{ij}^{tr} = R_{ij} \cdot D_j \cdot P_j^{pkt} \tag{5.14}$$

where D_j is the amount of data, number of packets, that user j want to send.

5.2.6 Problem Formulation

As illustrated in the system model, Fig.5.2, the MBS covers several APs and various users. Owing to the temporal and spatial dynamics of the mobility of AP users, some APs are underutilized and others are fully-loaded with their native users. Hence, the underutilized APs can offer, for a fee, their unused bands for the CR-enabled users of the MBS to access via the CR technique. However, the vulnerability indexes for these APs are different depending on their protective security mechanisms, and historical data of previous malicious attacks in these APs. Hence, and as shown in Fig. 5.3, not every CR-enabled user would benefit the most from these APs.

Thus, to optimally exploit the available bands offered by the APs, only the CR-enabled users that benefit the most should be permitted to participate in the CR process in order to access the APs' offered unutilized-bands. In this work, the benefit for the user j accessing the AP i is quantified as:

$$\varpi_{ij} = X_{ij} \cdot \daleth_{ij} \cdot \frac{\mathfrak{S}_{ij}}{P_{ij}^{cr}} \tag{5.15}$$

where $\mathfrak{S}_{ij}/P_{ij}^{cr}$ represents the dollar per unit of additional power required by user j to access AP j via the CR process, $\daleth_{ij}$ denotes the affordability of the user to access that AP as explained in section 5.2.2, and X_{ij} is a binary decision variable that takes a value of 1 if the user j is using the unutilized-bands offered by AP i and can be presented as follows:

$$X_{ij} = \begin{cases} 1 & \text{if user } j \text{ is using AP } i \\ 0 & \text{otherwise} \end{cases} \tag{5.16}$$

Once the MBS quantifies the benefits of all users, it can short list the users that can benefit the most from the CR procedures. This can be formulated mathematically as an optimization problem with the aggregated benefit expressed as follows:

$$Z = \sum_{i=1}^{M} \sum_{j=1}^{N} X_{ij} \cdot \daleth_{ij} \cdot \frac{\mathfrak{S}_{ij}}{P_{ij}^{cr}} \tag{5.17}$$

Hence, the objective function is derived as :

$$\text{maximize } Z \tag{5.18}$$

subject to

$$X_{ij} \cdot (C_m - Cij) > 0, \qquad \forall j \in \mathfrak{J} \quad \forall i \in \mathfrak{I} \tag{5.19a}$$

$$\sum_{i=1}^{M} X_{ij} \leq 1, \qquad \forall j \in \mathfrak{J} \tag{5.19b}$$

$$\sum_{j=1}^{N} X_{ij} \cdot R_{ij} \leq R_{max}, \qquad \forall i \in \mathfrak{I} \tag{5.19c}$$

$$0 < \sum_{j=1}^{N} X_{ij} \leq 2F_i, \qquad \forall i \in \mathfrak{I} \tag{5.19d}$$

$$X_{ij} \cdot SINR_{ij} \geq SINR_{ijmin}, \qquad \forall j \in \mathfrak{J} \tag{5.19e}$$

where,

- Eq (5.19a) ensures that only users that can attain monetary benefits are shortlisted.
- Eq (5.19b) makes sure that each user is only accessing the unutilized bands of a single AP.
- Eq (5.19c) ensures that the aggregated data rates of users accessing the AP are bounded by the maximum capacity of the AP.
- Eq (5.19d) to ensure that the maximum number of SUs to be associated to an AP is double the number of free bands at this AP. Such a constraint minimizes the SUs back-off period which results in minimizing the consumed power in the CR process [180].
- Eq (5.19e) ensures that SINR for each user is greater than a predefined threshold $SINR_{ijmin}$ to achieve seamless communication between the AP and the user

Here,

$$X = \begin{pmatrix} X_{1,1} & X_{1,2} & X_{1,3} & \dots & X_{1,M} \\ X_{2,1} & X_{2,2} & X_{2,3} & \dots & X_{2,M} \\ X_{3,1} & X_{3,2} & X_{3,3} & \dots & X_{3,M} \\ \vdots & \vdots & \vdots & \ddots & \\ X_{N,1} & X_{N,2} & X_{N,3} & \dots\dots & X_{N,M} \end{pmatrix} \tag{5.20}$$

For the above-mentioned integer linear programming problem (ILP), the IBM CPLEX studio was used to resolve it. The obtained results are demonstrated and discussed in section 5.3. However, solving such a problem in real-time with a large coverage area and a large number of users is a challenging task. Hence, the following heuristic was proposed.

5.2.7 Heuristic

With the objective to mitigate the computational complexity of the above-mentioned optimal solution (ILP solution), an algorithm-based heuristic was proposed. The introduced algorithm considers user data rate, amount saving, battery charging level, extra power required, and vulnerability index. Accordingly, user utility function can be expressed as follows:

$$Z_{ij} = X_{ij} \cdot \daleth_{ij} \cdot \frac{\mathfrak{S}_{ij}}{P_{ij}^{cr}} \tag{5.21}$$

The algorithm aims to increase the benefits in terms of monetary saving over additional power consumption that would be required to use CR. As the algorithm's objective is to increase the benefit and decrease the cost, it was named as "BC-algorithm". It should be noted that users here are originally connected to the MBS. However, the APs, which are covered by the MBS, have unutilized bands and are offering them, for a fee, to the users, named as CR-enabled users or secondary users (SUs). Using the proposed algorithm, the MBS will try to maximize the overall benefits for all users by short listing the users who benefit the most from their CR and allow them to access these APs via CR. In other words, the MBS has the upper hand in deciding who should participate and benefit from CR and who should refrain from participation.

In **Algorithm 7**, the MBS generates two lists. One list that contains the list of users who benefit the most Γ , and the other list,φ , contains users who should not be considered for the CR. Consequently, **Algorithm 8** is used to maximize the benefit of the total system.

As shown in **Algorithm 8**, Π represents the AP-SU assignment matrix, derived by the $(\hat{\Pi}, F) = \mathit{new\_AP\_search}\ (j^*, \Pi)$ algorithm. The flag F indicates whether $\hat{\Pi}$ is a more suitable AP-SUs assignment arrangement or not. In other words, if $F == 1$, $\hat{\Pi}$ is more suitable and vice verse. **Algorithm 8** begins with an initial assignment where each SU is assigned, allowed to access, a single AP. Then **Algorithm 8** adjusts the assignment of SUs to APs to maximize the value of the utility function during each iteration. To achieve this, during each iteration, **Algorithm 8** finds the SU with the lowest utility value and tries to locate another AP to increase the overall utility value of the network. If a new allocation is found, **Algorithm 8** begins a new iteration. However, if this is not achievable, **Algorithm 8** checks other SUs that are sharing the same AP with the SU one by one and finds an alternative better AP for them that can increase the overall utility value of the system. Upon finding this better AP, SU will be re-allocated to this AP. If the alternative AP is not found, **Algorithm 8** marks the SU and starts a new iteration until it finishes all users.

The recursive **Algorithm 9** is a crucial component for the BC-algorithm. **Algorithm 8** utilizes **Algorithm 9** to find a new AP for the chosen SU. In **Algorithm 9**, $\bar{\Pi}$ presents an intermediate AP-SUs assignment during a recursion. **Algorithm 9** checks the set of APs surrounding the chosen SU and the SU can access them. Subsequently, in each iteration **Algorithm 9** reallocates the chosen user to one of these APs and checks the overall utility function value. If it increases, it marks the AP and starts a new iteration until **Algorithm 9** marks all the AP for this SU and achieves the highest utility value. Then it returns the final assignment matrix to **Algorithm 8**. Consequently, **Algorithm 8** chooses the next user and begins a new iteration and so on until it terminates.

The AP marking mechanism utilized in the above-mentioned algorithms reduces the computational-complexity while solving the AP-SUs allocation problem. Without using this marking mechanism, M^N iterations are required to locate the best AP-SUs bets

Algorithm 7 The Cognitive Radio Algorithm

Input: SUs j $\in \mathcal{J}$; battery-level B_j; Data demand D_j;Confidentiality index μ_j
Output: The optimum-list of SUs to achieve maximum benefit
for every time slot $t \in 1, 2, \ldots, T$ **do**,
    for each user demanding APs accessibility via CR **do**
        Calculate ϖ_{ij} using equation (5.15).
        Sort N users in descending order
        if $\varpi_{ij} \leq \Lambda$ **then**,
            move the user to φ; Not-suitable-candidates list
        else
            move the user to Γ; suitable-candidates list
        end if
    end for
    Run Algorithm 2
    allow users to access APs according to Π
end for

Algorithm 8 The BC-algorithm

Step 1: For users Γ do initial assignment
Step 2: Set F=0; find $j = argmin_{j \in J} Z_{ij}$; $(\hat{\Pi}, F) = new\_AP\_search\ (j^*, \Pi)$;
if $F == 1$ **then**
    $\Pi = \hat{\Pi}$;
    Jump to step 2;
else
    Step 3:
    if $\{j$ can access other APs$\}$ **then**
        Find $Y_b = \{j | \Pi_{j,b} = 1, \Pi_{j,b} = 1, j \neq i, j \in \mathcal{J}\}$;
        for $j = 1 : |Y_b|$ **do**
            Remove the markers;
            $(\hat{\Pi}, F) = new\_AP\_search\ (j^*, \Pi)$;
            if $F == 1$ **then**
                $\Pi = \hat{\Pi}$ and terminate;
            end if
        end for
        if $F == 1$ **then**
            Jump to step 2;
        end if
    end if
end if
return Π

Algorithm 9 $(\hat{\Pi}, F) = new\_AP\_search\ (j^*, \Pi)$

Set F=0 , $\hat{\Pi} = \Pi$
Find $\bigcup_i = \{b | C_{i*,j} > min_{j \in Y_b} C_{ij}, b \in \bigcup\}$
if $\{C_{i*,j} > min_{j \in Y_b} C_{ij}, \exists b \in \bigcup\}$ **then**
if $\{\Pi_{ij} = 1, \exists j \in \bigcup\}$ **then**
Add AP-SU pair to jth pair and update Π;
end if
Mark the pair;
for $b = 1 : |\bigcup_i|$ **do**
if r_b not marked **then**
Mark r_b
if $\{j$ can access $r_b\}$ **then**
update Π. set F==1
Terminate
else
Find $Y_b = \{j | \Pi_{j,b} = 1, \Pi_{j,b} = 1, j \neq i, j \in \mathcal{J}\}$
for $j = 1 : |Y_b|$ **do**
$(\bar{\Pi}, F) = new\_AP\_search\ (j^*, \Pi)$;
if F==1 **then**
$\hat{\Pi} = \bar{\Pi}$;
Terminate
end if
end for
end if
end if
if F==1 **then**
Add AP-SU pair to jth pair and update Π;
Set $\hat{\Pi} = \Pi$
end if
end for
end if

allocation. However, in the proposed heuristic, the BC-algorithm requires M iterations maximum. Additionally, offloading unmarked SUs from marked AP to unmarked APs decreases the number of alternative APs for SUs and hence less computational processing power required. Hence, faster processing time.

5.2.8 Computational complexity analysis

This section evaluates the computational complexity of the proposed Cognitive Radio heuristic.**Algorithm 7** starts with assuming that all N users require the CR access to the nearby APs. Hence, the algorithm sort the users according to their ϖ_{ij} and only users with ϖ_{ij} that is higher than a certain value A will be allowed to participate in the CR procedures. Thus, the computational complexity, up to this point, is $O(TNlogN)$.

Assuming that the number of the allowed users is $N^{'}$, each user from these $N^{'}$ users will be allowed to access the nearest BS. Subsequently, **Algorithm 8** starts with a flag F equals zero, and all the $N^{'}$ allowed users, which are grouped in Γ. Then, **Algorithm 8** finds the CR user with the minimum ϖ_{ij} and by using **Algorithm 9**, it tries to find another AP, from the available M APs, that can increase the user's ϖ_{ij} and yet increases the total benefit Z_{ij} at the same time to meet the objective function. Once AP is found the algorithm will mark the user, and go to the next user.

As mentioned before, **Algorithm 8** tends to determine the best AP to serve the selected user, and the algorithm has two Find-procedure, two For-loop procedure. However, **Algorithm 8** utilizes other procedures in **Algorithm 9** to validate if the new AP is suitable of not. **Algorithm 9** has two find-procedure, two For-loops. Accordingly, for **Algorithm 8** and **Algorithm 9** the computational complexity can be derived as $O(N^{'} + M + M \cdot O(Algorithm5))$ and O($2M + M^2$), respectively.

Finally, presuming the worst case scenario where the heuristic searches all APs and users, the total heuristic complexity can be derived as $O(NlogN + N^{'} + 2M^2 + M^3)$. where N represents the total number of users, $N^{'}$ number of users that were selected to participate in the CR procedures, and M is the number of available APs. Hence, the proposed heuristic algorithms are of the type pseudo polynomial time algorithm.

5.3 Simulation Results and Discussion

To benchmark the proposed approach, a hypothetical simulation scenario for the city of Perth was implemented as presented in Fig. 5.4. The simulation scenario was implemented in Matlab R2019b using the simulation parameters in Table 5.2. In the simulation, users' packets generation followed a Poisson distribution with 0.5 as the mean rate [181]. The values of the "cost per bit" was obtained from one of the well-known operators in Australia [202]. In the simulated scenario, the radius of the macro base station was considered as 1000m and for the APs the radius was 200m [203]. Additionally, the number of users is set to range from 70 to 160. Such a range has been adopted in other research studies such as [204–206]

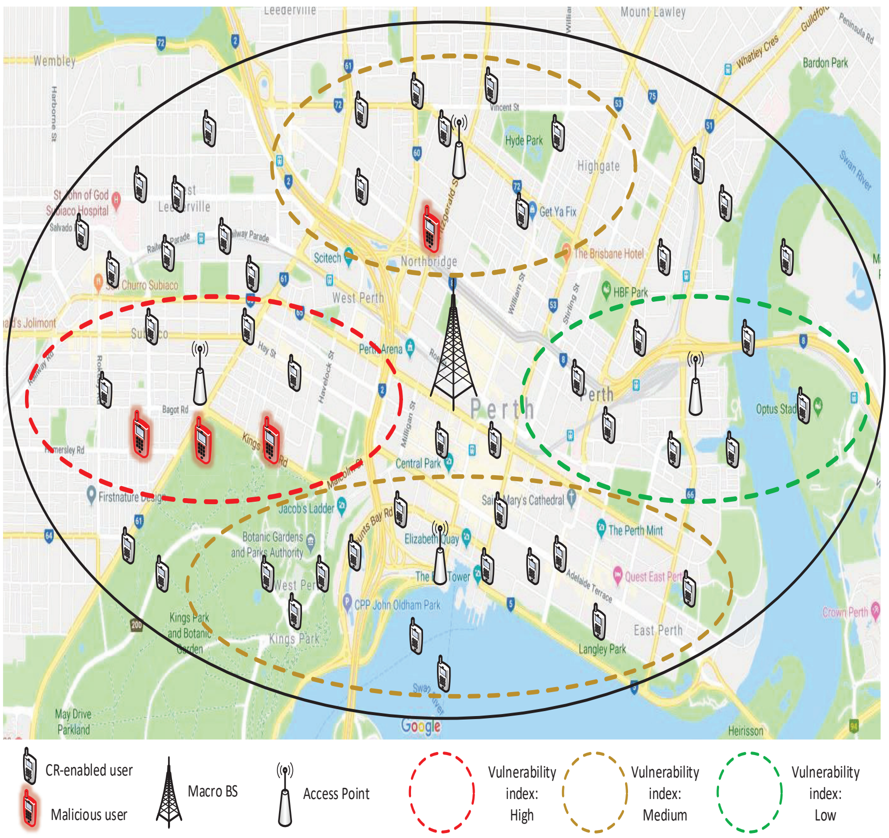


Fig. 5.4: Hypothetical simulation scenario for the CR-based communication system - Perth, Western Australia

Table 5.2: Parameters used in the simulation of the proposed secure and energy-aware approach for CR communication

Parameter	Value
PBSs number	1
SBSs number per PBS	4
SUs number per SBS	160
Power to transmit a bit [40]	$1.75 \cdot 10^{-8}\ mW$
Power to switch channels [40]	750 mW
Power to scan a channel[40]	700 mW
Time to switch channels [40]	0.06 ms
Time to scan a channel[40]	500 ms
Packet mean rate [40]	0.5 Packet/sec
Frequency of the Carrier[181]	1900 MHz
Bandwidth of the Channel [181]	10 MHz
Transmission Power of Macro BS [181]	20 W
Transmission Power of APs [181]	5 W
Battery power consumption co-efficient [181]	1
Cost per bit for the MBS	$(1.20 : 1.86) \cdot 10^{-5}$\$
Cost per bit for APs	$(2.00 : 2.74) \cdot 10^{-5}$\$

This section introduces the obtained simulation results and evaluates the proposed approach. Furthermore, it presents various comparisons between the proposed and the traditional CR approach [40, 181]. In the traditional approach, without any restrictions, all SUs are allowed to utilize their CR abilities to access any AP, irrespective of their battery level, traffic types, the AP's load, and AP's vulnerability level. However, unlike the traditional approach, the proposed approach shortlists SUs that benefit the most from the CR process and associates them to APs that increase the total benefit and yet meet the SUs requirements.

Fig. 5.5 presents a comparison between the traditional CR approach and the proposed approach in terms of total power consumed by SUs to send their data through the APs and the number of SUs influence on it. From Fig. 5.5, it is apparent that the proposed approach consumes less power in comparison to the traditional approach. This is because the proposed approach first shortlists SUs that benefit the most from the CR and then, in meeting its objective function (i.e. Eq.5.17), tends to associate

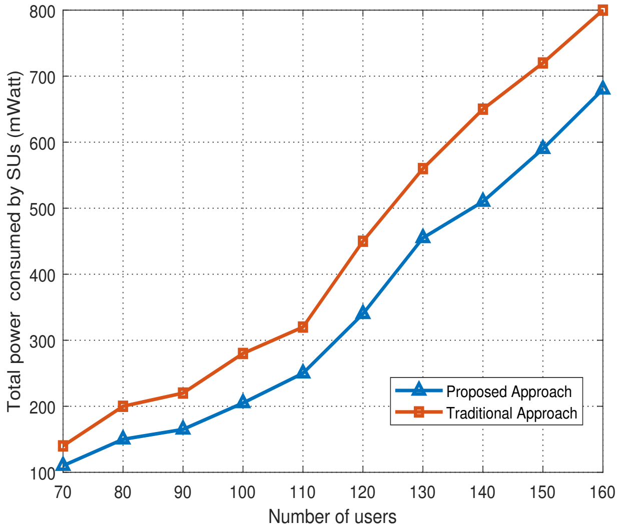


Fig. 5.5: Total power consumed by SUs

the SUs with APs that require less CR power consumption to be accessed. Hence, the majority of SUs are served by the minimum possible CR power consumption. However, on the other hand, the traditional approach tends to allow all SUs, without restrictions, to access the APs and to associate SUs with the nearest AP, irrespective of the AP load or the CR power consumption to access it. This leads to more SUs competing on the available bands resulting in a higher CR power consumption.

Fig. 5.6 shows a comparison between the traditional approach and the proposed CR approach in terms of throughput per SU and the number of users' impact on this throughput. Based on the results displayed in Fig. 5.6, it is clear that the proposed approach provides higher throughput per SU than the traditional approach. This occurs because the proposed approach restricts the access to the APs, via CR, to the users who benefit the most from them leading to a fewer number of contending SUs which results in lower blocking probability and hence higher throughput. Additionally, in satisfying its objective function, the proposed approach shows a tendency to associate SUs to APs that have more free bands, which translates to higher data rates/throughput. However, in the traditional approach, all SUs are allowed to access their nearest APs, irrespective of the number of available free bands at these APs and the APs' load. This leads to a high level of contention between the SUs on the free bands and results in high blocking probability, which translates to lower throughput.

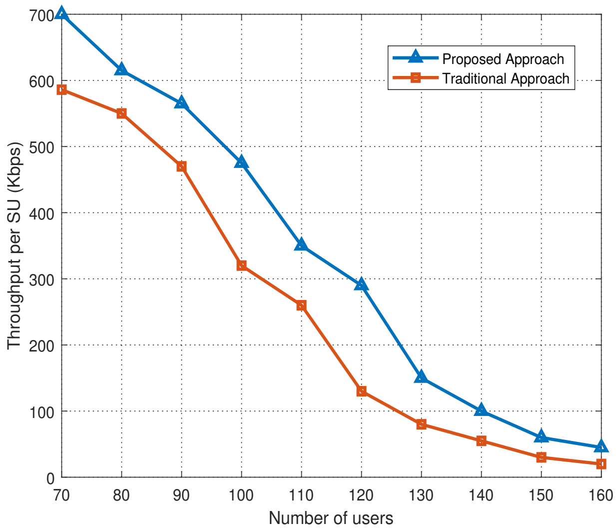


Fig. 5.6: Secondary users' throughput

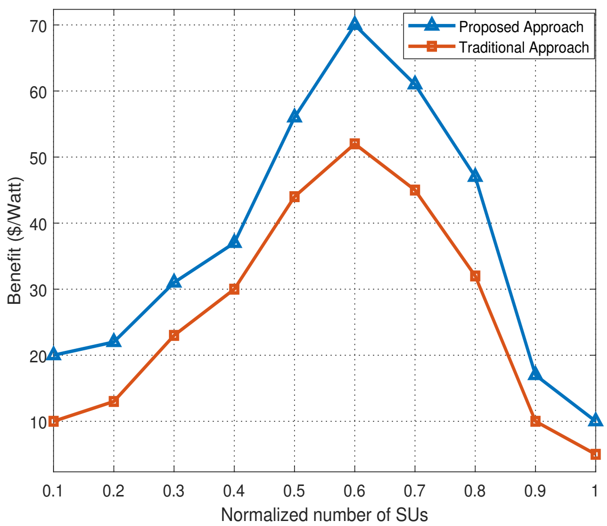


Fig. 5.7: Secondary users' Benefit

Fig. 5.7 displays the impact of the normalized number of users on the total benefit figure of the system, where the normalized number of users represents the ratio between the number of actual participating SUs to the total number of SUs who can access APs, using their CR abilities. For instance, a normalized value of 0.1 means allowing only 10% of total SUs to access APs by using their CR abilities. Additionally, in this context, Fig.

5.7 compares the traditional approach with the proposed approach. Based on the results in Fig. 5.7, it salient that the proposed approach achieves higher benefit figures than the traditional approach. This is because the proposed approach, in meeting its objective function (i.e. Eq.5.17), associates SUs to APs that maximize the overall benefit and yet meet SUs requirements. Such an approach balances the load between APs and alleviates the contention level at each AP which means less CR power consumption and higher throughput. This results in high overall benefit for the proposed approach. However, unlike the proposed approach, the traditional approach tends to associate SUs to their nearest APs, irrespective of the APs' load and the CR power consumption to access them. This results in some APs become overloaded and increases the level of contention among SUs on the available bands at these APs. Consequently, this leads to a higher CR power consumption and less throughput, hence less overall benefit. Fig. 5.7 shows also that increasing the number of SUs accessing the APs will increase benefit until some point where the level of contention between SUs becomes very high and overwhelms the benefit. At this point, the benefit figure starts to decline.

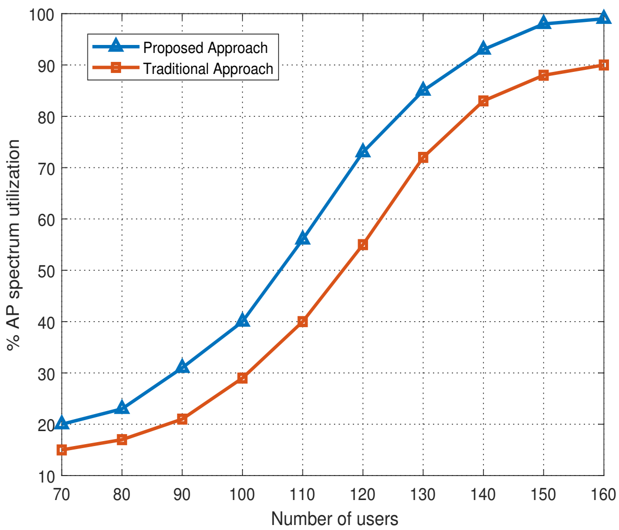


Fig. 5.8: APs Spectrum utilization of APs

Fig. 5.8 shows the influence of increasing the number of users on the total utilization of the APs' spectrum and it presents a comparison, in this context, between the proposed approach and the traditional approach. From Fig. 5.8, it is evident that the proposed approach provides better spectrum utilization than the traditional one. This is because the MB, unlike the traditional approach, tends to distribute users among the APs according to SUs' demands and benefits which provides better load balancing and avoids situations where some APs are over accessed and others are idle.

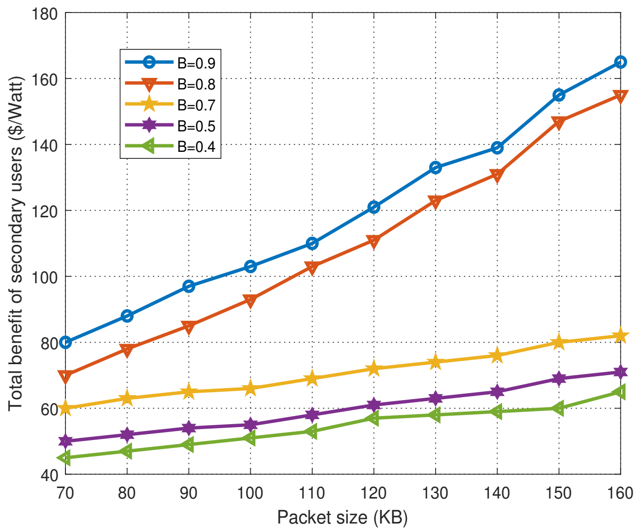


Fig. 5.9: The impact on the benefit figure while changing the packet size

Additionally, this study examined the influence of the size of the data, battery level, and users' confidentiality index on the total benefit of the SUs. Fig. 5.9 shows the influence of increasing the size of the data packet, that SUs send through the APs via CR, on the total benefit figure. Additionally, Fig. 5.9 presents that influence under different battery levels. The figure manifests that for small packet sizes and low battery levels, SUs' benefits are lower compared to the situation where SUs' battery levels are high and sending relatively large packets. This occurs because the extra power required for the CR technique is more precious for low battery users and, hence, the power cost is too high for them, resulting in less net-benefit for them.

Fig. 5.10 illustrates the impact of increasing the battery level of the SUs on the total benefit figure. Furthermore, it shows that impact while using different sizes of data. Based on the obtained results in Fig. 5.10, it is evident that increasing the battery level of the SUs improves the SUs benefits figure. However, using larger data sizes boosts the benefit figure even more. This occurs because, for SUs with abundant power resource,

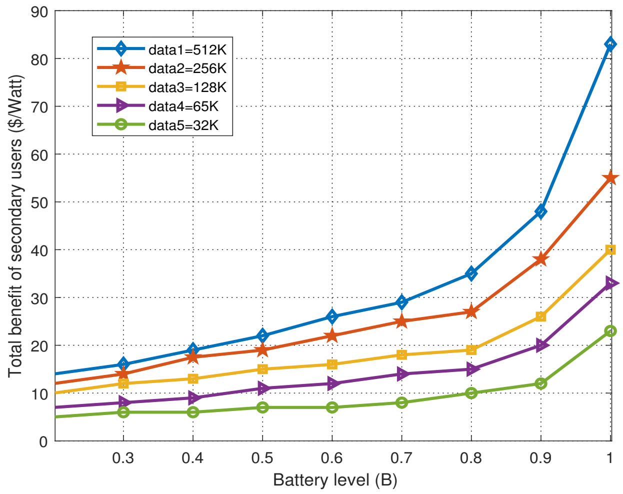


Fig. 5.10: The influence on the benefit figure while changing the battery level

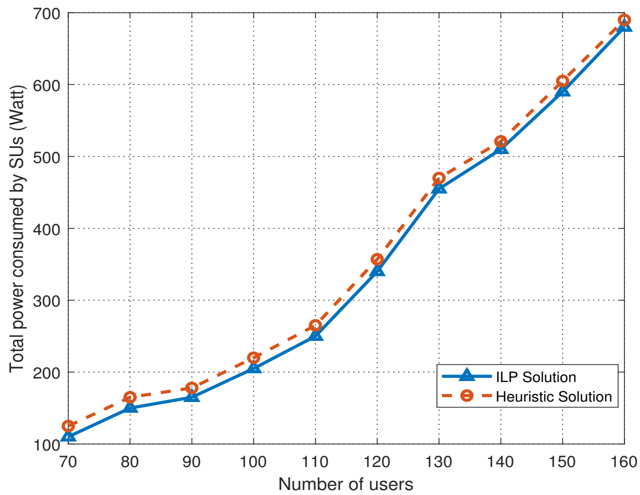


Fig. 5.11: Heuristic simulation results: Power consumption

the CR power cost is easily affordable and larger data size means larger savings, thus the benefit figure is high.

Fig. 5.11 shows a comparison between the integer linear programming (ILP) solution obtained via CPLEX, and the proposed heuristic solution in terms of total power consumed by SUs. From Fig. 5.11, it is evident that the proposed heuristic consumes marginally higher power than the ILP solution. On the other hand, Fig. 5.12 presents a

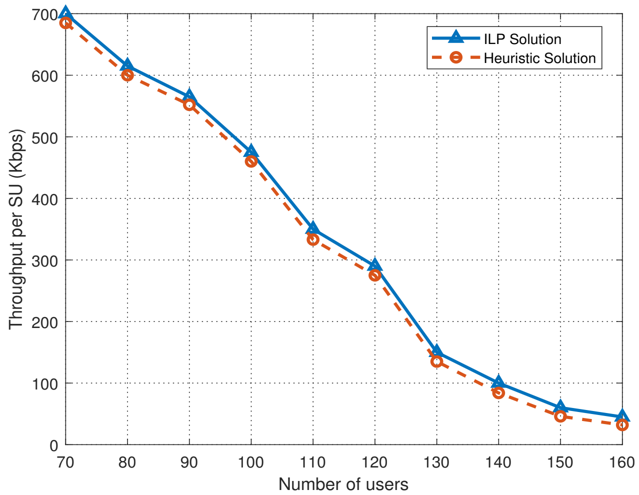


Fig. 5.12: Heuristic simulation results: Throughput

comparison between the ILP solution and the proposed heuristic in terms of throughput per SU. From Fig. 5.12, it is notable that the proposed heuristic offers slightly less throughput than the ILP solution. Furthermore, Fig. 5.13 illustrates a comparison between the proposed heuristic and the ILP solution in terms of total benefit figure. From Fig. 5.13, it is evident that the proposed heuristic offers almost identical benefit to the ILP solution. From Fig. 5.11, 5.12, and 5.13 it is notable that the proposed heuristic can be used to attain near-optimal results for the above-mentioned research problem.

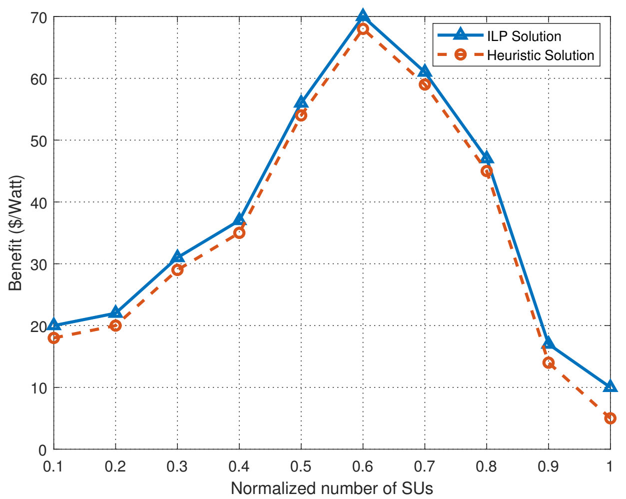


Fig. 5.13: Heuristic simulation results: Total benefit

Table 5.3: Summary of the findings

Cognitive radio Technique	Total Power Consumed By SUs (Watt)	Throughput/SU (Kbps)	APs Spectrum Utilization (%)
Traditional approach [40, 181]	808	586	88
Proposed approach	680	703	98

Table 5.3 summarizes the findings in this work. The table introduces a comparison between the traditional CR approach and the proposed approach. As demonstrated in Table 5.3 the proposed approach consumes less power compared to the traditional approach. Additionally, the proposed approach offers higher throughput. It also achieves better utilization for the APs unutilized spectrum.

5.4 Concluding Remarks

Owing to its multi-dimensional awareness and ability to sense, learn and decide subsequent actions, the CR technique, supported by the SDR technology, offers great potential to fulfill users' ever-increasing demands and mitigate the looming problem of spectrum scarcity. However, due to its power-hungry procedures and security risks, these offered benefits can be overwhelmed by the costs associated with extra power requirements and/or security breaches. This chapter has introduced a new CR-based communication approach that has maximized the users' benefits while taking the power consumption and security risk into consideration. Furthermore, while quantifying the benefit figures, the proposed approach has considered the device's battery level, type of traffic, vulnerability level of the accessed network, and the number of free bands in the accessed spectrum. The obtained results have shown that the proposed approach has saved up to 18% of the power consumption, has increased the total throughput per user by 20%, and has provided better spectrum utilization reaching up to 98%. This research study opens a new research area towards safer and greener CR solutions. The following chapter concludes all the findings in all the previous chapters. Additionally, it introduces the recommendations for future research studies.

Chapter 6

Conclusion and Future Recommendations

6.1 Concluding remarks

Fueled by the widespread adoption of wireless-enabled devices and their data-hungry applications, mobile data traffic has dramatically increased in recent years. Mobile data traffic is anticipated to witness another seven-fold growth, reaching 86% of global data traffic by 2022. Additionally, owing to the random nature of user demands and mobility, mobile data traffic has become more random, diverse, and unevenly distributed across time and space. This trend of growth has not only forced mobile-network operators to intensify their power consumption, but also to add more spectrum to expand their network capacity to accommodate users' ever-increasing demands. Nevertheless, licensed-spectrum is scarce and imposes extra operational costs on network operators. Augmented by scarce spectral resources, these drastic challenges result in a dilemma for mobile-network operators in managing and maintaining network capacity, user demands, and quality of experience.

Restlessly, researchers across the globe are investigating various communication techniques that can be utilized to alleviate the anticipated increase in power consumption while boosting the overall throughput within the spectrum scarcity problem. This effort includes enhancing the performance of Heterogeneous networks (HetNets) in terms of power consumption and aggregated throughput. In this context, this thesis, exploiting the flexible nature of software-defined radio (SDR) technology, has introduced novel communication strategies to boost the HetNets overall throughput and reduce their overall power consumption. To boost the throughput, these strategies have utilized state-of-the-art technologies such as long-term evolution licensed assisted access (LTE-LAA) and Cognitive Radio (CR) to extend the operation spectrum to include the unlicensed bands. To reduce the power consumption, these strategies have adopted energy-efficient spectrum-based traffic steer/user-association techniques to efficiently steer the traffic loads to the optimum BSs and put other BSs on sleep mode to reduce power consumption. Based on the obtained results, the proposed strategies have offered a considerable boost in throughput and substantial savings in power consumption when bench-marked against existing strategies.

6.2 Contribution of the thesis

List of publications that have been resulted from this thesis is as follows;

- H. Khaled, I. Ahmad, D. Habibi, and Q. V. Phung, "A Green Traffic Steering Solution for Next Generation Communication Networks," *IEEE Transactions on Cognitive Communications and Networking,* Early Access, 2020. doi: 10.1109/TCCN.2020.2987799.

- H. Khaled, I. Ahmad, D. Habibi, and Q. V. Phung, "A Secure and Energy-Aware Approach For Cognitive Radio Communications," *IEEE Open Journal of the Communications Society,* Vol. 1, P900-915, 2020.

- H. Khaled, I. Ahmad, D. Habibi, and Q. V. Phung, "An Energy-aware Cognitive Radio-Based Communication Approach for Next Generation Wireless Networks," *IEEE 21st International Conference on High Performance Computing and Communications.*, IEEE, 2019, pp. 1817-1824, 2019.

- H. Khaled, I. Ahmad, D. Habibi, and Q. V. Phung, "Enhancing Throughput and Energy Efficiency in Heterogeneous Networks for Next-Generation Communication Systems," *IEEE Transactions on communications* (Under Review).

The major contributions of the thesis can be summarized as follows;

- Chapter 3 has shown that the conventional HetNet concept is constrained by its hardware abilities. Such a limitation manifests itself in the ability of HetNets to adapt to variations in network dynamics. Hence, this chapter has proposed a SDR-based and LTE-LAA-enabled architecture for next-generation communication networks that offers more flexibility and a higher level of adaptability. In the proposed architecture, the SDR technology has been used to introduce open-access/shared SDR-based BSs that support LTE-LAA and can serve users from different operators. Hence, its benefits can be realised by both operators and users. The proposed architecture has exploited the LTE-LAA along with SDR technology to maximize the throughput and minimize the overall power consumption of the network in HetNets. The resource management challenge within the proposed architecture has been formulated as a constrained optimization problem. The solution for the optimization problem was found to outperform existing approaches by a significant margin. The simulation results have shown that the proposed approach has consumed up to 17% less energy compared to current approaches. With regard to network data rate and licensed spectrum utilization percentage, the proposed solution has provided up to 31% more data rate and has utilized almost 22% of the licensed spectrum because of the use of the LTE-LAA technology.

- Chapter 4 has exploited SDR technology, LTE-LAA concept, and green-energy to develop a green traffic-steering framework. This framework has utilized the spectrum-based cell zooming technique to steer users across the network toward the optimum BSs, which have abundant unlicensed carriers and abundant renewable energy, to minimize overall network on-grid power consumption and maximize aggregated throughput. In this chapter, the research problem of finding the optimum BSs has been formulated as a multi-objective function. Based on the simulation results, the proposed framework has saved up to 15% of on-grid power and has increased aggregated throughput by 23%.

- Chapter 5 has shown that not all SUs would benefit equally from the CR technique and the more SUs compete for free/idle bands, the more power they would all consume to send their data. Hence, the chapter has introduced an energy-and-security-aware CR-based communication technique that alleviates the power consumption of the CR technique and enhances its security measures according to the confidentiality level of the data being sent. Furthermore, the proposed approach has taken into account user-related factors, such as users battery levels and users data types, and network-related factors, such as the number of unutilized bands and vulnerability level. In this study, the Macro BS has shortlisted only the optimum SUs, who benefit the most from the CR-process, and has instructed them to use their CR capabilities to access the nearby BSs. By following this approach, the number of contending users has been reduced, and consequently less power has been consumed and less transmission-blocking has occurred, which translates to higher throughput. In this chapter, the research problem of finding the optimum SUs has been formulated as a multi-objective function. The obtained results have shown that the proposed approach has saved energy consumption by up to 18%, has increased user throughput by up to 20%, and has achieved better spectrum utilization, up to 98%.

6.3 Future research direction

This thesis opens a new research area towards safer and greener communication solutions for the next generation networks. This section introduces some open research points/issues that are anticipated to be further investigated or tackled in the future.

6.3.1 The LTE-LAA and MulteFire Coupling

MulteFire is one of the most recent communication technology that was introduced to develop an LTE system that is entirely running in the unlicensed band. Accordingly, MulteFire is most suitable for small cells. The small coverage area for each small cell results in better spectrum reuse and offers greater capacity in highly dense environments, such as malls, stadiums, train stations, and airports.

Such a system was developed to alleviate the licensed-spectrum scarcity problem. As LTE-LAA is also a new technology that extends the LTE, not entirely, to the unlicensed band, further research and investigation on how to couple the two technologies to boost the overall network throughput by using both of the licensed and unlicensed bands together at the same time. Such a study can have enormous benefits for both users and operators in terms of users' throughput and operators' capacities.

6.3.2 Utilization of the Cloud Computing Technology

In the future, an extended effort can be directed towards developing a cloud-based traffic steering model that utilizes the powerful computation capabilities of cloud computing to rapidly predict and detect available bands and their suitability in terms of SUs' security and quality requirements. Cloud computing offers ubiquitous on-demand access to a shareable pool of computing resources that can be utilized to process various tasks in a timely manner.

Such an approach will offload the computational complexity, and its corresponding power consumption, from the BSs to the cloud resulting in less power reduction. Additionally, the decisions on which SUs access which bands and for how long will be processed faster, more efficiently, and securely leading to less power to be consumed and a more efficient and secure way of handling the radio spectrum.

6.3.3 Guaranteed Quality of Service in the Unlicensed Spectrum

The unlicensed spectrum has an open-access nature and is inherently "un-managed". Hence, such a spectrum does not have any central controller that manages channel access between all competing systems in the spectrum. For systems that rely on the unlicensed spectrum, such as MulteFire and LTE-LAA, maintaining a consistent level of quality of service (QoS) imposes a great challenge. In particular, when dealing with a data traffic that is random and diverse, such as mobile data.

Accordingly, developing a robust radio resource scheduling scheme that can mitigate that QoS challenge, by proving a guaranteed level of QoS, and offers a better coexistence between different systems within the unlicensed spectrum, will be very beneficial for both the network operators and users. Additionally, such a scheme can improve the overall utilization of the unlicensed spectrum and open new doors for more systems to co-exist in the spectrum.

6.3.4 Artificial Intelligence and machine learning for Cognitive Radio

As mentioned in this thesis, cognitive radio (CR) is considered as one of the solutions for the spectrum scarcity problem. However, as covered in the literature review chapter, we rely on the intelligence of the CR-enabled device to detect the absence of the primary user (PU) and use the vacant bands. Hence, if CR technology lacks this intelligence, the reliability of the CR system will be questionable.

In the machine learning and artificial intelligence (AI) era, like humans, machines have learning abilities and can interact with the surroundings. Additionally, it becomes easier to utilize AI in communication systems and HetNets is no exception. Such capabilities can be utilized to maximize the utilization of the unused/idle bands by various AI-enabled devices with minimal interference with the primary user or other secondary users. Additionally, various machine learning techniques can be utilized to minimize the complexity of finding the optimum solutions. Consequently, in the future, more research efforts should take place towards developing an AI-based CR communication technique that is smart, reliable, and can guarantee high QoS.

Bibliography

[1] Cisco. (2020) Cisco annual internet report. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.pdf

[2] P. Gandotra, R. K. Jha, and S. Jain, "Green communication in next generation cellular networks: a survey," *IEEE Access*, vol. 5, pp. 11 727–11 758, 2017.

[3] Ericsson. (2020) Ericsson mobility report. [Online]. Available: https://www.ericsson.com/491b06/assets/local/mobility-report/documents/2019/ericsson-mobility-report-q4-2019-update.pdf

[4] M. Agiwal, A. Roy, and N. Saxena, "Next generation 5g wireless networks: A comprehensive survey," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 3, pp. 1617–1655, 2016.

[5] C. Zhang, P. Patras, and H. Haddadi, "Deep learning in mobile and wireless networking: A survey," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 3, pp. 2224–2287, 2019.

[6] J. Wu, Y. Zhang, M. Zukerman, and E. K.-N. Yung, "Energy-efficient base-stations sleep-mode techniques in green cellular networks: A survey," *IEEE communications surveys & tutorials*, vol. 17, no. 2, pp. 803–826, 2015.

[7] D. Harutyunyan and R. Riggio, "How to migrate from operational lte/lte–a networks to c–ran with minimal investment?" *IEEE Transactions on Network and Service Management*, vol. 15, no. 4, pp. 1503–1515, 2018.

[8] E. Gourdin, P. Maillé, G. Simon, and B. Tuffin, "The economics of cdns and their impact on service fairness," *IEEE Transactions on Network and Service Management*, vol. 14, no. 1, pp. 22–33, 2017.

[9] Z. Zhou, M. Dong, K. Ota, and Z. Chang, "Energy-efficient context-aware matching for resource allocation in ultra-dense small cells," *IEEE Access*, vol. 3, pp. 1849–1860, 2015.

[10] I. Humar, X. Ge, L. Xiang, M. Jo, M. Chen, and J. Zhang, "Rethinking energy efficiency models of cellular networks with embodied energy," *IEEE Network*, vol. 25, no. 2, 2011.

[11] N. I. Osman, "Will video caching remain energy efficient in future core optical networks?" *Digital Communications and Networks*, vol. 3, no. 1, pp. 39–46, 2017.

[12] M. Ismail, W. Zhuang, E. Serpedin, and K. Qaraqe, "A survey on green mobile networking: From the perspectives of network operators and mobile users," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 3, pp. 1535–1556, 2014.

[13] A. Khreishah, H. B. Salameh, I. Khalil, and A. Gharaibeh, "Renewable energy-aware joint caching and routing for green communication networks," *IEEE Systems Journal*, vol. 12, no. 1, pp. 768–777, 2016.

[14] L. A. Fletscher, L. A. Suárez, D. Grace, C. V. Peroni, and J. M. Maestre, "Energy-aware resource management in heterogeneous cellular networks with hybrid energy sources," *IEEE Transactions on Network and Service Management*, vol. 16, no. 1, pp. 279–293, 2018.

[15] H. A. H. Hassan, A. Pelov, and L. Nuaymi, "Integrating cellular networks, smart grid, and renewable energy: Analysis, architecture, and challenges," *IEEE access*, vol. 3, pp. 2755–2770, 2015.

[16] A. Abrol and R. K. Jha, "Power optimization in 5g networks: A step towards green communication," *IEEE Access*, vol. 4, pp. 1355–1374, 2016.

[17] M. R. Hassan, G. C. Karmakar, J. Kamruzzaman, and B. Srinivasan, "Exclusive use spectrum access trading models in cognitive radio networks: A survey," *IEEE COMMUNICATIONS SURVEYS AND TUTORIALS*, vol. 19, no. 4, pp. 2192–2231, 2017.

[18] X. Hong, J. Wang, C.-X. Wang, and J. Shi, "Cognitive radio in 5g: a perspective on energy-spectral efficiency trade-off," *IEEE Communications Magazine*, vol. 52, no. 7, pp. 46–53, 2014.

[19] M. Shafi, A. F. Molisch, P. J. Smith, T. Haustein, P. Zhu, P. De Silva, F. Tufvesson, A. Benjebbour, and G. Wunder, "5g: A tutorial overview of standards, trials, challenges, deployment, and practice," *IEEE journal on selected areas in communications*, vol. 35, no. 6, pp. 1201–1221, 2017.

[20] W. Ahmad, N. Radzi, F. Samidi, A. Ismail, F. Abdullah, M. Jamaludin, and M. Zakaria, "5g technology: Towards dynamic spectrum sharing using cognitive radio networks," *IEEE Access*, vol. 8, pp. 14 460–14 488, 2020.

[21] M. N. Patwary, S. J. Nawaz, M. A. Rahman, S. K. Sharma, M. M. Rashid, and S. J. Barnes, "The potential short-and long-term disruptions and transformative impacts of 5g and beyond wireless networks: Lessons learnt from the development of a 5g testbed environment," *IEEE Access*, vol. 8, pp. 11 352–11 379, 2020.

[22] F. Al-Turjman, E. Ever, and H. Zahmatkesh, "Small cells in the forthcoming 5g/iot: Traffic modelling and deployment overview," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 1, pp. 28–65, 2018.

[23] F. Han, S. Zhao, L. Zhang, and J. Wu, "Survey of strategies for switching off base stations in heterogeneous networks for greener 5g systems," *IEEE Access*, vol. 4, pp. 4959–4973, 2016.

[24] E. J. Oughton and Z. Frias, "The cost, coverage and rollout implications of 5g infrastructure in britain," *Telecommunications Policy*, vol. 42, no. 8, pp. 636–652, 2018.

[25] S. Buzzi, I. Chih-Lin, T. E. Klein, H. V. Poor, C. Yang, and A. Zappone, "A survey of energy-efficient techniques for 5g networks and challenges ahead," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 4, pp. 697–709, 2016.

[26] C. Yang, J. Li, M. Guizani, A. Anpalagan, and M. Elkashlan, "Advanced spectrum sharing in 5g cognitive heterogeneous networks," *IEEE Wireless Communications*, vol. 23, no. 2, pp. 94–101, 2016.

[27] Z. Shen, A. Papasakellariou, J. Montojo, D. Gerstenberger, and F. Xu, "Overview of 3gpp lte-advanced carrier aggregation for 4g wireless communications," *IEEE Communications Magazine*, vol. 50, no. 2, pp. 122–130, 2012.

[28] W. Gao, L. Ma, and G. Chuai, "Joint optimization of component carrier selection and resource allocation in 5g carrier aggregation system," *Physical Communication*, vol. 25, pp. 293–297, 2017.

[29] J. Yi, W. Sun, S. Park, and S. Choi, "Performance analysis of lte-laa network," *IEEE Communications Letters*, vol. 22, no. 6, pp. 1236–1239, 2018.

[30] J. Liu and G. Shen, "Performance of multi-carrier lbt mechanism for lte-laa," in *2016 IEEE 83rd Vehicular Technology Conference (VTC Spring)*. IEEE, 2016, pp. 1–5.

[31] R. Zhang, M. Wang, L. X. Cai, Z. Zheng, X. Shen, and L.-L. Xie, "Lte-unlicensed: the future of spectrum aggregation for cellular networks," *IEEE Wireless Communications*, vol. 22, no. 3, pp. 150–159, 2015.

[32] F. Hu, B. Chen, and K. Zhu, "Full spectrum sharing in cognitive radio networks toward 5g: A survey," *IEEE Access*, vol. 6, pp. 15 754–15 776, 2018.

[33] K.-L. A. Yau, J. Qadir, C. Wu, M. A. Imran, and M. H. Ling, "Cognition-inspired 5g cellular networks: a review and the road ahead," *IEEE Access*, vol. 6, pp. 35 072–35 090, 2018.

[34] "Fedral communications comission." [Online]. Available: https://transition.fcc.gov/sptf/files/SEWGFinalReport_1.pdf

[35] S. Bhattarai, J.-M. J. Park, B. Gao, K. Bian, and W. Lehr, "An overview of dynamic spectrum sharing: Ongoing initiatives, challenges, and a roadmap for future research," *IEEE Transactions on Cognitive Communications and Networking*, vol. 2, no. 2, pp. 110–128, 2016.

[36] R. Riggio, M. K. Marina, J. Schulz-Zander, S. Kuklinski, and T. Rasheed, "Programming abstractions for software-defined wireless networks," *IEEE Transactions on Network and Service Management*, vol. 12, no. 2, pp. 146–162, 2015.

[37] I. T. Haque and N. Abu-Ghazaleh, "Wireless software defined networking: A survey and taxonomy," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 4, pp. 2713–2737, 2016.

[38] M. Dabbagh, B. Hamdaoui, M. Guizani, and A. Rayes, "Energy-efficient resource allocation and provisioning framework for cloud data centers," *IEEE Transactions on Network and Service Management*, vol. 12, no. 3, pp. 377–391, 2015.

[39] X. Tang, P.-E. Gaillardon, and G. De Micheli, "A high-performance low-power near-vt rram-based fpga," in *Field-Programmable Technology (FPT), 2014 International Conference on*. IEEE, 2014, pp. 207–214.

[40] V. Namboodiri, "Are cognitive radios energy efficient? a study of the wireless lan scenario," in *Performance Computing and Communications Conference (IPCCC), 2009 IEEE 28th International*. IEEE, 2012, pp. 437–442.

[41] M. Y. Arslan, K. Sundaresan, and S. Rangarajan, "Software-defined networking in cellular radio access networks: potential and challenges," *IEEE Communications Magazine*, vol. 53, no. 1, pp. 150–156, 2015.

[42] A. Gudipati, D. Perry, L. E. Li, and S. Katti, "Softran: Software defined radio access network," in *Proceedings of the second ACM SIGCOMM workshop on Hot topics in software defined networking*. ACM, 2013, pp. 25–30.

[43] F. M. Abinader, E. P. Almeida, F. S. Chaves, A. M. Cavalcante, R. D. Vieira, R. C. Paiva, A. M. Sobrinho, S. Choudhury, E. Tuomaala, K. Doppler *et al.*, "Enabling the coexistence of lte and wi-fi in unlicensed bands," *IEEE Communications Magazine*, vol. 52, no. 11, pp. 54–61, 2016.

[44] M. Hawasli and S. A. Çolak, "Toward green 5g heterogeneous small-cell networks: power optimization using load balancing technique," *AEU-International Journal of Electronics and Communications*, vol. 82, pp. 474–485, 2017.

[45] S. Manap, K. Dimyati, M. N. Hindia, M. S. A. Talip, and R. Tafazolli, "Survey of radio resource management in 5g heterogeneous networks," *IEEE Access*, 2020.

[46] H. Zhang, F. Fang, J. Cheng, K. Long, W. Wang, and V. C. Leung, "Energy-efficient resource allocation in noma heterogeneous networks," *IEEE Wireless Communications*, vol. 25, no. 2, pp. 48–53, 2018.

[47] J. Chen, X. Ge, and Q. Ni, "Coverage and handoff analysis of 5g fractal small cell networks," *IEEE Transactions on Wireless Communications*, vol. 18, no. 2, pp. 1263–1276, 2019.

[48] Y. Teng, M. Liu, F. R. Yu, V. C. Leung, M. Song, and Y. Zhang, "Resource allocation for ultra-dense networks: A survey, some research issues and challenges," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 3, pp. 2134–2168, 2018.

[49] S. Tombaz, P. Monti, F. Farias, M. Fiorani, L. Wosinska, and J. Zander, "Is backhaul becoming a bottleneck for green wireless access networks?" in *Communications (ICC), 2014 IEEE International Conference on.* IEEE, 2014, pp. 4029–4035.

[50] P. Lassila, M. E. Gebrehiwot, and S. Aalto, "Optimal energy-aware load balancing and base station switch-off control in 5g hetnets," *Computer Networks*, vol. 159, pp. 10–22, 2019.

[51] M. Goudarzi, M. Palaniswami, and R. Buyya, "A fog-driven dynamic resource allocation technique in ultra dense femtocell networks," *Journal of Network and Computer Applications*, vol. 145, p. 102407, 2019.

[52] C. Mergenci and I. Korpeoglu, "Generic resource allocation metrics and methods for heterogeneous cloud infrastructures," *Journal of Network and Computer Applications*, vol. 146, p. 102413, 2019.

[53] T. W. Li S, Zhao J and G. Chuai, "Green resource allocation for user access in cloud-based networks," *Physical Communication*, vol. 37, p. 100853, 2019.

[54] S. Nie, G. R. MacCartney, S. Sun, and T. S. Rappaport, "28 ghz and 73 ghz signal outage study for millimeter wave cellular and backhaul communications," in *Communications (ICC), 2014 IEEE International Conference on.* IEEE, 2014, pp. 4856–4861.

[55] C. Dehos, J. L. González, A. De Domenico, D. Kténas, and L. Dussopt, "Millimeter-wave access and backhauling: the solution to the exponential data traffic increase in 5G mobile communications systems?" *IEEE Communications Magazine*, vol. 52, no. 9, pp. 88–95, 2014.

[56] D. Bojic, E. Sasaki, N. Cvijetic, T. Wang, J. Kuno, J. Lessmann, S. Schmid, H. Ishii, and S. Nakamura, "Advanced wireless and optical technologies for small-cell mobile backhaul with dynamic software-defined management," *IEEE Communications Magazine*, vol. 51, no. 9, pp. 86–93, 2013.

[57] R. Akeela and B. Dezfouli, "Software-defined radios: Architecture, state-of-the-art, and challenges," *Computer Communications*, vol. 128, pp. 106–125, 2018.

[58] M. Karakus and A. Durresi, "A survey: Control plane scalability issues and approaches in software-defined networking (sdn)," *Computer Networks*, vol. 112, pp. 279–293, 2017.

[59] S. Saraswat, V. Agarwal, H. P. Gupta, R. Mishra, A. Gupta, and T. Dutta, "Challenges and solutions in software defined networking: A survey," *Journal of Network and Computer Applications*, vol. 141, pp. 23–58, 2019.

[60] I. F. Akyildiz, P. Wang, and S.-C. Lin, "Softair: A software defined networking architecture for 5g wireless systems," *Computer Networks*, vol. 85, pp. 1–18, 2015.

[61] T. Han and N. Ansari, "A traffic load balancing framework for software-defined radio access networks powered by hybrid energy sources," *IEEE/ACM Transactions on Networking*, vol. 24, no. 2, pp. 1038–1051, 2016.

[62] Q. H. A. S. Khan BS, Jangsher S, "Predicted mobility based profitable relay selection in cooperative cellular network with mobile relays," *Physical Communication*, vol. 37, p. 100808, 2019.

[63] E. Coronado, S. N. Khan, and R. Riggio, "5g-empower: A software-defined networking platform for 5g radio access networks," *IEEE Transactions on Network and Service Management*, 2019.

[64] A. Betzler, D. Camps-Mur, E. Garcia-Villegas, I. Demirkol, and J. J. Aleixendri, "Sodalite: Sdn wireless backhauling for dense 4g/5g small cell networks," *IEEE Transactions on Network and Service Management*, vol. Early Access, 2019.

[65] P. Pirinen, "A brief overview of 5g research activities," in *5G for Ubiquitous Connectivity (5GU), 2014 1st International Conference on.* IEEE, 2014, pp. 17–22.

[66] F. Boccardi, R. W. Heath, A. Lozano, T. L. Marzetta, and P. Popovski, "Five disruptive technology directions for 5g," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 74–80, 2014.

[67] S. Zhang, Q. Wu, S. Xu, and G. Y. Li, "Fundamental green tradeoffs: Progresses, challenges, and impacts on 5g networks," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 1, pp. 33–56, 2017.

[68] M. Jaber, M. A. Imran, R. Tafazolli, and A. Tukmanov, "5g backhaul challenges and emerging research directions: A survey," *IEEE Access*, vol. 4, pp. 1743–1766, 2016.

[69] M. M. Mowla, I. Ahmad, D. Habibi, and Q. V. Phung, "A green communication model for 5g systems," *IEEE Transactions on Green Communications and Networking*, 2017.

[70] M. Dardaillon, K. Marquet, T. Risset, and A. Scherrer, "Software defined radio architecture survey for cognitive testbeds," in *2012 8th International Wireless Communications and Mobile Computing Conference (IWCMC).* IEEE, 2012, pp. 189–194.

[71] T. Chen, M. Matinmikko, X. Chen, X. Zhou, and P. Ahokangas, "Software defined mobile networks: concept, survey, and research directions," *IEEE Communications Magazine*, vol. 53, no. 11, pp. 126–133, 2015.

[72] M. Yang, Y. Li, D. Jin, L. Zeng, X. Wu, and A. V. Vasilakos, "Software-defined and virtualized future mobile and wireless networks: A survey," *Mobile Networks and Applications*, vol. 20, no. 1, pp. 4–18, 2015.

[73] W. Xia, Y. Wen, C. H. Foh, D. Niyato, and H. Xie, "A survey on software-defined networking," *IEEE Communications Surveys Tutorials*, vol. 17, no. 1, pp. 27–51, 2015.

[74] H. I. Kobo, A. M. Abu-Mahfouz, and G. P. Hancke, "A survey on software-defined wireless sensor networks: Challenges and design requirements," *IEEE Access*, vol. 5, pp. 1872–1899, 2017.

[75] L. Peizhe, W. Muqing, L. Wenxing, and Z. Min, "A game-theoretic and energy-efficient algorithm in an improved software-defined wireless sensor network," *IEEE Access*, vol. 5, pp. 13 430–13 445, 2017.

[76] G. A. Akpakwu, B. J. Silva, G. P. Hancke, and A. M. Abu-Mahfouz, "A survey on 5g networks for the internet of things: Communication technologies and challenges," *IEEE Access*, vol. 6, pp. 3619–3647, 2018.

[77] A. Nauman, Y. A. Qadri, M. Amjad, Y. B. Zikria, M. K. Afzal, and S. W. Kim, "Multimedia internet of things: A comprehensive survey," *IEEE Access*, vol. 8, pp. 8202–8250, 2020.

[78] S. Al-Rubaye and J. Aulin, "Grid modernization enabled by sdn controllers: Leveraging interoperability for accessing unlicensed band," *IEEE Wireless Communications*, vol. 24, no. 5, pp. 60–67, 2017.

[79] H. Luo, K. Wu, R. Ruby, Y. Liang, Z. Guo, and L. M. Ni, "Software-defined architectures and technologies for underwater wireless sensor networks: A survey," *IEEE Communications Surveys Tutorials*, vol. 20, no. 4, pp. 2855–2888, 2018.

[80] Z. Ding, L. Shen, F. Yan, W. Xia, and Z. Li, "Energy-efficient routing algorithm with interference mitigation for software-defined wireless sensor networks," in *2018 IEEE 29th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, 2018, pp. 1–5.

[81] H. I. Kobo, A. M. Abu-Mahfouz, and G. P. Hancke, "Fragmentation-based distributed control system for software-defined wireless sensor networks," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 2, pp. 901–910, 2019.

[82] I. Haque, M. Nurujjaman, J. Harms, and N. Abu-Ghazaleh, "Sdsense: An agile and flexible sdn-based framework for wireless sensor networks," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 2, pp. 1866–1876, 2019.

[83] J. Xie, F. R. Yu, T. Huang, R. Xie, J. Liu, C. Wang, and Y. Liu, "A survey of machine learning techniques applied to software defined networking (sdn): Research issues and challenges," *IEEE Communications Surveys Tutorials*, vol. 21, no. 1, pp. 393–430, 2019.

[84] Y. Zhao, Y. Li, X. Zhang, G. Geng, W. Zhang, and Y. Sun, "A survey of networking applications applying the software defined networking concept based on machine learning," *IEEE Access*, vol. 7, pp. 95 397–95 417, 2019.

[85] R. C. A. Alves, D. A. G. Oliveira, G. A. Nunez Segura, and C. B. Margi, "The cost of software-defining things: A scalability study of software-defined sensor networks," *IEEE Access*, vol. 7, pp. 115 093–115 108, 2019.

[86] M. H. Rehmani, A. Davy, B. Jennings, and C. Assi, "Software defined networks-based smart grid communication: A comprehensive survey," *IEEE Communications Surveys Tutorials*, vol. 21, no. 3, pp. 2637–2670, 2019.

[87] N. Marriwala, "Error control coding for software defined radios using soft computing," in *Recent Trends in Image and Signal Processing in Computer Vision.* Springer, 2020, pp. 211–233.

[88] A. Capponi, C. Fiandrino, B. Kantarci, L. Foschini, D. Kliazovich, and P. Bouvry, "A survey on mobile crowdsensing systems: Challenges, solutions, and opportunities," *IEEE Communications Surveys Tutorials*, vol. 21, no. 3, pp. 2419–2465, 2019.

[89] B. Chen, J. Chen, Y. Gao, and J. Zhang, "Coexistence of lte-laa and wi-fi on 5 ghz with corresponding deployment scenarios: A survey," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 1, pp. 7–32, 2016.

[90] A. Roy, S. Midya, K. Majumder, S. Phadikar, and A. Dasgupta, "Optimized secondary user selection for quality of service enhancement of two-tier multi-user cognitive radio network: a game theoretic approach," *Computer Networks*, vol. 123, pp. 1–18, 2017.

[91] N. D. Chatzidiamantis, E. Matskani, L. Georgiadis, I. Koutsopoulos, and L. Tassiulas, "Optimal primary-secondary user cooperation policies in cognitive radio networks," *IEEE Transactions on Wireless Communications*, vol. 14, no. 6, pp. 3443–3455, 2015.

[92] A. Gouissem, R. Hamila, N. Aldhahir, and S. Foufou, "Secondary users selection and sparse narrow-band interference mitigation in cognitive radio networks," *Computer Communications*, vol. 123, pp. 97–115, 2018.

[93] G. Ding, Y. Jiao, J. Wang, Y. Zou, Q. Wu, Y.-D. Yao, and L. Hanzo, "Spectrum inference in cognitive radio networks: Algorithms and applications," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 1, pp. 150–182, 2017.

[94] Z. Khan, J. J. Lehtomäki, L. A. DaSilva, E. Hossain, and M. Latva-Aho, "Opportunistic channel selection by cognitive wireless nodes under imperfect observations and limited memory: A repeated game model," *IEEE Transactions on Mobile Computing*, vol. 15, no. 1, pp. 173–187, 2015.

[95] G. Yang, J. Wang, J. Luo, O. Y. Wen, H. Li, Q. Li, and S. Li, "Cooperative spectrum sensing in heterogeneous cognitive radio networks based on normalized energy detection," *IEEE Transactions on vehicular technology*, vol. 65, no. 3, pp. 1452–1463, 2016.

[96] A. Ali and W. Hamouda, "Advances on spectrum sensing for cognitive radio networks: Theory and applications," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 2, pp. 1277–1304, 2017.

[97] S. Chatterjee, S. P. Maity, and T. Acharya, "Energy -spectrum efficiency trade-off in energy harvesting cooperative cognitive radio networks," *IEEE Transactions on Cognitive Communications and Networking*, 2019.

[98] M. Yousefvand, T. Han, N. Ansari, and A. Khreishah, "Distributed energy-spectrum trading in green cognitive radio cellular networks," *IEEE Transactions on Green Communications and Networking*, vol. 1, no. 3, pp. 253–263, 2017.

[99] X. Huang, T. Han, and N. Ansari, "On green-energy-powered cognitive radio networks," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 2, pp. 827–842, 2015.

[100] G. Naik, J. Liu, and J.-M. J. Park, "Coexistence of wireless technologies in the 5 ghz bands: A survey of existing solutions and a roadmap for future research," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 3, pp. 1777–1798, 2018.

[101] B. Bojović, L. Giupponi, Z. Ali, and M. Miozzo, "Evaluating unlicensed lte technologies: Laa vs lte-u," *IEEE Access*, vol. 7, pp. 89 714–89 751, 2019.

[102] E. Pei and J. Jiang, "Performance analysis of licensed-assisted access to unlicensed spectrum in lte release 13," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 2, pp. 1446–1458, 2018.

[103] B. Wang and K. R. Liu, "Advances in cognitive radio networks: A survey," *IEEE Journal of selected topics in signal processing*, vol. 5, no. 1, pp. 5–23, 2011.

[104] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "Next generation/dynamic spectrum access/cognitive radio wireless networks: A survey," *Computer networks*, vol. 50, no. 13, pp. 2127–2159, 2006.

[105] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *IEEE communications surveys & tutorials*, vol. 11, no. 1, pp. 116–130, 2009.

[106] T. C. Clancy and B. Walker, "Spectrum shaping for interference management in cognitive radio networks," in *SDR Forum Technical Conference*, 2006.

[107] E. Hossain, D. Niyato, and D. I. Kim, "Evolution and future trends of research in cognitive radio: a contemporary survey," *Wireless Communications and Mobile Computing*, vol. 15, no. 11, pp. 1530–1564, 2015.

[108] J. M. Chapin and W. H. Lehr, "Cognitive radios for dynamic spectrum access-the path to market success for dynamic spectrum access technology," *IEEE Communications Magazine*, vol. 45, no. 5, 2007.

[109] A. He, S. Srikanteswara, J. H. Reed, X. Chen, W. H. Tranter, K. K. Bae, and M. Sajadieh, "Minimizing energy consumption using cognitive radio," in *Performance, Computing and Communications Conference, 2008. IPCCC 2008. IEEE International.* IEEE, 2008, pp. 372–377.

[110] H. Y. Lateef, M. Dohler, A. Mohammed, M. M. Guizani, and C. F. Chiasserini, "Towards energy-aware 5g heterogeneous networks," in *Energy Management in Wireless Cellular and Ad-hoc Networks.* Springer, 2016, pp. 31–44.

[111] Y. Pei, Y.-C. Liang, K. C. Teh, and K. H. Li, "Energy-efficient design of sequential channel sensing in cognitive radio networks: optimal sensing strategy, power allocation, and sensing order," *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 8, pp. 1648–1659, 2011.

[112] A. T. Hoang, Y.-C. Liang, D. T. C. Wong, Y. Zeng, and R. Zhang, "Opportunistic spectrum access for energy-constrained cognitive radios," *IEEE Transactions on Wireless Communications*, vol. 8, no. 3, pp. 1206–1211, 2009.

[113] X. Feng, X. Gan, and X. Wang, "Energy-constrained cooperative spectrum sensing in cognitive radio networks," in *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE*. IEEE, 2011, pp. 1–5.

[114] G. Gür and F. Alagöz, "Green wireless communications via cognitive dimension: an overview," *IEEE network*, vol. 25, no. 2, 2011.

[115] D. J. Kadhim, S. Gong, W. Xia, W. Liu, and W. Cheng, "Power efficiency maximization in cognitive radio networks," in *Wireless Communications and Networking Conference, 2009. WCNC 2009. IEEE*. IEEE, 2009, pp. 1–6.

[116] R. Min and A. Chandrakasan, "A framework for energy-scalable communication in high-density wireless networks," in *Proceedings of the 2002 international symposium on Low power electronics and design*. ACM, 2002, pp. 36–41.

[117] M. Pirmoradian, O. Adigun, and C. Politis, "An analytical evaluation of energy consumption in cooperative cognitive radio networks," in *ITU Kaleidoscope: Building Sustainable Communities (K-2013), 2013 Proceedings of*. IEEE, 2013, pp. 1–6.

[118] M. C. Oto and O. B. Akan, "Energy-efficient packet size optimization for cognitive radio sensor networks," *IEEE Transactions on Wireless Communications*, vol. 11, no. 4, pp. 1544–1553, 2012.

[119] Y. Liu, S. Xie, Y. Zhang, R. Yu, and V. C. Leung, "Energy-efficient spectrum discovery for cognitive radio green networks," *Mobile networks and applications*, vol. 17, no. 1, pp. 64–74, 2012.

[120] M. Pirmoradian, O. Adigun, and C. Politis, "Adaptive power control scheme for energy efficient cognitive radio networks," in *Communications (ICC), 2012 IEEE International Conference on*. IEEE, 2012, pp. 6988–6992.

[121] E. Bedeer, O. Amin, O. A. Dobre, and M. H. Ahmed, "Energy-aware cognitive radio systems," in *Energy Management in Wireless Cellular and Ad-hoc Networks*. Springer, 2016, pp. 247–272.

[122] S. Wang, M. Ge, and W. Zhao, "Energy-efficient resource allocation for ofdm-based cognitive radio networks," *IEEE Transactions on Communications*, vol. 61, no. 8, pp. 3181–3191, 2013.

[123] B. Ismaiel, M. Abolhasan, D. Smith, W. Ni, and D. Franklin, "A survey and comparison of device-to-device architecture using lte unlicensed band," in *2017 IEEE 85th Vehicular Technology Conference (VTC Spring)*, 2017, pp. 1–5.

[124] A. Mukherjee, J. Cheng, S. Falahati, H. Koorapaty, D. H. Kang, R. Karaki, L. Falconetti, and D. Larsson, "Licensed-assisted access lte: coexistence with ieee 802.11 and the evolution toward 5g," *IEEE Communications Magazine*, vol. 54, no. 6, pp. 50–57, 2016.

[125] V. Maglogiannis, A. Shahid, D. Naudts, E. De Poorter, and I. Moerman, "Enhancing the coexistence of lte and wi-fi in unlicensed spectrum through convolutional neural networks," *IEEE Access*, vol. 7, pp. 28 464–28 477, 2019.

[126] U. Challita, L. Dong, and W. Saad, "Proactive resource management for lte in unlicensed spectrum: A deep learning perspective," *IEEE Transactions on Wireless Communications*, vol. 17, no. 7, pp. 4674–4689, 2018.

[127] L. Li, J. P. Seymour, L. J. Cimini, and C. Shen, "Coexistence of wi-fi and laa networks with adaptive energy detection," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 11, pp. 10 384–10 393, 2017.

[128] C. Zhang, P. Patras, and H. Haddadi, "Deep learning in mobile and wireless networking: A survey," *IEEE Communications Surveys Tutorials*, vol. 21, no. 3, pp. 2224–2287, 2019.

[129] W. Wu, Q. Yang, R. Liu, and K. S. Kwak, "Protocol design and resource allocation for lte-u system utilizing licensed and unlicensed bands," *IEEE Access*, vol. 7, pp. 67 068–67 080, 2019.

[130] J. Jeon, H. Niu, Q. C. Li, A. Papathanassiou, and G. Wu, "Lte in the unlicensed spectrum: Evaluating coexistence mechanisms," in *2014 IEEE Globecom Workshops (GC Wkshps)*, 2014, pp. 740–745.

[131] Y. Li, F. Baccelli, J. G. Andrews, T. D. Novlan, and J. C. Zhang, "Modeling and analyzing the coexistence of wi-fi and lte in unlicensed spectrum," *IEEE Transactions on Wireless Communications*, vol. 15, no. 9, pp. 6310–6326, 2016.

[132] H. Zhang, Y. Xiao, L. X. Cai, D. Niyato, L. Song, and Z. Han, "A multi-leader multi-follower stackelberg game for resource management in lte unlicensed," *IEEE Transactions on Wireless Communications*, vol. 16, no. 1, pp. 348–361, 2017.

[133] S. Zhang, N. Zhang, S. Zhou, J. Gong, Z. Niu, and X. Shen, "Energy-aware traffic offloading for green heterogeneous networks," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 5, pp. 1116–1129, 2016.

[134] F. Kong, X. Sun, V. C. Leung, and H. Zhu, "Delay-optimal biased user association in heterogeneous networks," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 8, pp. 7360–7371, 2017.

[135] H. Kim, G. De Veciana, X. Yang, and M. Venkatachalam, "Distributed α-optimal user association and cell load balancing in wireless networks," *IEEE/ACM Transactions on Networking (TON)*, vol. 20, no. 1, pp. 177–190, 2012.

[136] P. Naghavi, S. H. Rastegar, V. Shah-Mansouri, and H. Kebriaei, "Learning rat selection game in 5g heterogeneous networks," *IEEE Wireless Communications Letters*, vol. 5, no. 1, pp. 52–55, 2016.

[137] N. Trabelsi, C. S. Chen, R. El Azouzi, L. Roullet, and E. Altman, "User association and resource allocation optimization in lte cellular networks," *IEEE Transactions on Network and Service Management*, vol. 14, no. 2, pp. 429–440, 2017.

[138] S. Singh, H. S. Dhillon, and J. G. Andrews, "Offloading in heterogeneous networks: Modeling, analysis, and design insights," *IEEE Transactions on Wireless Communications*, vol. 12, no. 5, pp. 2484–2497, 2013.

[139] Q. Ye, B. Rong, Y. Chen, M. Al-Shalash, C. Caramanis, and J. G. Andrews, "User association for load balancing in heterogeneous cellular networks," *IEEE Transactions on Wireless Communications*, vol. 12, no. 6, pp. 2706–2716, 2013.

[140] E. Aryafar, A. Keshavarz-Haddad, M. Wang, and M. Chiang, "Rat selection games in hetnets," in *INFOCOM, 2013 Proceedings IEEE*. IEEE, 2013, pp. 998–1006.

[141] Y. Bejerano and S.-J. Han, "Cell breathing techniques for load balancing in wireless lans," *IEEE transactions on Mobile Computing*, vol. 8, no. 6, pp. 735–749, 2009.

[142] A. Damnjanovic, J. Montojo, Y. Wei, T. Ji, T. Luo, M. Vajapeyam, T. Yoo, O. Song, and D. Malladi, "A survey on 3gpp heterogeneous networks," *IEEE Wireless communications*, vol. 18, no. 3, 2011.

[143] P. Gandotra and R. K. Jha, "A survey on green communication and security challenges in 5g wireless communication networks," *Journal of Network and Computer Applications*, vol. 96, pp. 39–61, 2018.

[144] D. Liu, L. Wang, Y. Chen, M. Elkashlan, K. K. Wong, R. Schober, and L. Hanzo, "User association in 5g networks: A survey and an outlook," *IEEE Communications Surveys Tutorials*, vol. 18, no. 2, pp. 1018–1044, Secondquarter 2016.

[145] Y. Wang, X. Tao, X. Zhang, and G. Mao, "Joint caching placement and user association for minimizing user download delay," *IEEE Access*, vol. 4, pp. 8625–8633, 2016.

[146] T. Van Chien, E. Bjrnson, and E. G. Larsson, "Joint power allocation and user association optimization for massive mimo systems," *IEEE Transactions on Wireless Communications*, vol. 15, no. 9, pp. 6384–6399, 2016.

[147] X. Ge, X. Li, H. Jin, J. Cheng, and V. C. M. Leung, "Joint user association and user scheduling for load balancing in heterogeneous networks," *IEEE Transactions on Wireless Communications*, vol. 17, no. 5, pp. 3211–3225, 2018.

[148] L. Qi, M. Peng, Y. Liu, and S. Yan, "Advanced user association in non-orthogonal multiple access-based fog radio access networks," *IEEE Transactions on Communications*, vol. 67, no. 12, pp. 8408–8421, 2019.

[149] M. L. Attiah, A. A. M. Isa, Z. Zakaria, M. Abdulhameed, M. K. Mohsen, and I. Ali, "A survey of mmwave user association mechanisms and spectrum sharing approaches: an overview, open issues and challenges, future research trends," *Wireless Networks*, pp. 1–28, 2019.

[150] X. Sun, N. Ansari, and R. Fierro, "Jointly optimized 3d drone mounted base station deployment and user association in drone assisted mobile access networks," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 2, pp. 2195–2203, 2020.

[151] F. Cheng, D. Zou, J. Liu, J. Wang, and N. Zhao, "Learning-based user association for dual-uav enabled wireless networks with d2d connections," *IEEE Access*, vol. 7, pp. 30 672–30 682, 2019.

[152] T. H. L. Dinh, M. Kaneko, and L. Boukhatem, "Energy-efficient user association and beamforming for 5g fog radio access networks," in *2019 16th IEEE Annual Consumer Communications Networking Conference (CCNC)*, 2019, pp. 1–6.

[153] M. Kamel, W. Hamouda, and A. Youssef, "Ultra-dense networks: A survey," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 4, pp. 2522–2545, 2016.

[154] Q. Fan and N. Ansari, "Green energy aware user association in heterogeneous networks," in *2016 IEEE wireless communications and networking conference.* IEEE, 2016, pp. 1–6.

[155] Y. Kim, S. Lee, and D. Hong, "Performance analysis of two-tier femtocell networks with outage constraints," *IEEE Transactions on Wireless Communications*, vol. 9, no. 9, pp. 2695–2700, 2010.

[156] R. Fantacci, D. Marabissi, D. Tarchi, and I. Habib, "Adaptive modulation and coding techniques for ofdma systems," *IEEE Transactions on Wireless Communications*, vol. 8, no. 9, 2009.

[157] A. Ladányi, D. López-Pérez, A. Jüttner, X. Chu, and J. Zhang, "Distributed resource allocation for femtocell interference coordination via power minimisation," in *GLOBECOM Workshops (GC Wkshps), 2011 IEEE.* IEEE, 2011, pp. 744–749.

[158] M. M. Mowla, I. Ahmad, D. Habibi, and Q. V. Phung, "An energy efficient resource management and planning system for 5g networks," in *Consumer Communications & Networking Conference (CCNC), 2017 14th IEEE Annual.* IEEE, 2017, pp. 216–224.

[159] L. Kleinrock, *Queueing systems, volume 2: Computer applications.* wiley New York, 1976, vol. 66.

[160] T. Han and N. Ansari, "Heuristic relay assignments for green relay assisted device to device communications," in *Global Communications Conference (GLOBECOM), 2013 IEEE.* IEEE, 2013, pp. 468–473.

[161] H.-S. Jo, Y. J. Sang, P. Xia, and J. G. Andrews, "Heterogeneous cellular networks with flexible cell association: A comprehensive downlink sinr analysis," *IEEE Transactions on Wireless Communications*, vol. 11, no. 10, pp. 3484–3495, 2012.

[162] T. Zhou, Y. Huang, L. Fan, and L. Yang, "Load-aware user association with quality of service support in heterogeneous cellular networks," *IET Communications*, vol. 9, no. 4, pp. 494–500, 2015.

[163] M. Ismail, W. Zhuang, E. Serpedin, and K. Qaraqe, "A survey on green mobile networking: From the perspectives of network operators and mobile users," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 3, pp. 1535–1556, 2015.

[164] T. Han and N. Ansari, "A traffic load balancing framework for software-defined radio access networks powered by hybrid energy sources," *IEEE Transactions on Networking*, vol. 24, no. 2, pp. 1038–1051, 2017.

[165] D. S. Baum, J. Hansen, J. Salo, G. Del Galdo, M. Milojevic, and P. Kyösti, "An interim channel model for beyond-3g systems: extending the 3gpp spatial channel model (scm)," in *2005 IEEE 61st Vehicular Technology Conference*, vol. 5. IEEE, 2005, pp. 3132–3136.

[166] T. Han and N. Ansari, "On optimizing green energy utilization for cellular networks with hybrid energy supplies," *IEEE Transactions on Wireless Communications*, vol. 12, no. 8, pp. 3872–3882, 2013.

[167] T. O. Olwal, K. Djouani, and A. M. Kurien, "A survey of resource management toward 5g radio access networks," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 3, pp. 1656–1686, 2016.

[168] F. Richter and G. Fettweis, "Cellular mobile network densification utilizing micro base stations." in *ICC*. Citeseer, 2010, pp. 1–6.

[169] T. Han and N. Ansari, "A traffic load balancing framework for software-defined radio access networks powered by hybrid energy sources," *IEEE/ACM Transactions on Networking*, vol. 24, no. 2, pp. 1038–1051, 2015.

[170] R. L. Kurrle, "Resource allocation for smart phones in 4g lte-advanced carrier aggregation," Ph.D. dissertation, Virginia Tech, 2012.

[171] A. R. Elsherif, W.-P. Chen, A. Ito, and Z. Ding, "Resource allocation and inter-cell interference management for dual-access small cells," *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 6, pp. 1082–1096, 2015.

[172] B. Chen, J. Chen, Y. Gao, and J. Zhang, "Coexistence of lte-laa and wi-fi on 5 ghz with corresponding deployment scenarios: A survey," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 1, pp. 7–32, 2017.

[173] Y. Wu, Y. He, L. P. Qian, J. Huang, and X. Shen, "Optimal resource allocations for mobile data offloading via dual-connectivity," *IEEE Transactions on Mobile Computing*, vol. 17, no. 10, pp. 2349–2365, 2018.

[174] F. Wang, C. Xu, L. Song, and Z. Han, "Energy-efficient resource allocation for device-to-device underlay communication," *IEEE Transactions on Wireless Communications*, vol. 14, no. 4, pp. 2082–2092, 2015.

[175] F. Capozzi, G. Piro, L. A. Grieco, G. Boggia, and P. Camarda, "Downlink packet scheduling in lte cellular networks: Key design issues and a survey," *IEEE Communications Surveys & Tutorials*, vol. 15, no. 2, pp. 678–700, 2016.

[176] "Evolution of land mobile radio (including personal) communications: Cost 231," https://www.awe-communications.com/propagation/urban/cost, accessed: 2019-10-24.

[177] T. Han and N. Ansari, "Network utility aware traffic load balancing in backhaul-constrained cache-enabled small cell networks with hybrid power supplies," *IEEE Transactions on Mobile Computing*, vol. 16, no. 10, pp. 2819–2832, 2017.

[178] "Synergy australia," https://www.synergy.net.au, accessed: 2019-11-01.

[179] M. R. Mili, L. Musavian, K. A. Hamdi, and F. Marvasti, "How to increase energy efficiency in cognitive radio networks," *IEEE Transactions on Communications*, vol. 64, no. 5, pp. 1829–1843, 2016.

[180] M. R. Amini, M. Mahdavi, and M. J. Omidi, "Discrete-time markov chain analysis of energy efficiency in a cr network regarding primary and secondary traffic with primary user returns," *IEEE Access*, vol. 6, pp. 22 305–22 323, 2018.

[181] E. F. Orumwense, T. J. Afullo, and V. M. Srivastava, "Secondary user energy consumption in cognitive radio networks," in *AFRICON, 2015*. IEEE, 2015, pp. 1–5.

[182] "Ieee standard for safety levels with respect to human exposure to radio frequency electromagnetic fields, 3 khz to 300 ghz." [Online]. Available: http://emfguide.itu.int/pdfs/C95.1-2005.pdf

[183] Z. Shu, Y. Qian, and S. Ci, "On physical layer security for cognitive radio networks," *IEEE Network*, vol. 27, no. 3, pp. 28–33, 2013.

[184] M. Bouabdellah, N. Kaabouch, F. El Bouanani, and H. Ben-Azza, "Network layer attacks and countermeasures in cognitive radio networks: A survey," *Journal of information security and applications*, vol. 38, pp. 40–49, 2019.

[185] K. An, M. Lin, J. Ouyang, and W.-P. Zhu, "Secure transmission in cognitive satellite terrestrial networks," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 11, pp. 3025–3037, 2016.

[186] M. Jo, L. Han, D. Kim, and H. P. In, "Selfish attacks and detection in cognitive radio ad-hoc networks," *IEEE network*, vol. 27, no. 3, pp. 46–50, 2013.

[187] A. G. Fragkiadakis, E. Z. Tragos, and I. G. Askoxylakis, "A survey on security threats and detection techniques in cognitive radio networks," *IEEE Communications Surveys & Tutorials*, vol. 15, no. 1, pp. 428–445, 2013.

[188] L. Zhang, G. Ding, Q. Wu, Y. Zou, Z. Han, and J. Wang, "Byzantine attack and defense in cognitive radio networks: A survey," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 3, pp. 1342–1363, 2016.

[189] I. S. Association *et al.*, "Ieee standard for information technology-telecommunications and information exchange between systems-local and metropolitan area networks-specific requirements, part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications," *IEEE Std*, vol. 802, p. 2793, 2012.

[190] S. Xu, Y. Li, Y. Gao, Y. Liu, and H. Gačanin, "Opportunistic coexistence of lte and wifi for future 5g system: Experimental performance evaluation and analysis," *IEEE Access*, vol. 6, pp. 8725–8741, 2018.

[191] "Multifire release 1.0 technical paper: a new way to wireless," www.multifire.org, accessed 1 Oct. 2019.

[192] C. Rosa, M. Kuusela, F. Frederiksen, and K. I. Pedersen, "Standalone lte in unlicensed spectrum: Radio challenges, solutions, and performance of multefire," *IEEE Communications Magazine*, vol. 56, no. 10, pp. 170–177, 2018.

[193] Y. Gu, H. Chen, C. Zhai, Y. Li, and B. Vucetic, “Minimizing age of information in cognitive radio-based iot systems: Underlay or overlay?” *IEEE Internet of Things Journal*, vol. 6, no. 6, pp. 10 273–10 288, 2019.

[194] S. Sun, Y. Ju, and Y. Yamao, “Overlay cognitive radio ofdm system for 4g cellular networks,” *IEEE Wireless Communications*, vol. 20, no. 2, pp. 68–73, 2013.

[195] W. Liang, K. Di Wang, J. Shi, L. Li, and G. K. Karagiannidis, “Distributed sequential coalition formation algorithm for spectrum allocation in underlay cognitive radio networks,” *IEEE Access*, vol. 7, pp. 56 803–56 816, 2019.

[196] L. Xiang, D. W. K. Ng, R. Schober, and V. W. Wong, “Cache-enabled physical layer security for video streaming in backhaul-limited cellular networks,” *IEEE Transactions on Wireless Communications*, vol. 17, no. 2, pp. 736–751, 2018.

[197] R. Khan, P. Kumar, D. N. K. Jayakody, and M. Liyanage, “A survey on security and privacy of 5g technologies: Potential solutions, recent advancements and future directions,” *IEEE Communications Surveys & Tutorials*, 2019.

[198] H. Kim, G. De Veciana, X. Yang, and M. Venkatachalam, “Distributed *alpha*-optimal user association and cell load balancing in wireless networks,” *IEEE/ACM Transactions on Networking*, vol. 20, no. 1, pp. 177–190, 2011.

[199] D. A. Chekired, L. Khoukhi, and H. T. Mouftah, “Decentralized cloud-sdn architecture in smart grid: A dynamic pricing model,” *IEEE Transactions on Industrial Informatics*, vol. 14, no. 3, pp. 1220–1231, 2017.

[200] H. Khaled, I. Ahmad, D. Habibi, and Q. V. Phung, “An energy-aware cognitive radio-based communication approach for next generation wireless networks,” in *2019 IEEE 21st International Conference on High Performance Computing and Communications; IEEE 17th International Conference on Smart City; IEEE 5th International Conference on Data Science and Systems (HPCC/SmartCity/DSS)*. IEEE, 2019, pp. 1817–1824.

[201] G. Bianchi, “Performance analysis of the ieee 802.11 distributed coordination function,” *IEEE Journal on selected areas in communications*, vol. 18, no. 3, pp. 535–547, 2000.

[202] “Optus australia,” https://www.optus.com.au, accessed: 2019-10-03.

[203] Q. Fan and N. Ansari, “Towards throughput aware and energy aware traffic load balancing in heterogeneous networks with hybrid power supplies,” *IEEE Transactions on Green Communications and Networking*, vol. 2, no. 4, pp. 890–898, 2018.

[204] A. Mesodiakaki, F. Adelantado, A. Antonopoulos, E. Kartsakli, L. Alonso, and C. Verikoukis, “Energy impact of outdoor small cell backhaul in green heterogeneous networks,” in *2014 IEEE 19th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*. IEEE, 2014, pp. 11–15.

[205] X. Liu and N. Ansari, “Profit-driven user association and smart grid energy transfer in green cellular networks,” *IEEE Transactions on Vehicular Technology*, vol. 68, no. 10, pp. 10 111–10 120, 2019.

[206] J. Opadere, Q. Liu, T. Han, and N. Ansari, "Energy-efficient virtual radio access networks for multi-operators cooperative cellular networks," *IEEE Transactions on Green Communications and Networking*, vol. 3, no. 3, pp. 603–614, 2019.