HAWASSA UNIVERSITY
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PERFORMANCE EVALUATION OF INTERFERENCE MANAGEMENT STRATEGIES IN 5G HETEROGENEOUS NETWORKS

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A THESIS

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As members of the board of examiners of the final master’s degree open defense. we certify that we have lead evaluated the thesis prepared by Elias Mamushet under the title performance evaluation of interference management strategies in 5G heterogeneous networks, and recommend that it be accepted as fulfilling the thesis requirement for the degree of M.Sc. in Communication Engineering and Networking.

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Declaration

I hereby declare that this M.Sc. thesis is my original work and has not been presented for a degree in Hawassa University and other institutions, and all sources of material used for this thesis have been duly acknowledged.

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Abstract

In the rapid growth of the internet, connected mobile devices need ultra-high-speed and high-definition multimedia services. In order to meet the demands of the future networks, International Mobile Telecommunication system for 2020 (IMT-2020) indicates that the wireless spectrum resource requirements for 5G wireless networks are primarily a result of the growing demand for system capacity. Due to the increase of mobile data traffic, heterogeneous networks (HetNets) are the promising approach to handle the demand of the recent mobile traffic load. The development of HetNets facilitates subscribers Quality of Experience (QoE) guarantee and higher data rate. However, the interference management is one of the challenges in HetNets due to the coexistence of multiple small cells. In this thesis focus on the capacity and reliability improvement investigation of HetNets deployment using stochastic geometry base station deployment. The simulation result shows that the smaller user densities have higher per-user capacity due to the sufficient available channel resources relative to the user density and smaller interference is resulting from the smaller quantity that a given sub-channel is occupied. As the number of subscribers increases the per-user capacity decreases because the available spectrum resource is allocated to each user.

The increment in Pico Base Station (PBS) density causes more interference between picocells and when PBS density is high enough, the receivers in picocells severely suffer interference from neighboring receivers. The area spectral efficiency of picocells is lower while the MU power is high. The outage probability of both uplink and downlink transmissions are increasing as PBS density increases. This is due to the fact that high PBS density causes more interference to the overall network and with higher MU density, the outage probabilities for picocells is high. Finally, when the number of cooperating BSs and transmit power of BSs increases the energy efficiency of the HetNets is decreased while the number of cooperating BSs and transmit power of BSs increases the spectral efficiency of the HetNets is increased.

Keywords:- Heterogeneous Networks (HetNets), Macrocell User (MU), Base Stations (BSs), Pico Base Station (PBS), 5G (Fifth Generations), stochastic geometry, outage probability, and data rate.

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List of abbreviations

Acronym	**Description**
3G	3rd Generation
3GPP	3rd Generation Partnership Project
4G	4th Generation
5G	5th Generations
BS(s)	Base Station(s)
CCDF	Complementary Cumulative Distribution Function
CDF	Cumulative Distribution Function
CoMP	Coordinated Multi-Point
D2D	Device to Device
DL	Downlink
DSL	Digital Subscriber Line
EE	Energy Efficiency
eICIC	Enhanced ICIC
eMBB	enhanced Mobile Broadband
eNB	Evolved Node Base station
FAP(s)	Femto Access Point(s)
FFR	Fractional Frequency Factor
Gbps	Gigabits per second
HetNet(s)	Heterogeneous Network(s)

ICIC	Inter-cell interference coordination
IEEE	Institute of Electrical and Electronics Engineers
i.i.d.	Independent and identically distributed
IMT-A	International Mobile Telecommunication-Advanced
IoT	Internet of Things
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
MBS(s)	Macro Base Station(s)
MHCPP	Matern Hard Core Process
MNO	Mobile Network Operators
MU(s)	Macro User(s)
NGMN	Next Generation Mobile Network
PG	Promotion Group
PPP	Poisson Point Process
PU(s)	Pico User(s)
QoE	Quality of Experience
QoS	Quality of Service
RAT	Radio Access Technologies
RATGs	Radio Access Technologies Groups

RRM	Radio Resource Management
SBS(s)	Small cell BS(s)
SE	Spectral Efficiency
SINR	Signal to Interference plus Noise Ratio
SIR	Signal to Interference Ratio
SNR	Signal to Noise Ratio
UE(s)	User Equipment(s)
UL	Uplink
WRC	World Radio-communication Conference

Notations

Notation	Description
$\mathbf{E}[.]$	Expectation
$\|.\|$	The absolute value of a scalar or determinant of a matrix
$\|\|.\|\|$	Euclidean norm
$\boldsymbol{\Phi_m}$	The location of MBSs in homogeneous PPP
$\boldsymbol{\Phi_p}$	The location of PBSs in independent MHCPP
$\boldsymbol{\Phi_l}$	The parent point process
$\boldsymbol{\mu_m}(\boldsymbol{P_M})$	The transmit power of each MBSs
$\boldsymbol{\mu_p}$	The transmit power of each PBSs
$\boldsymbol{\lambda_m}$	The density of MBSs
$\boldsymbol{\lambda_p}$	The density of PBSs
$\boldsymbol{\lambda_l}$	The density of MBSs and PBSs
$\boldsymbol{\theta_m}$	SIR threshold for MUs
$\boldsymbol{\theta_p}$	SIR threshold for PUs
$\boldsymbol{r_m}$	The distance between MU and served MBS
$\boldsymbol{r_p}$	The distance between PU and served PBS
$\boldsymbol{I_{mm}}$	The interference from the MBSs to the MUs
$\boldsymbol{I_{pm}}$	The interference from the PBSs to the MUs
$\boldsymbol{I_{pp}}$	The interference from the PBSs to the PUs

I_{mp}	The interference from the MBSs to the PUs
α	Path loss constant
D_m	The coverage regions of the MBS
D_p	The coverage regions of the PBS
$\mathbb{R}^{\mathbf{d}}$	d- dimensional set
$\mathbb{R}^{\mathbf{2}}$	2- dimensional set
$\bar{c}$	The average number of points per cluster
ϵ_m	The outage probability of the MUs
ϵ_p	The outage probability of the PUs
$\mathcal{L}_{I_{mm}}$	The Laplace transform of I_{mm}
$\mathcal{L}_{I_{pp}}$	The Laplace transform of I_{pp}
$\mathcal{L}_{I_{mp}}$	The Laplace transform of I_{mp}
$\mathcal{L}_{I_{pm}}$	The Laplace transform of I_{pm}
C_m	Per-user capacity of MU
C_p	Per-user capacity of PU
p_C	The coverage probability

Chapter One

Introduction

According to research and industry forecasts, the demand for cellular broadband data is increasing as the number of massive internet connected devices [1]. Ericsson illustration shows that there will be 50 billion internet-connected devices by 2020. Users replace their home desktop with smartphones and tablets to make video calls, download videos, and transfer data. These applications served by service providers consume more bandwidth than before [2]. At the aforementioned time, users demand high capacity, reliable and fast service with affordable price from their service provider regardless of their location and application they are using. In order to cope with the dramatic growth of customer demand and overcome the limits of existing cellular networks, it is necessary for operators to increase the data capacity and their network coverage significantly.

1.1 Background

In order to meet the demands of future networks and the approaching of higher performance for mobile communications, regulatory groups such as the International Mobile Telecommunication (IMT) system for 2020 and beyond (IMT-2020), the International Telecommunication Union (ITU) under the United Nations in 2012, the Mobile and Wireless Communications enablers for the Twenty-twenty Information Society, and the 5G Infrastructure Public-Private Partnership have officially presented the 5G mobile network and standardization. The current goal is to reach a consensus on demand and index and to achieve unity in concept, paradigm, and views on key technologies. Compared to 3G and 4G, 5G represents a series of forward-looking technologies with an accent on integrity and entireness to advance and complement existing systems. Wireless access technologies including 3G, 4G, and Wi-Fi remain essential components of 5G [3], [4] .

Most mobile communications industries have started out to express constituent opinions of emerging 5G technologies. 5G technical essential requirements include peak data transmission rates greater than 10 Gbps, neighborhood edge data transmission rates of at least 100 Mbps and a 1-millisecond end-to-end delay. The draft recommendation also determine three key usage scenarios for 5G: (1) enhanced mobile broadband; (2) ultra-high reliable and low-latency communication; and (3) massive machine type communications.

1.2 Statement of the problem

The deployment of HetNets infrastructure improves the coverage and data rate of end users. However, interference is the primary cause for impacting the network performance due to the coexistence of small cells power allocation, the similarity of frequency bands, time slots or resource blocks. Hence, independent resource allocation is performed at each BS and cell edge users of adjacent BSs may use the same radio resources result in interference and degradation in network performance.

1.3 Objectives

1.3.1 General objective

The primary aim of this thesis is performance evaluation of interference management in 5G two-tier HetNets using stochastic geometry of BSs deployment.

1.3.2 Specific objectives

- ✓ To investigate the interference in intra-tier MBSs and PBSs dependency in 5G HetNets using PPP and MHCPP BSs deployment.
- ✓ To investigate and analyze the density of MU and PU on the HetNets interference based on per-user spectral efficiency and area spectral efficiency.
- ✓ To evaluate the performance of picocells density and transmission power of MBSs in uplink and downlink transmissions for HetNets based on outage probability and area spectral efficiency.

- ✓ To compare and evaluate the effects of a number of cooperating BSs and transmitting power of BSs approach for HetNets based on spectral and energy efficiency.

1.4 Methodology

The following activities are using to achieve the aforementioned objectives.

I) Literature Review

Present theory in a heterogeneous network and 5G interference characterizations and management strategies from different journals, books, and conferences.

II) System Design

Exhibit the system model requirements, operating environment, system, and subsystem architecture in MBSs and PBSs using stochastic geometry BSs deployment respectively.

III) Mathematical Model and Analysis

Describes the detail mathematical modeling and interferences analysis of MBSs and PBSs in HetNets deployment.

IV) Simulation Implementation and Analysis

Involves configuration of the network parameters in HetNets and performance is evaluated by considering MU density, PU density, PBSs density, hotspot area, number of cooperating BSs, and transmitting power of BSs in intra-tier dependency with point process BSs deployment. The result are analyzed based on outage probability, per-user spectral efficiency, area spectral efficiency, and energy efficiency. Then, the results are analyzed using those performance metrics.

1.5 Related work

During the last decade, extended research in the inter-cell interference (ICI) management has been carried out and remarkable progress has been achieved [4], [5], [7]. As the next generation wireless mobile communication system follows a large change in its network structure and deployment plan, there are so many challenges toward the direct application of conventional inter-cell interference management schemes. To make out with the different technical challenges along with the effective interference mitigation several techniques have proposed by researchers that vary depending on the specific scenarios and physical layer of technology [8], [9] .

Some key challenges to mitigate the interference in multi-tier heterogeneous cellular networks, as a result of the comparison between the existing cell association and power control schemes are as follows:

In [10], discusses new theoretical models for understanding the 5G heterogeneous cellular networks of tomorrow, and the practical constraints and challenges that operators must tackle in order for these networks to reach their potential. However, it is not addressed the density of macro users and stochastic geometry BSs deployment.

In [11], proposed the optimum solutions for downlink Optimized Cell Association and Power Control (CAPC) problems in 5G for the UL due to the various aspects such as the status of the BSs and state of the channel of each UE. In order to optimize this issue, joint optimization frameworks must be provided or as proposed in, the mobile users can connect with two different BSs for uplink and downlink transmissions, which are expected to be the case in 5G multi-tier cellular networks. However, BSs are deployed in rectangular pattern and it not consider the relationship betewwn MUs and PUs density effect.

In [12], A UE may experience the highest DL power from the Macrocell, whereas the highest UL path gain may be from a nearby small cell. In this case, the UE can associate to the Macrocell in the DL and to the small cell in the UL. In this scenario, the CoMP scheme can be used to mitigate the interference in the network which requires strong integration between low power nodes and the network in order to obtain the user’s location and channel state. However, it is not consider intra-tier dependence between MBSs and PBSs

In [13], Cell Range Expansion (CRE) connects UEs to the cell that provides the strongest DL received signal. But in the case when all the UEs are connected to the macrocell because of their large transmit power rather than to Picocells located at a shorter distance with less number of serving UEs, the traffic load were unevenly distributed. In this technique, the DL power of a low power BSs increases so that more users can be associated to the low power BSs. Due to CRE, the offload users which will get an adverse channeling effect from the low power BSs will get a strong interference from the high power BSs. However, it is not consider intra-tier dependence between MBSs and PBSs interference anlysis HetNets.

1.6 Scope and limitation of the thesis

In this thesis, it addressed the problem of interference in 5G two-tier HetNets performances due to the intra-tier dependence between MBSs and PBSs using stochastic geometry BSs deployment. It consisting of MBSs with higher transmission power and PBSs with lower transmission power is considered. In addition, the HetNets performance is evaluated by considering MU density, PU density, PBSs density, hotspot area , number of cooperating BSs, and transmitting power of BSs in intra-tier dependency in point process BSs deployment. The result are analyzed based on outage probability, per-user spectral efficiency, area spectral efficiency, and energy efficiency.

1.7 Thesis outline

The rest of the thesis is organized as follows:

Chapter 2 gives an overview of 5G network architecture requirements, 5G spectrum demand, HetNets architecture, HetNets challenges, types of the interference management approach, and types of stochastic geometry in BSs deployment.

Chapter 3 describes the overview of HetNets model, two-tier HetNets with intra-tier dependencies, interference and outage analysis of MUs and PUs, comparison of two-tier HetNets independent PPP model, and Simulation assumption metrics value.

Chapter 4 focuses on the simulation result and discussion of per-user spectral efficiency vs threshold SIR, describes per-user spectral efficiency vs threshold SIR at average number of resource block, ASE Vs user density, ASE Vs hotspot area, ASE Vs PBS density, outage probabilities of picocells Vs PBSs density, Energy efficiency Vs number of cooperating BSs, Spectral efficiency Vs number of cooperating BSs, Energy efficiency Vs transmitting power of BSs, and Spectral efficiency Vs transmitting power of BSs are discussed on this chapter.

Chapter 5 concludes this thesis along with some limitation and future research scopes.

Chapter Two

5G and Heterogeneous Networks

2.1 Introduction

A mobile and connected society is emerging in the near future, which is characterized by an enormous amount of growth in connectivity, traffic and a much broader range of use scenarios [15]. G. Some typical trends are summarized as follows:

- **The explosive growth of data traffic:** The global data traffic will increase by more than 200 times from 2010 to 2020, and about 20,000 times from 2010 to 2030;
- **The great increase in connected devices:** While smartphones are expected to remain as the main personal devices and Machine Type Communication (MTC) will continue to increase;
- **Continuous emergence of new services:** Different kinds of services, e.g., services from enterprises, from vertical industries and Internet companies will be exploited.

There are two phases of 5G requirements research by different organizations. Phase 1 focuses on 5G use cases and high-level key capabilities of 5G networks and can be regarded as the 5G vision stage. In Phase 1, ITU has released the vision recommendation and defined the key capabilities of 5G. 3GPP started the smarter program and studied 5G use cases and requirements. Next Generation Mobile Network (NGMN) completed a 5G whitepaper and defined a large number of 5G use cases and requirements. IMT-2020 Promotion Group (PG) released the 5G vision and requirements whitepaper in May 2014, which aims to contribute to the ITU-R work in Phase 1. Phase 2 focuses on 5G deployment scenarios and detailed technical requirements. There are two important reports in Phase 2. One is the IMT-2020 technical performance requirements from ITU-R is completed in February 2017, while the other is the scenarios and requirements technical report from 3GPP which will be completed in March 2017. NGMN has started the relevant work at the beginning of 2015 and drafted several liaisons to 3GPP and ITU by March 2016. IMT-2020 PG plans to complete the evaluation scenarios and the Key Performance

Indicator (KPI) report in the first half of 2016, and it have an impact on the work of ITU and 3GPP in Phase 2 [15], [16].

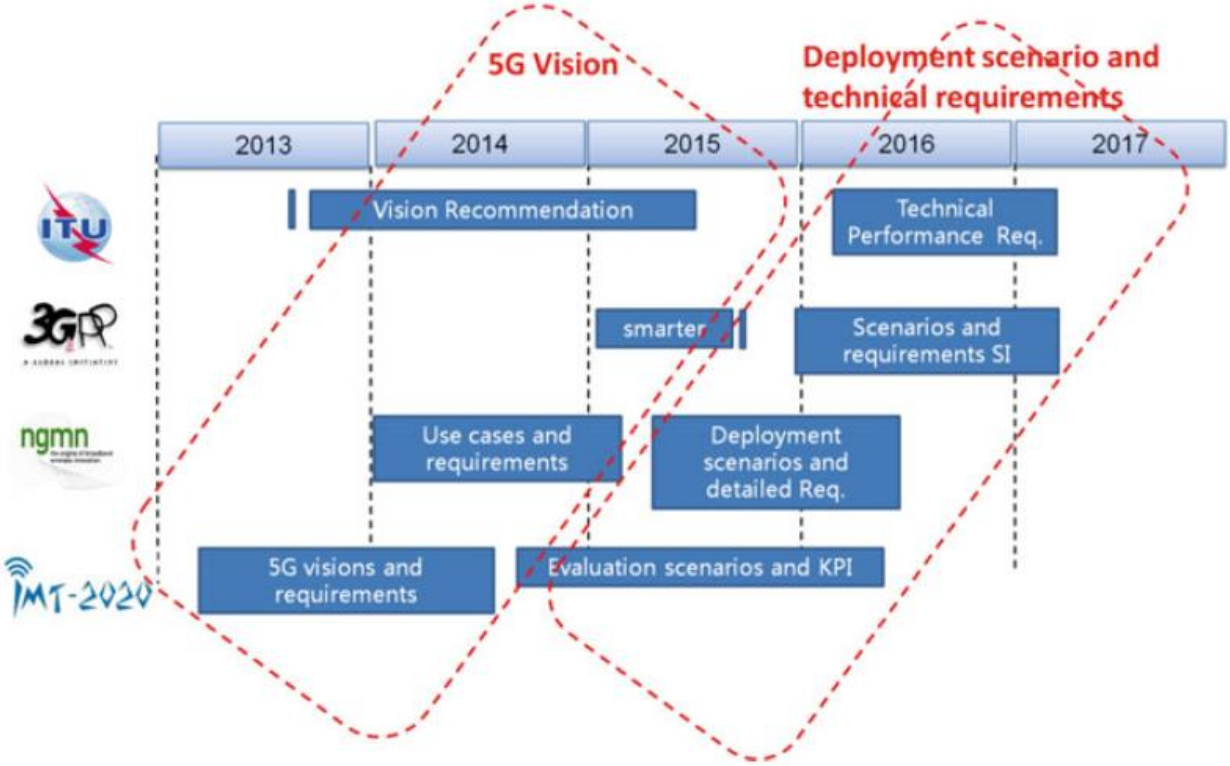


Figure 2.1: Overview of 5G requirements research by different organizations [15].

5G will support a large variety of use cases which are emerging now or has been emerge in the future. Different use cases have varying characteristic and requirements. It is helpful to group countless emerging use cases into different use case families. Use cases in each use case family share similar characteristic and requirements.

NGMN has developed 25 use cases for 5G as representative examples, which are grouped into eight use case families. ITU-R has concluded three usage scenarios (use case groups) addressing different use case characteristics in Figure 2.2 [17]:

- **Enhanced mobile broadband:** Mobile broadband addresses human-centric use cases for access to multimedia content, services, and data. The demand for mobile broadband will continue to increase, leading to enhanced mobile broadband. The enhanced mobile broadband usage scenario will come with new application areas and requirements in addition to existing mobile broadband applications for improved performance and increasingly seamless user experience.

- **Ultra-reliable and low latency communications:** This use case has stringent requirements for capabilities such as throughput, latency, and availability. Some examples include wireless control of industrial manufacturing or production processes, remote medical surgery, distribution automation in a smart grid, transportation safety, etc.
- **Massive machine type communications:** This use case is characterized by a very large number of connected devices typically transmitting a relatively low volume of non-delay-sensitive data. Devices are required to be of low cost and have a very long battery life.

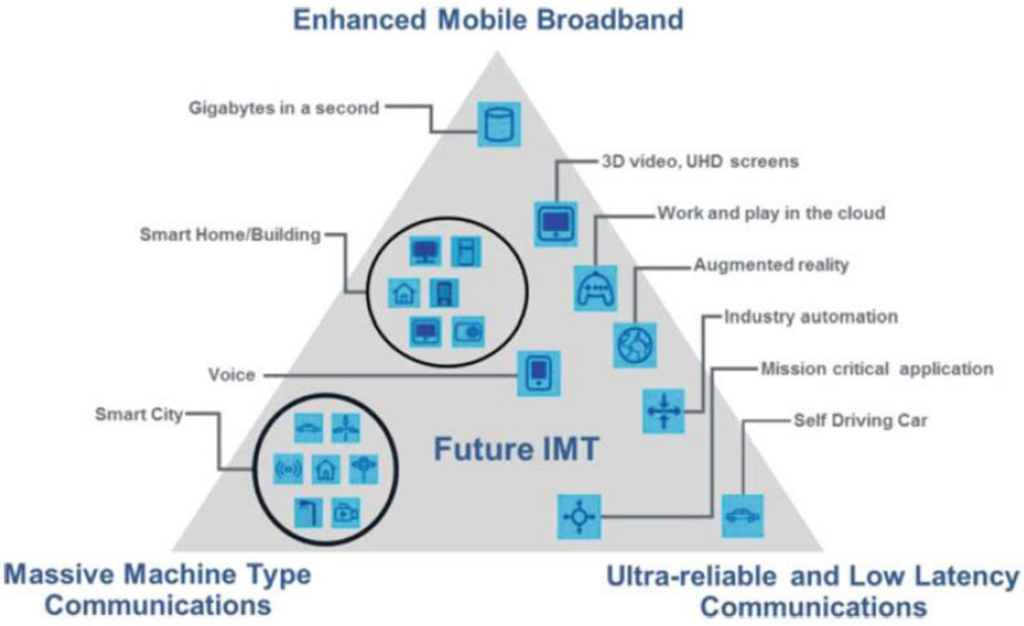


Figure 2.2: 5G usage scenarios [18].

The main difference is that the enhanced Mobile Broadband (eMBB) scenario from ITU-R is divided into two technical scenarios, i.e., the seamless wide-area coverage scenario and high capacity hot-spot scenario. For the seamless wide-area coverage scenario, seamless coverage and medium to high mobility are desired, with much-improved user data rate compared to existing data rates. However, the data rate requirement may be relaxed compared to the hotspot scenario. For the high-capacity hot-spot scenario, i.e., for an area with high user density, very high traffic capacity is needed, while the requirement for mobility is low and the user data rate is higher than that of wide area coverage. For the wide area coverage case, seamless coverage and medium to high mobility are desired, with much-improved user data rate compared to existing data rates. However, the data rate requirement may be relaxed compared with the hotspot [19].

2.2 High-level key capabilities

IMT-2020, the 5G high-level requirements into several performance indicators and efficiency indicators. The key performance indicators for 5G include the user experienced data rate, connection density, end-to-end delay, traffic volume density, mobility, and peak data rate. Their definitions are listed in Table 2.1 [10].

Table 2.1: 5G Performance indicators [20].

Performance indicators	**Definition**
User experienced data rate (bps)	The minimum achievable data rate for a user in the real network environment
Connection density (/km^2)	Total number of connected devices per unit area
End-to-end latency (ms)	The duration between the transmission of a data packet from the source node and the successful reception a destination node
Traffic volume density (bps/km^2)	The total data rate of all users per unit area
Mobility (km/h)	The relative speed between receiver and transmitter under certain performance requirement
Peak date rate (bps)	Maximum achievable data rate per user

Several problems are anticipated if today’s networks are used to handle the explosive development of mobile Internet and IoT [21] ,[22]:

- ✓ The energy efficiency level, the overall cost per bit and complexity of network deployment and maintenance cannot effectively handle 1000 times traffic growth and the massive number of connected devices in the next decade;

- ✓ Co-existence of multiple Radio Access Technologies (RAT) causes increased complexity and degraded user experience;
- ✓ Existing networks can not realize accurate monitoring of network resources and effective awareness of services, and therefore they cannot intelligently fulfill the diversified requirements of future users and services;
- ✓ Widely distributed and fragmented spectrum will cause interference and coexistence complexity.

To solve these problems, 5G should have the following capabilities to achieve sustainability. In terms of network construction and deployment, 5G networks need to [23]:

- ✓ Provide higher network capacity and better coverage, while decreasing the complexity and cost of network deployment, especially the deployment of ultra-dense networks.
- ✓ Have a flexible and scalable architecture to adapt to the diverse needs of users and services.
- ✓ Make flexible and efficient use of various spectrum resources, including paired and unpaired spectrum, re-farmed spectrum and new spectrum, low-frequency and high-frequency bands, and licensed and unlicensed bands.
- ✓ Have stronger device-connection capabilities to deal with the access requirements of huge amounts of IoT devices.

In [24] terms of operation and maintenance (O and M), 5G needs to:

- ✓ Improve network energy efficiency and the O and M cost-per-bit to cope with data traffic growth and the diverse needs of various services and applications.
- ✓ Reduce the complexity caused by the co-existence of multiple radio access technologies, network upgrades, and the introduction of new features and functions, to improve users' experience.
- ✓ Make intelligent optimization based on awareness of users behaviors and services contents.
- ✓ Provide a variety of network security solutions to meet the needs of all types of devices and services of mobile internet and IoT.

Table 2.2: 5G Key efficiency indicators [24].

Efficiency indicators	**Definition**
Spectrum efficiency (bps/Hz/cell or bps/Hz/km^2)	Data throughput per unit of spectrum resource per cell (or per unit area)
Energy efficiency (bit/J)	Number of bits that can be transmitted per joule of energy
Cost efficiency (bit/¥)	Number of bits that can be transmitted per unit cost

5G systems must dramatically outperform previous generation systems. 5G should support:

- ✓ User experienced data rate: 0.1–1 Gbps
- ✓ Connection density: one million connections per square kilometer
- ✓ End-to-end latency: millisecond level
- ✓ Traffic volume density: tens of Gbps per square kilometer
- ✓ Mobility: higher than 500 km per hour
- ✓ Peak data rate: tens of Gbps

Among these requirements, the user experienced data rate, connection density, and end-to-end latency are the three most fundamental ones. Meanwhile, 5G needs to significantly improve the efficiency of network deployment and operations. Compared with 4G, 5G should have 3–5 times improvement on spectrum efficiency and more than 100 times improvement on energy and cost efficiency [25].

The performance requirements and efficiency requirements define the key capabilities of 5G, which can be illustrated as a “blooming flower” depicted in Figure 2.3. The petals and leaves rely on each other. The petals represent the six key capabilities in terms of performance and can fulfill the diverse requirements of future services and scenarios. The leaves represent the three key capabilities in terms of efficiency and can guarantee the sustainable development of 5G. The top of each petal means the maximum value of the corresponding capability.

The key capabilities of IMT-2020 defined[38] by ITU-R are shown in Figure 2.4, compared with those of IMT-Advanced. The values for each key capability are shown in Table 2.3.

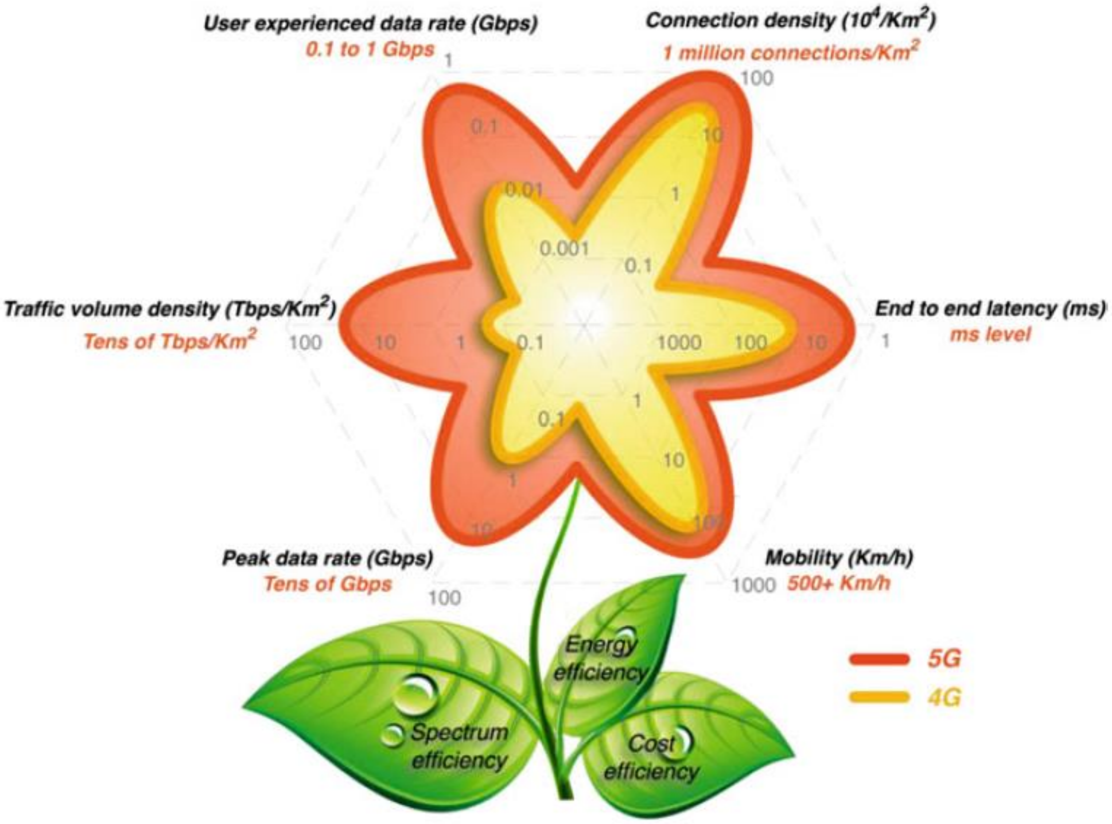


Figure 2.3:5G key capabilities [26].

All key capabilities may to some extent be important for most use cases, and the relevance of certain key capabilities may be significantly different, depending on the use cases/scenario.

Table 2.3:5G Key capabilities and values from ITU-R [26].

Key capabilities	**Values**
Peak data rate	20 Gbps
User experienced data rate	0.1–1 Gbps
Latency	1 ms over-the-air
Mobility	500 km/h
Connection density	10^6/km^2
Energy efficiency	100 times compared with IMT-Advanced
Spectrum efficiency	3–5 times compared with IMT-Advanced
Area traffic capacity	10 Mbit/s/m^2

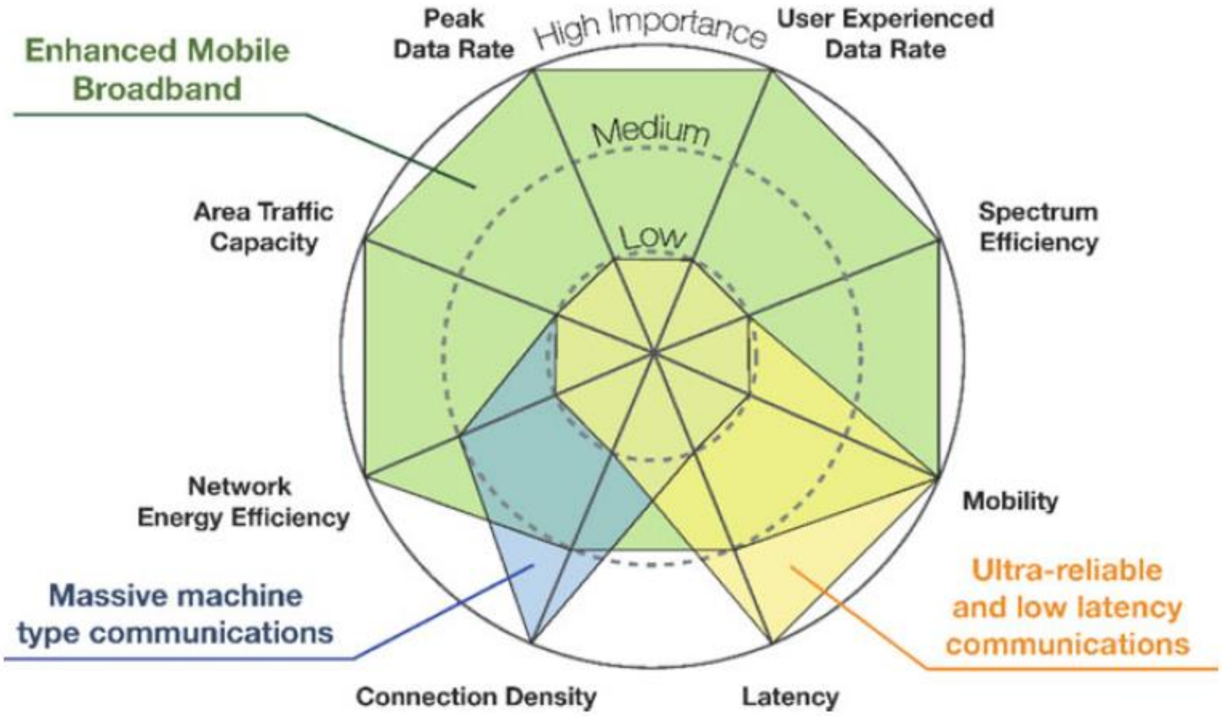


Figure 2.4: Importance of key capabilities in different usage scenarios [29].

The importance of each key capability for the usage scenarios enhanced mobile broadband, ultra-reliable and low latency communication and massive machine-type communication are illustrated in Figure 2.4. This is done using an indicative scaling in three steps as “high”, “medium” and “low”.

In the enhanced mobile broadband scenario, the user experienced data rate, area traffic capacity, peak data rate, mobility, energy efficiency, and spectrum efficiency all have high importance, but mobility and the user experienced data rate would not have equal importance simultaneously in all use cases. For example, in hotspots, a higher user experienced data rate, but lower mobility would be required than in the wide area coverage case.

In the ultra-reliable and low latency communications scenarios, low latency is of the highest importance, e.g., safety-critical applications. Such capability would be required in some high mobility cases as well, e.g., transportation safety, while high data rates could be less important [28].

In the massive machine type communication scenario, high connection density is needed to support a tremendous number of devices in the network that may transmit only occasionally, at the low bit rate and with zero/very low mobility. A low-cost device with long operational lifetime is vital for this usage scenario.

2.3 5G Spectrum demand

Every few years, ITU-R sets up agenda items in advance to study the future spectrum demand for IMT, and to support the consideration of additional spectrum allocations. Currently, ITU-R has already finished the study on IMT spectrum demand towards the year 2020. Some countries have also started the study on spectrum demand beyond 2020 [29].

How to calculate IMT spectrum demands? Generally, a methodology starts with an analysis of future market and traffic volume, moves on to calculate and distribute the traffic on different RATs, and then calculates the required capacity, before concluding the estimation. The actual calculation process can be very complicated when there are a variety of traffic types, different environments and multiple cell types of different RATs. For example, imagine how to estimate the data rates of a high-quality video streaming user located in indoor offices, connecting with future 5G small cells, in the year 2025.

Many countries have made contributions to the calculation methodology and output results. It summarizes national spectrum requirements as provided by some countries and organizations during the study of ITU-R, in the form of the total amount for all the operators in one country. It should be noted that these national spectrum requirements have differences in the methodology used and assumptions made (e.g., differences in traffic/radio-aspects related parameters, differences in estimation year, differences in estimates based on whether the spectrum requirements are total or additional, etc.) [30].

Some of them, such as GSMA (GSM Association) and the UK, focused on the improvements of existing ITU-R method specified in RecommendationM.1768-1. The methodology of Recommendation ITU-R M.1768-1 is developed by ITU-R Study Group, which is used in WRC-07 to calculate the spectrum demand in the future. The methodology provides the spectrum requirements of IMT as a whole, and divided between two RAT Groups (RATGs) [31] :

- RATG 1: Pre-IMT systems, IMT-2000, and its enhancements;
- RATG 2: IMT-Advanced.

The methodology reflects certain recent advances in IMT technologies and the deployment of IMT networks such as the introduction of spectrum sharing between the macro and micro cell layers in IMT Advanced, and the introduction of a new spectrum granularity parameter for IMT systems.

There are differences in the markets and deployments and timings of the mobile data growth in different countries. Therefore, two settings are developed to characterize lower and higher user density settings. These two sets of market study input parameter values are considered in the calculations to characterize differences in the user densities in different countries. Table 3 shows the calculated spectrum requirements for both RATGs 1 and 2.

Table 2.4: Total spectrum requirements for both RATG 1 and RATG 2 in the year 2020 [32]

Total spectrum requirements	**RATG 1**	**RATG 2**	**RATGs 1 and 2**
Lower user density settings	440 MHz	900 MHz	1340 MHz
Higher user density settings	540 MHz	1420 MHz	1960 MHz

Is the world ready to provide sufficient frequency bands for 5G? From the study point of view, the potential bands can be divided into two parts: bands below 6 GHz and above. For wireless communications, lower frequencies provide better coverage. Currently, almost all countries are using spectrum below 6 GHz for IMT systems. Besides achieving high data rates, it is also necessary to guarantee wide-area coverage and outdoor-to-indoor coverage in 5G. Therefore, the spectrum below 6 GHz forms a very important part of the 5G spectrum solution.

2.4 Heterogeneous network

Over the past few years, network densification works as a solution, this creates a hybrid system where the existing macro base stations overlaid with a low power and less coverage small cells called Heterogeneous networks (HetNets).

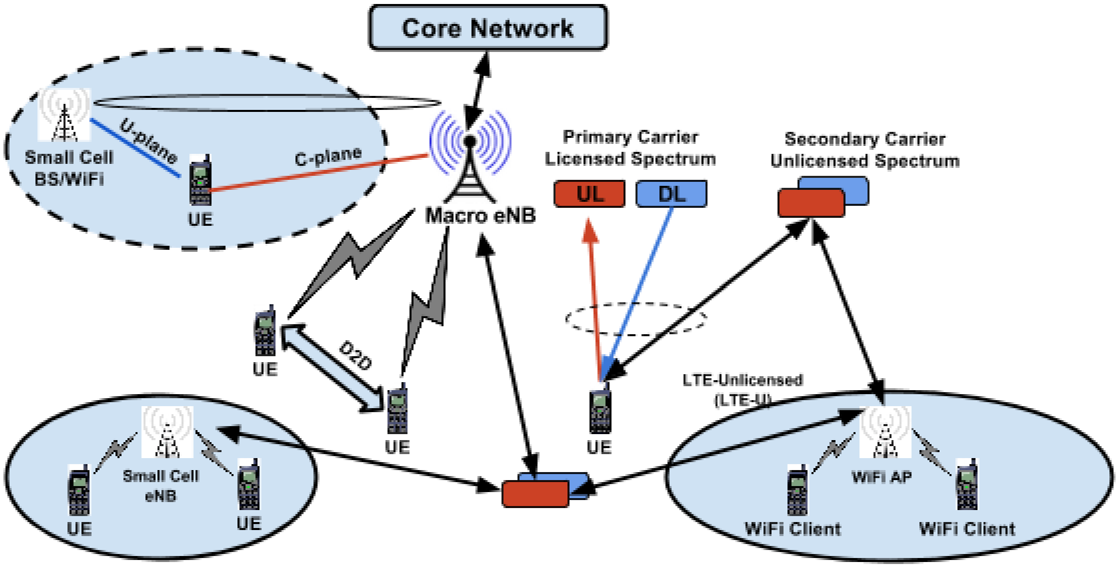


Figure 2.5: Heterogeneous Network [33].

In HetNets architecture, several base stations of different sizes and transmission power level such as Macrocells and small cells, deployed throughout the whole network.

2.4.1 Small cells

Small cell is an umbrella term for low power wireless access points. In HetNets Small cells is a vital component, which provides an efficient and cost-effective solution for load balancing by offloading the macrocellular traffic. Small cell enhances cellular capacity and network coverage for home users, small medium enterprises, and rural public places. Small cells are served by types of base station or node, which comes in a variety of coverage ranges, transmit power and size different, decreasing order from microcell base station to Femtocell access point.

The integration of small cells with macrocell in a network brings enhancement in overall system performance. For service providers, HetNets deployment is of special interest with the aim of guaranteeing high quality and improves network capacity for high data rate services to increasing numbers of users. Comparing with a homogeneous macro cellular network, a small cell-based heterogeneous network is much more energy efficient and cost-effective. In high macrocells, the power amplifier, which requires a fixed Direct Current (DC) power supply, and a cooling unit consume more energy. However, the low power characteristics of small cells reduce this impact [34].

2.4.2 Heterogeneous network nodes

Macro base stations are large cells providing the whole network coverage with powerful Macro base stations deployed by an operator. Macro-cell is the backbone in the HetNets solution and provides a large coverage. Transmit power a level of macro base stations typically varies between 5 W and 100 W [35].

Micro base stations are categorized under small cell base stations and give coverage to the microcell with lower transmit power than macro base stations over the backhaul. Micro base stations are regular base stations that are usually installed outdoors to fill macro coverage gaps in dense spot areas such as train stations. Microcells configured to operate in open access modes in which every subscriber can associate to the base stations.

Pico base station is typically used in indoor public areas and offer good capacity in the range of tens of meters. It is difficult to distinguish pico base stations, serving pico-cells, precisely with micro base stations but they are of smaller sizes and lower transmit power.

Femtocell base station are small, low power access points designed to give coverage of about 10-20 meters. Users perform the deployment and configuration of pico base stations at their own premises. Connectivity of femtocell access points with a core network is through consumer's own broadband connection, which makes deployment of femtocells simple. They offer better broadband service for residential users, small enterprises and good indoor network coverage. The deployment of femtocell access points allows service providers and operators to alleviate indoor mobile user problems and provide strengthened cellular signals. Hence, femtocells play a significant role for indoor and cell-edge users data capacity improvement and the offloading macrocell.

Table 2.5: Types of base stations/access points in HetNets [36].

Type	Typical deployment	Power level (Indoor)	Power Level (Outdoor)	No of users	Cell range
Macro	Urban areas, Rural areas	-	20-100 W	200-1000 users	1Km to 100Kms
Micro	Urban areas	-	5-10 W	100-200 users	Few hundred meters
Metro	Urban areas	-	10-20 W	100-200 users	Hundreds of meters
Pico	Public areas Indoor/Outdoor	100-250 mW	1-5 W	32-100 users	Tens of meters
Femto	Residential, enterprise environments	10-100 mW	0.2-1 W	Residential Femto:4-8 users	Tens of meters
WiFi	Residential, enterprise environments	20-100 mW	0.2-1 W	<50 users	Few tens of meters

2.4.3 Challenges of HetNets

The integration of small cells with macro cells creating a HetNets has a substantial benefit over the homogeneous network [37].

- ✓ Small cells assist and offload macro cells data traffic and minimize macro cell coverage holes.
- ✓ Enhances link quality by providing short transmitter-receiver distance.
- ✓ HetNets increases network coverage for hotspot and rural areas.
- ✓ Low power small nodes allow operators to minimize their power consumption.
- ✓ Improves spectral efficiency by using less coverage of small cells, and so on.

However, the mass deployment of small cells introduces certain technical challenges that need to be solved properly to maximize the benefits of HetNets. Backhaul, Mobility management, and interference are the main technical challenges.

2.4.3.1 Backhaul

Small cells backhaul is a connectivity link between the small cells and the Mobile Network Operators (MNO) core network. Backhaul provides connectivity to the core network and another network. In the case of Femtocells, it provides connectivity to the macrocell through the core network. Comparing to macrocell backhaul, small cell backhaul becomes more challenging for mobile operators. Table 2 provides a brief summary of small cell backhaul requirements.

Table 2.6: Small cell backhaul requirements [38].

Backhaul requirements	Compared to Macrocells	Notes
Cost	Cheaper	Cost per link should be lower. Cost per bit may be similar.
Capacity	Traffic load is lighter but burster.	Small cells generate less backhaul traffic than multi-cell/mode/band macrocells, but the traffic is much burster.
Scalability	More scalable	Faster growth requires rapid deployment despite shorter lead times.
Latency	More delay tolerant	Delay sensitivity depends on service level expectations. Femtocells are designed to cope with lower quality connections. Femtocells handover is less important.
Availability	Five nines not needed	Small cells will form an offload underlay to a higher-availability macrocell.
Size and Weight	Smaller and Lighter stations	Small cells require deployment locations with limited space availability. The compact backhauling solution is essential.
Access to backhaul	More difficult	Small cells are close to users on the street and indoors, relatively far from backhaul sites. These sites are harder to reach than tower-based macrocells.
Installation and Commissioning	Faster, simpler and cheaper	Consumer femtocells are plug and play. Femtocell backhauling should also work this way.

2.4.3.2 Mobility management

Handover and mobility management are essential to provide seamless connectivity for mobile UEs. Depending on where the handover intelligence resides, mobility decisions can be a UE or network-initiated [38].

Handover is a process in which a user is transferred from the serving cell to another cell to maintain the quality of service and ensure that a UE is connected to the best serving cell [15]. Handovers triggered based on signal strength measurements on the UE. In addition, handovers triggered for traffic load-balancing purpose in which a UE connected to a highly congested cell can be handed to a less loaded cell.

However, in heterogeneous network environments due to the dense deployment of different size small cells with different backhaul links handover management is challenging.

2.4.3.3 Interference in HetNets

Integration of small cells with macro cells alters the existing network topology, introducing a multi-layer also called multi-tier hierarchical cell network. This deployment of small cells in the network, as discussed above, enhances capacity and network coverage. However, the main technical challenge with the mass deployment of the small cell increases interference. The interference takes place within and between tiers and can be distinguished into two types: co-tier interference and cross-tier interference [39], [40], [41], [44].

Co-tier interference also known as co-layer interference refers to interference which takes place between cells belonging to the same network layer. The interference caused by a femtocell to neighbor femtocell users or interference caused by microcell to adjacent microcell is an example of co-tier interference.

Cross-tier interference refers to the interference between base stations belonging to different layers of the network. The downlink interference from femtocell FAP to microcell and macro-cell users or vice versa is cross-tier interference. To realize the advantage of HetNets, the co-tier and cross-tier interference in a network should be managed properly by applying different interference mitigation techniques.

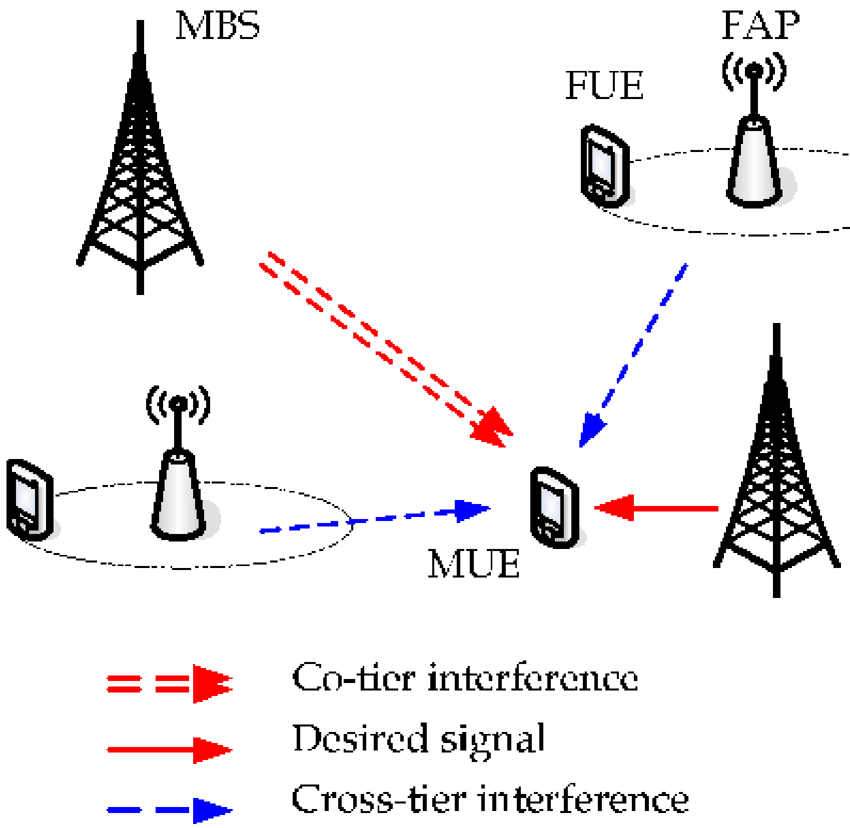


Figure 2.6: Co-tier and Cross-tier Interference in a HetNets [46].

In order to mitigate interference in HetNets for the next-generation network, different approaches have been considered in the literature. Mostly to achieve high performing dense wireless networks, efficient and low complexity interference mitigation strategies are required for HetNets. So while designing efficient interference mitigation techniques some other aspects e.g. environmental, installation and antenna parameters can also be taken into account for the successful deployment of HetNets. Some key challenges to mitigate the interference in multi-tier HetNets, as a result of the comparison between the existing cell association and power control scheme are as follows .

Based on the network deployment and aspects of interference the interference management techniques can be divided into the following categories:

Decentralized Interference Management [48]: In these techniques such as fractional frequency reuse, advanced receivers, distributed power control, and static resource partition there is no coordination in between cells [49 –51].

Coordinated Interference Management: In these techniques, the neighboring cells coordinate with each other by overhead messaging in order to manage the interference in the network mutually, e.g. eICIC, joint power control and CoMP communications.

Resource management based Interference Management [45], [52]: The main objective of Resource Management/Radio Resource Management (RRM) in HCNs includes, resource allocation among Macrocells and small cells, Radio Admission Control (RAC), handover management, packet scheduling, etc. Depending upon the evolved network architecture and enhanced technologies, there are several challenges that arise in resource management like, interference mitigation, QoS, resource utilization, etc. Several associated works have been proposed to focus on both uplink and downlink power control in two-tier femtocell.

In general, RRM schemes can be classified into centralized, decentralized and hybrid approaches. But based upon the under-laying technologies and working principle, the RRM can be classified into resource allocation, frequency scheduling, femto-aware spectrum allocation, graph theory, Femtocell clustering, cognitive radio, distributed learning, frequency reuse, co-operative approach, and power control approach.

Hardware-based Interference Management [54]: There are several interference management techniques which are hardware based like the directional antenna, a multichannel multi-antenna-based beamforming-codebook-restriction strategy, which enables the Femtocell users to select the channels that are least influenced by Cross-tier interference .

In particular, no specific classification standard criterion for interference management techniques exists in HetNets. Most of the interference management techniques are designed in combination with resource allocation schemes. Based on different air interface technologies, some different interference management approach in this thesis are discussed below.

2.4.3.3.1 Power control techniques

Power Control techniques are one of the most important aspects in order to mitigate the interference issues in HetNets. The most important parameters to compare the performance of different power control schemes are, (i) Aggregate transmits power, (ii) Outage ratio, (iii) Aggregate throughput. So the objective of the power control approach, is to support a user with its minimum acceptable throughput and a system with maximum aggregate throughput, but the main problem with this technique is that the reduction of the radiated power at a Femtocell also leads to reduction of the total throughput of Femtocell users, which may significantly improve the performance of victim MUs [57].

2.4.3.3.2 Coordinated approach

The authors in [55] propose a framework based on the iterative water-filling approach to be applicable in the mobile environment depending upon its adequate speed. To realize this ICI management scheme coordination among the cells is necessary. Depending upon the quality of the back-haul link the coordination between the cells can be implemented in two ways i.e. semi-static and dynamic coordination approach. Dynamic coordination provides better performance due to its flexibility as compared to semi-static coordination. But the area of coverage of the dynamic coordination is smaller than that of semi-static coordination. In dynamic coordination, joint transmission and coordinated scheduling or beamforming can be used to reduce ICI. To achieve the benefits of both the coordination in an efficient way a Hybrid coordination scheme is used, which gives a significant gain of more than 28% average throughput gain and more than 30% cell edge throughput gain over semi-static coordination with different bias values.

2.4.3.3.3 Resource allocation approach

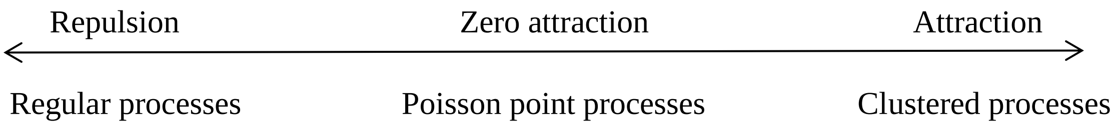
Focusing on co-tier interference, Kaimaletu et al. [53] propose a cognitive resource allocation interference management scheme on the DL, which is able to deal with co-tier and cross-tier interference in heterogeneous cellular wireless networks comprising of Macrocells and Femtocells. Here depending upon the ability to cause interference with each other’s UEs, the Macrocells and Femtocells get the transmission opportunities and allocated resources (in time and frequency which are near/fully orthogonal), assuming that the Femtocells are operated in closed subscriber group. Considering no interference management scenario, when this scheme is compared with frequency reuse techniques this scheme significantly enhances the average cell-edge UE throughput (5%-tile throughput) with a slight degradation in overall sum throughput. It is observed that without any interference management, there is up to 270% increase in cell-edge throughput for the MUs and 50% when the reuse factor is 3, whereas for HUEs the increase is about 140%. Also, the scheme decreases the probability of cell-edge users in the system experiencing degraded SINR. In [56] the authors propose a cognitive-based interference management solution by sharing measured path loss information among neighbors and selecting component carriers

, according to the estimated mutual interference. Based on the existing distributed methods [67, 68], this approach sets an improved cognitive based spectrum selection scheme by which each Femtocell is able to select spectrum intelligently by considering the interference from neighboring Femtocells, as well as the potential interference caused to the neighbor cell by itself, so that a balance between overall capacity and frequency reuse efficiency can be achieved.

2.5 Stochastic geometry

Stochastic geometry was firstly introduced by Krickerberg in the 1960s to model positions of particles in a given area [39]. Based on sophisticated models and random geometrical patterns, stochastic geometry provides suitable mathematical tools allowing studying the average behavior over many spatial realizations of a process whose points are generated according to the given probability distribution. It provides a natural way of characterizing the location of the BSs and thus modeling and analyzing the cellular network from a microscopic view. Compared with the traditional model (deterministic model), modeling scale cellular networks in terms of stochastic geometry model is more suitable and general. A random point pattern or point process is a set of points (locations) which is generated randomly through some mechanism. Formally, a point process is countable random set $\Phi = \{x_1, x_2, \dots\} \in \mathbb{R}^2$.

Point process can be classified into different types reflecting: attraction, repulsion, and independence between points of the process.



2.5.1 Poisson Point Process (PPP)

PPP is the point process with zero attraction [38] where points are distributed independently with no relationship with each other. It is characterized by two properties: the number of points in disjoint bounded sets is independent and has a Poisson distribution.

For every compact set B ϵ $\mathbb{R}^{\mathrm{d}}$, $N(B)$ (the number of the process in B) has a Poisson distribution with mean $M(B)$ [35]. The probability that the number of points in B is k is given by

$$\mathbb{P}(N(B) = k) = \exp(\int_B^{\cdot} \lambda(x)dx).\frac{(\int_B^{\cdot} \lambda(x)dx)^k}{k!} \tag{2.1}$$

If $B_1, B_2, \dots, B_m$ are disjoint compact sets, then $N(B_1), N(B_2), \dots, N(B_k)$ are independent random variables.

For the two dimensional cases, d=2, and a homogeneous PPP $(\lambda(x) = \lambda),$ the first property can be written as:

$$\mathbb{P}(N(B) = k) = \exp(\lambda|B|).\frac{(\lambda|B|)^k}{k!} \tag{2.2}$$

The independence of points generated in a PPP makes the process analytically tractable. More precisely, the useful properties of PPP help to derive closed forms of performance metrics.

Although its tractability, PPP does not model correctly nodes deployment in real scenarios. For example, as shown in Figure 2.7, PPP can generate points close to each other, that is, two BSs covering roughly the same network area. This would generate very harmful interference if nodes use the same radio resources. This fact motivates the need for more regular and repulsive point process [39]. Ensuring a minimum distance between points to model nodes distribution.

2.5.2 Matern Hard Core Process (MHCPP)

MHCPP firstly introduced by Matern to model point's repeal each other. MHCPP are not analytically tractable due to the non-independent nature of points [51].

Two types of MHCPP have been considered, Matern I and Matern II depending on the section criterion of the points.

The **Matern I** is derived from a stationary homogeneous PPP Φ_p of intensity λ_p by removing all points having neighbors within a distance δ.Points not satisfying the Matern I condition are removed simultaneously. The intensity of the Matern I, for the two dimensions case, is

$$\lambda_m^{(I)} = \lambda_p \exp(-\lambda_p \pi \delta^2) \qquad (2.3)$$

The **Matern II** is generated from a stationary homogeneous PPP as follows:

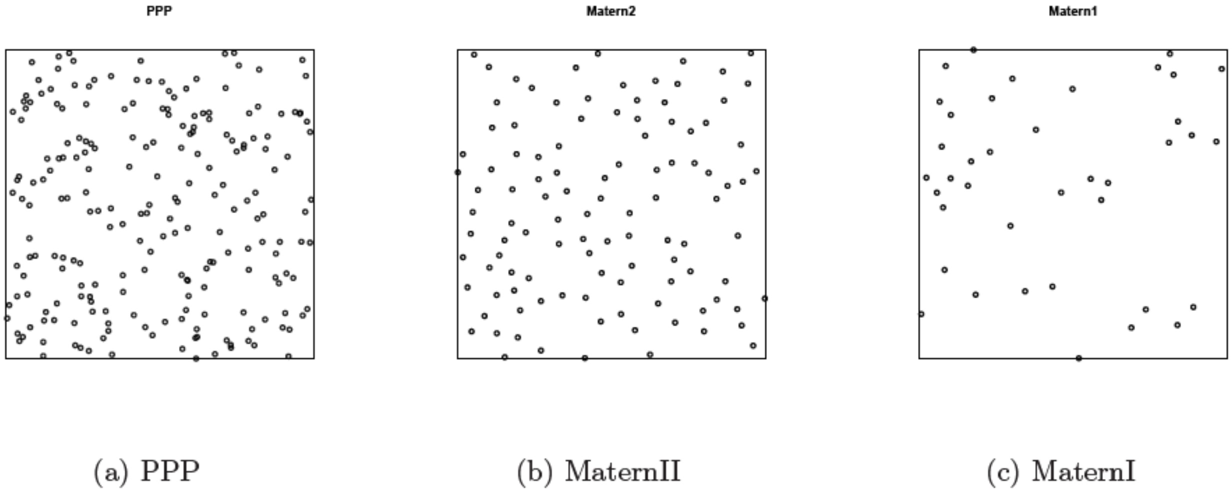
Generate a parent PPP Φ_p with intensity λ_p.Associate each point $x = \Phi_p$ to an independent uniform mark ($u_x \sim [0,1]$).Retain a point in the daughter process Φ_m if it has the lowest mark in $B(x,\delta)$, the circle centered at x and with radius δ.

Analytically, the MHCPP can be expressed as:

$$\Phi_m = \{x \in \Phi_p : m_x < m_y \forall y \epsilon \Phi_p \cap B(x,\delta)\{x\}\} \qquad (2.4)$$

The intensity of Matern II is given by

$$\lambda_m^{(II)} = \frac{1-exp(-\lambda_p \pi \delta^2)}{\lambda_p \pi \delta^2} \qquad (2.5)$$



(a) PPP (b) MaternII (c) MaternI

Figure 2.7: Illustration of Point process at λ=200 and δ = 0.05 [53].

Chapter Three

System Model

3.1 Two-tier HetNets model

Due to the randomness of BSs deployment in HetNets, the traditional hexagonal cellular model cannot reflect the network deployment in reality. This thesis focuses on the tractable analytical model for two-tier HetNets, based on stochastic geometry theory, where the location distribution of BSs is modeled as PPP for MBSs and MHCPP for PBSs forms weighted Poisson Voronoi Tessellation (PVT).

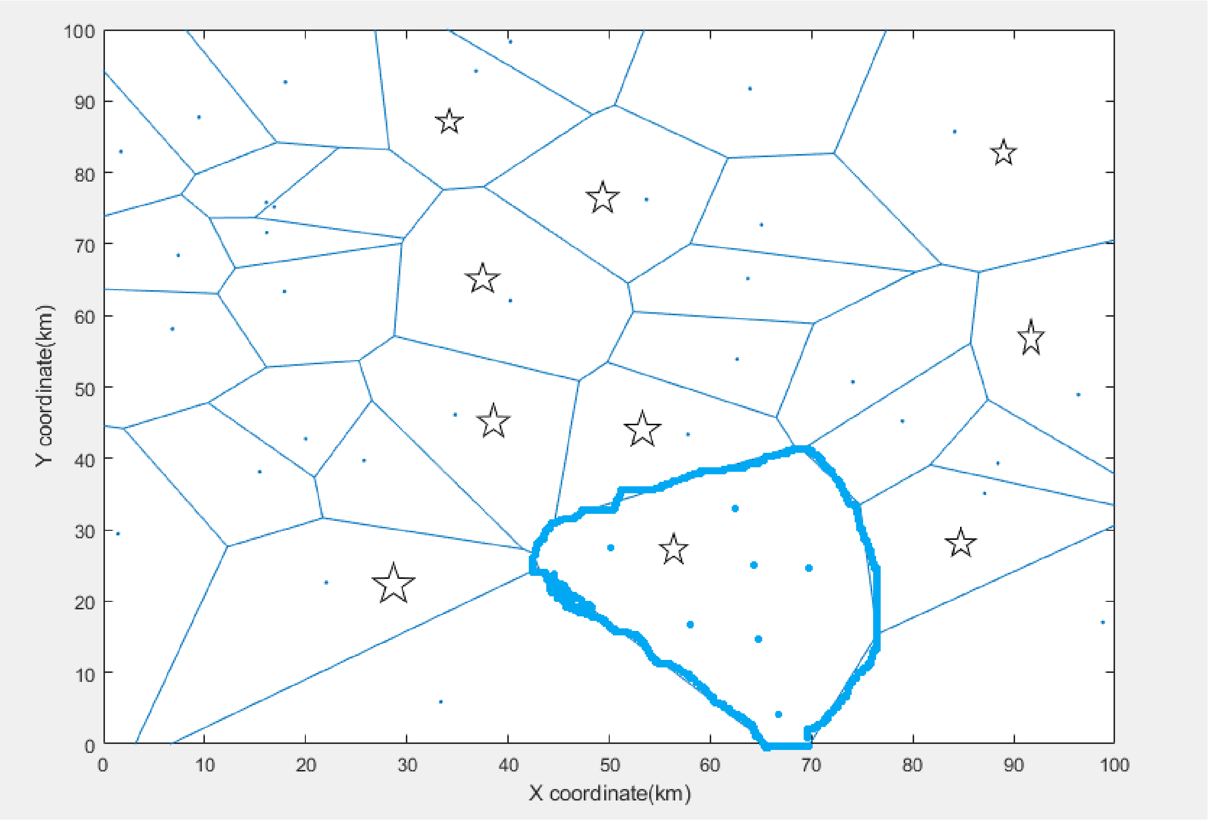


Figure 3.1: PVT for the two-tier HetNet including MBSs (pentagons) and PBSs (dots).

A two-tier HetNets consisting of MBSs with higher transmission power and PBSs with lower transmission power is considered. Assume that the MBSs and PBSs are spatially located according to a homogeneous PPP Φ_m and MHCPP Φ_p with density λ_m and λ_p, respectively in the Euclidean plane. The UEs are also distributed according to a different and independent homogeneous PPP Φ_u with density λ_u.The transmit power is μ_m for each MBS and μ_p for each PBS. It consider the universal frequency reuse over the total available bandwidth B.The power recive by a reciver located at z due to a transmitter at x is modeled as

$$\mu h_x l(x-z), \tag{3.1}$$

where h_x is the power fading coefficent(square of the amplitude of fading coefficient) associated with the channel between x and z, and μ is either μ_m or μ_p.Assume that the fading coefficents are IID exponential (Rayleigh fading) with

$$\boldsymbol{E}[h] = 1, l(x) = \|x\|^{-\alpha} \tag{3.2}$$

is large scale path loss exponent model with $\alpha > 2$ .This thesis focus on MU at distance r_m from the serving MBS in random direction and PU at distance r_p from the serving PBS in a random direction.The Signal to Intrferance Ratio(SIR) threshold is denoted as θ_m for MUs and θ_p for PUs.

3.1.1 Two-tier HetNet model with intra-tier dependencies (case 1)

Consider a two-tier HetNet with MBSs overlaied with PBSs, shown in figure 3.1. The location of the MBSs follow a homogeneous PPP $\Phi_m = \{x_1, x_2, x_3, \dots\} \subset \mathbb{R}^2$ of density λ_m, and the locations of the PBSs follow an independent Mattern cluster process $\Phi_p = \{y_1, y_2, y_3, \dots\} \subset \mathbb{R}^2$ of density λ_p .Each MBS has an execution region which is a disk with radius D centered at the location of the MBS. Each MBS has an exclusion region which is a disk with radius D centered at the location of the MBS. Considering the critical issues of the current HetNets, such as interference, resource utilization and cost, PBSs are only deployed outside the exclusion regions to fill the coverage holes and thus provide better service to users, while guaranteeing that PBSs will not generate an aggregate interference resulting in the outage of macro users through designing the exclusion radius D.

The radius D of the exclusion region is chosen as

$$D = \zeta r_m \left(\frac{\mu_p}{\mu_m}\right)^{\frac{1}{\alpha}} \tag{3.3}$$

Where ζ is a design factor. It is intitutive why D is in this form since the radius D be proportional to the distance between the serving MBS and its user $\mathrm{r_m}$ $(\mathrm{r_m} < D)$ and the transmission power of the PBSs μ_p, and inversely proportional to the transmission power of the MBSs μ_m. The path loss exponent should also be taken into account since it greatly affects the interference. Adding a design parameter ζ is to make the formula of D more general, which allows imitate the concept of Cell Range Expansion (CRE), i.e., allowing a user to be served by a cell with weaker received power [29], [56].

The value of ζ is chosen to guarantee that PBSs will not generate an aggregate interference resulting in the outage of macro users, and, conversely, the MBSs will not generate an aggregate interference resulting in the outage of PUs since the minimum distance between a MBS and a PU is $D - r_p$.

Assume that the MBSs and the PBSs share the same spectrum, and each of them has N_b resource blocks (RBs) and serves one UE at most using one RB at a time. The users are assumed to be distributed in the whole plane according to a homogeneous PPP with density λ_u. Under this setup, the users located within distance D of an MBS get served by MBSs within that distance, i.e., a fraction of $k_m = 1 - \exp(-\lambda_m \pi D^2)$ of the users will be served by MBSs, and the rest are served by PBSs. N_{mu} and N_{pu} as the number of UEs served by the typical MBS and the typical PBS, respectively. Due to the fact that exclusion regions may overlap, an exact calculation of the distribution of N_{mu} seems unfeasible. Thus, we approximate the distribution of Nmu by the Poisson distribution with mean $k_m \lambda_u / \lambda_m$, which is the mean of N_{mu}, denoted as $\overline{N_{mu}}$ since the average number of UEs located in the Voronoi region of a MBS is λ_u / λ_m.

3.1.2 Two-tier HetNet model with intra-tier dependencies (case 2)

Consider a two-tier HetNet with MBSs overlaied with PBSs, shown in figure 3.1 2, where the user density in those regions covered by PBSs (i.e., the hotspots) is higher than in the rest of the network.. The location of the MBSs follow a homogeneous PPP $\Phi_m = \{x_1, x_2, x_3, \dots\} \subset \mathbb{R}^2$ of density λ_m, and the locations of the PBSs follow an independent Mattern cluster process $\Phi_p = \{y_1, y_2, y_3, \dots\} \subset \mathbb{R}^2$ of density λ_p, whose parent PPP Φ_l has density λ_l.For the user distrubution ,the population centers of radius R are assumed to be posson distrbuted and covered using PBSs forming a MHCPP such that each PU can be served by its own PBS.The average number of points per cluster as $\bar{c}$, the density of the PBS is $\lambda_p = \lambda_l \bar{c}$. Since points in each cluster are uniformely distrbuted in the circle of radius R centered at its parent point,the density of the active users,i.e., the PU density, in these popultion center is $\bar{c}/\pi R^2$. The MU distrbuted in the rest of the networkare served by their own MBSs.

There are four types of interfrences, i.e. the interfrence from MBSs to the MU I_{mm}, the intrfernce from the MBSs to the PUs I_{mp}, the interfrence from PBSs to the MUs I_{pm}, and the intrference from PBs to the PUs I_{pp}. Each of them can be defined as $I(z) = \sum_{x \in \Phi\{x_0\}} \mu h_x l(x - z)$ to represent the interference at z resulting from the interferers positioned at the points of the process Φ (either Φ_m or Φ_p), where x_0 is the serving BS, and μ is either μ_m or μ_p, depending on which type of interference is considered. To calculate the interference to the MUs having a MU at the origin, the typical user, i.e., there is an extra MBS, namely, the serving MBS, on the circle of radius r_m centered at 0, which yields the Palm distribution for the MBSs. By Slivnyak's theorem [47], this conditional distribution is the same as the original one for the macro-tier in the region $\mathbb{R}^2 \setminus b(0,\ r_m)$. For the pico-tier, however, conditioning on a PBS at a certain location generally changes the distance distribution since whether a PBS is deployed is determined by the locations of the MBSs.

3.1.1.1 Interference and Outage analysis of MUs

The MUs experience from two types of interference, i.e. $I_{mm}$and I_{pm}. The typical MU accesses the nearest MBS x_0,assumed at distant r_m.Since the Rayleigh fading and MBSs are distributed as a PPP, the Laplace transform of I_{mm} is

$$\mathcal{L}_{I_{mm}}(s) = \boldsymbol{E}^{x_0}_{\Phi_m,h}\left(exp\left(-s \sum_{x \in \Phi_m} \mu_m h_x \, l(x) \right)\right)$$

$$= exp\left(\left\{-\boldsymbol{\pi}\boldsymbol{\lambda}_{\boldsymbol{m}}\frac{\boldsymbol{\mu}_{\boldsymbol{m}}{}^{\boldsymbol{s\delta}}}{\mathbf{1}-\boldsymbol{\delta}}\boldsymbol{r}_{\boldsymbol{m}}{}^{\mathbf{2}-\boldsymbol{\alpha}}\boldsymbol{F}(\mathbf{1},\mathbf{1}-\boldsymbol{\delta};\mathbf{2}-\boldsymbol{\delta};-\boldsymbol{\mu}_{\boldsymbol{m}}{}^{s r_m{}^{-\alpha}})\right\}\right) \tag{3.4}$$

Since the PBSs are least at distance D from the MBSs, I_{pm} is stochastically dominated by the interference I_{pm} caused by the points in Φ_p except those that are within distance D from the desired MBS. Denoting the disk centered at the location of the serving MBS with radius D as $\varkappa_m$ and letting $\varkappa_m^C = \mathbb{R}^2 \setminus \varkappa_m$ obtain the Laplace transform of I_{pm} using a modified path loss law $\widetilde{l(x)} = l(x)\mathbf{1}_{x\in\varkappa_m^C}$ as

$$\mathcal{L}_{I_{pm}}(s) = \boldsymbol{E}_{\Phi_p,h}^{x_0}\left(exp\left(-s\sum_{x\in\Phi_m}\mu_m h_x\, l(x)\right)\right)$$

$$= exp\left\{-\boldsymbol{\lambda}_{\boldsymbol{p}}\left(\frac{\boldsymbol{\pi}^{\mathbf{2}}\boldsymbol{\delta}}{\boldsymbol{sin}(\boldsymbol{\pi\delta})}\boldsymbol{\mu}_{\boldsymbol{p}}^{\boldsymbol{\delta}}\boldsymbol{s}^{\boldsymbol{\delta}} - \int_{\mathbf{0}}^{\mathbf{2\pi}}\int_{\mathbf{0}}^{r_m \boldsymbol{cos\varphi}+\sqrt{\boldsymbol{D}^{\mathbf{2}}-\boldsymbol{r}_{\boldsymbol{m}}^{\mathbf{2}}\boldsymbol{sin}^{\mathbf{2}}\boldsymbol{\varphi}}}\frac{\boldsymbol{rdrd\varphi}}{\mathbf{1}+\boldsymbol{S}^{-\mathbf{1}}\boldsymbol{\mu}_{\boldsymbol{p}}^{-\mathbf{1}}\boldsymbol{r}^{\boldsymbol{\alpha}}})\right)\right\} \tag{3.5}$$

With Rayleigh fading, the transmission success probability of MU is the Laplace transform evaluated at $s = \theta_m\mu_m^{-1}r_m^{\alpha}$. Since the typical user, for the MBS considered, there is at least one user. So N_{mu} in the typical user's cell is larger by 1 compared to the N_{mu} of the typical MBS. Thus, the calculation of the outage probability of MU should be conditioned on $N_{mu} \geq 1$, i.e., $P_r(N_{mu} \geq 1) = 1 - P_r(N_{mu} = 0) = 1 - e^{-N_{mu}}$ and $P_r(N_{mu} = i|N_{mu} \geq 1) = P_r(N_{mu} = i)/P_r(N_{mu} \geq 1)$.

The outage probability ($\in$) is one of the most common performance measures in wireless communication systems. It is dened as the probability , $\in = P(\gamma < a) = \int_0^a f_\gamma(x)dx$

that the system SNR falls below a certain quality of service thresholdFinally, the outage probability of an arbitrary MU can be derived as

$$\in_m = \sum_{i=1}^{\infty}\left(\frac{\min\{N_b,i\}}{i}\in_m^s + 1 - \frac{min\{N_b,i\}}{i}\right)\frac{P_r(N_{mu}=i)}{P_r(N_{mu}\geq 1)} \tag{3.6}$$

3.1.1.2 Interference and Outage analysis of PUs

Similar to the interfrennce to the MUs, the PU also experience two types of interferences, i.e. I_{mp} and I_{pp}.Consider the interference from the other PBS I_{pp} Laplace transform from MHCPP at typical PU located at the origin. Since the typical PU is served by the nearest PBS located at $(r_p, 0)$,there is no PBS in the disk centered at the origin with radius r_p. Denoting the disk centered at the location of the serving MBS with radius D as $\varkappa_p$ and letting $\varkappa_p^C = \mathbb{R}^2 \setminus \varkappa_p$ obtain the Laplace transform of I_{mp} using a modified path loss law $\widetilde{l(x)} = l(x)\mathbf{1}_{x \in \varkappa_p^C}$ as

Thus, using the modified path loss law $\ell'(x) = \ell(x)1_{\|x\|>r_p}$

Thus,

$$\mathcal{L}_{I_{pp}}(s) = e^{\left\{-\lambda_l \int_{\mathbb{R}^2} [1-e^{(-\bar{c}v(s,y))}]dy\right\}} * \int_{\mathbb{R}^2} e^{-\bar{c}v(s,y)} f(y)dy \tag{3.7}$$

Where $v(s,y) = \int_{\mathbb{R}^2} \frac{f(x)}{1+(s\mu_p\ell'(x-y))^{-1}} dx$

Again the interference from MBSs is I_{mp} Laplace transform of the interference from a PPP at typical PU located at the origin is

$$\mathcal{L}_{I_{mp}}(s) = e^{-\lambda_m \frac{\pi^2 \delta}{\sin(\pi\delta)} \mu_m^\delta s^\delta} \tag{3.8}$$

The success probability of PU is the Laplace transform evaluated at $s = \theta_p \mu_p^{-1} r_p^\alpha$

Since , I_{mp} and I_{pp} are independent, the outage probability of the PU is

$$\epsilon_p = 1 - \mathcal{L}_{I_{mp}}(\theta_p \mu_p^{-1} r_p^\alpha) \mathcal{L}_{I_{pp}}(\theta_p \mu_p^{-1} r_p^\alpha) \tag{3.9}$$

3.1.2 Randomizing the distance between a UE and its serving BS in intra-tier HetNets

Consider the distance between a UE and its nearest serving BS is random and give the outage performance in intra-tier dependences. Based on the analysis of the outage, per-user capacity and area spectral efficiency is derived.

With intra-tier dependence, the average and coverage area of each MBS or each cluster of PBS is $1/(\lambda_l + (\lambda_m)$, and since there are c' PBSs in one cluster on average, the average coverage area of each PBS is $\frac{1}{c'(\lambda_l+(\lambda_m)}$.The coverage regions of the MBs and PBS are approximated by circular regions and the corresponding radii are $D_m = 1/\sqrt{\pi(\lambda_l + (\lambda_m)}$ and $D_p = D_m/\sqrt{C'}$,respectively. Assume that the MU is uniformly distributed in the circle centered at the serving PBS with radius D_p ,the assumptions can reflect the stochastic behavior of the distance between UE and its serving BS and the UE aggregation behavior.

Since the MU is uniformly distributed in the circle centered at the serving MBS with radius D_m ,the outage probability can be obtained as

$$\epsilon_m = 1 - \int_0^{D_m} \mathcal{L}_{I_{mm}}(\theta_m \mu_m^{-1} t^{\alpha}) \mathcal{L}_{I_{pm}}(\theta_m \mu_m^{-1} t^{\alpha}) \frac{2t}{D_m^2}\, dt$$

$$= 1 - \frac{1}{D_m^2} \int_0^{D_m^2} \mathcal{L}_{I_{mm}}\left(\theta_m \mu_m^{-1} t^{\alpha/2}\right) \mathcal{L}_{I_{pm}}\left(\theta_m \mu_m^{-1} t^{\alpha/2}\right) dt \tag{3.10}$$

Again the outage probability of a PU is

$$\epsilon_p = 1 - \frac{1}{D_p^2} \int_0^{D_p^2} \mathcal{L}_{I_{mp}}\left(\theta_p \mu_p^{-1} t^{\alpha/2}\right) \mathcal{L}_{I_{pp}}\left(\theta_p \mu_p^{-1} t^{\alpha/2}\right) dt \tag{3.11}$$

Since the densities of MUs and PUs are equal to that of MBSs and PBSs, respectively, and the PU is concentrated in the densely populated regions, the MUs take the proportion $k_m = \frac{\lambda_m}{\lambda_m+\lambda_p}$ of total UEs and the population of PUs is $k_p = 1 - k_m$.Then, the per-user capacity of the MU and PU for a fixed transmission based on SIR threshold, respectively as follows

$$C_m = (1 - \epsilon_m)\log_2(1 + \theta_m), \tag{3.12}$$

$$C_p = \left(1 - \epsilon_p\right)\log_2\left(1 + \theta_p\right) \tag{3.13}$$

Thus, the overall per-user spectral efficiency C_u is given by

$$C_u = k_m C_m + k_p C_p$$

$$= \frac{\lambda_m(1-\epsilon_m)\,log_2(1+\theta_m)+\lambda_p\left(1-\epsilon_p\right)log_2\left(1+\theta_p\right)}{\lambda_m+\lambda_p} \tag{3.14}$$

The area spectral efficiency (ASE) in intra-tier dependence can be defined as

$$ASE = \lambda_m(1-\epsilon_m)\,log_2(1+\theta_m) + \lambda_p\left(1-\epsilon_p\right)log_2\left(1+\theta_p\right) \tag{3.15}$$

3.1.3 Comparison with the Two-tier Independent PPP Model

Compared with the two-tier independent PPP model, i.e., the MBSs and PBSs follow two mutually independent homogeneous PPPs with the same densities λ_m and λ_p, respectively. Under the same user distribution, in order to make this comparison relatively fair , assume that at least one PBS is located in each hotspot region and hence model the PBSs in the two-tier independent PPP model as the superposition of Φ_l and another independent homogeneous PPP Φ_p' with density $\lambda_l(\overline{c}-1)$.

First, the outage probability of the MU can be obtained as

$$\epsilon_m = 1 - exp\left\{-\pi\lambda_m \frac{\theta_m\delta}{1-\delta} r_m^2 F(1,1-\delta;2-\delta;-\theta_m) - \frac{\pi^2\delta\theta_p^\delta}{\sin(\pi\delta)} r_m^2 \lambda_p (\frac{\mu_p}{\mu_m})^\delta\right\} \tag{3.16}$$

Then, for that PUs that actually have a serving PBS, the outage probability is

$$\epsilon_p^\delta = 1 - exp\left\{-\frac{\pi^2\delta\theta_p^\delta}{\sin(\pi\delta)} r_p^2 \lambda_p (\frac{\mu_m}{\mu_p})^\delta - \pi\lambda_p \frac{\theta_m\delta}{1-\delta} r_p^2 F\left(1,1-\delta;2-\delta;-\theta_p\right)\right\} \tag{3.17}$$

and the outage probability of the PU not served is 1.Since $\Phi_p = \Phi_p' + \Phi_l$,there are $N_p = \frac{\lambda_l(\overline{c}-1)}{\lambda_l+\lambda_m} + 1$ PBS on each hotspot region to serve the $\overline{c}\,(1+\lambda_l\pi R^2)$ PUs i.e. the mean number of points in a disk, where the second term reflects the extra points due to the overlap.

Thus, the outage probability of an arbitrary PU can be derived as

$$\in_p = \frac{N_p}{\overline{c}\,(1+\lambda_l\pi R^2)}\epsilon_p^s + 1 - \frac{N_p}{\overline{c}\,(1+\lambda_l\pi R^2)} \tag{3.18}$$

Note that for the two-tier independent PPP model, as $\overline{c}$ increases, the number of PUs that are actually served will decrease until when $\overline{c} \to \infty$, the proportion of the served PUs reaches the maximum of $\lambda_l/((\lambda_l+\lambda_m)(1+\lambda_l\pi R^2))$.

The per-user capacity for a fixed-rate transmission based on the SIR threshold of the MU and PU, respectively, are

$$C_m = \frac{1}{N_b}(1-\epsilon_m)log_2(1+\theta_m) \tag{3.19}$$

$$C_p = \frac{1}{N_b}(1-\epsilon_p)log_2(1+\theta_p) \tag{3.20}$$

Thus, per-user spectral efficiency for the model with inter-tier dependence is defined as

$$C_u = k_m C_m + k_p C_p = \frac{k_m}{N_b}(1-\epsilon_m)log_2(1+\theta_m) + \frac{k_p}{N_b}\left(1-\epsilon_p\right)log_2\left(1+\theta_p\right) \tag{3.21}$$

Finally, ASE of the model with inter-tier dependence is defined as

$$ASE = \lambda_m \frac{N_{mu}}{N_b}(1-\epsilon_m)log_2(1+\theta_m) + \lambda_p \frac{N_{pu}}{N_b}(1-\epsilon_p)\ log_2\left(1+\theta_p\right) \tag{3.22}$$

3.2 BSs cooperation and sleeping scheme

The cooperative set is composed of the closest BSs in each network tier to the user. The density of cooperation is the same as the tier contains BSs with the lowest density

The received SINR of MBSs located at the cell boundary is given by:

$$\mathrm{SINR}_m = \frac{\mu_m h_m r_m^{-\alpha}}{\sigma^2} \tag{3.23}$$

The received SINR of PBSs at picocell edge is written as:

$$\mathrm{SINR}_p = \frac{\mu_p h_p r_p^{-\alpha}}{\sigma^2} \tag{3.24}$$

The probability of cooperation happens is equal to the probability of awake MBSs q, and its density is $q\lambda_m$. We assume that the awake MBSs can always cooperate with PBSs to transmit, so that n = K = 2. Where, n is the number of cell cooperatives. The following expression shows the coverage probability of the combined coordination scheme and BSs sleeping control.Thus, the total power consumed by each BS in the macro and femto tiers is modeled as follows:

In two-tier HetNets with BSs cooperation and BSs sleeping, the coverage probability of a randomly located user is given by:

$$p_C = 4\pi^2 q^2 \lambda_m \lambda_P \int_0^n e^{-2\pi q \lambda_m {S_1}^{2/\alpha}} F\left(r_1 {S_1}^{-1/\alpha}\right) \times$$

$$e^{-2\pi q \lambda_p {S_2}^{2/\alpha}} F\left(r_2 {S_2}^{-1/\alpha}\right) \times e^{-\pi q (\lambda_m {r_1}^2 + \lambda_P {r_1}^2)} r_1 r_2 dr_1 dr_2 \tag{3.25}$$

Where $S_i = \frac{TP_i}{P_1 {r_1}^{-\alpha} + P_2 {r_2}^{-\alpha}}$ for $r_i \geq 0\,, i = \{1,2\}$ and $F_x = \int_x^\infty \frac{r}{1+r^\alpha} dr$, and T is SINR threshold.

The active/sleep modes reduce the interference and power consumption as well as improve the energy efficiency of the cellular networks. Thus, the total power consumed by each BS in the macro and femto tiers is modeled as follows:

$$P_m = \begin{cases} \mu_{m0} + \Delta m \beta \mu_m\,, for\ active\ mode \\ 0, for\ sleeping\ mode \end{cases} \tag{3.26}$$

$$P_p = \begin{cases} \mu_{p0} + \Delta p \beta \mu_p\,, for\ active\ mode \\ 0, for\ sleeping\ mode \end{cases} \tag{3.27}$$

The energy efficiency of the networks for BS cooperation

$$\boldsymbol{EE} = \lambda_m p_C \log_2(1 + SINR_m) + \pi {r_m}^2 \lambda_p p_C \log_2(1 + SINR_P) + \lambda_m q_m (\mu_{m0} + \Delta m \beta P_m\ ) +$$

$$\lambda_m (1 - q_m) P_{m,sleep} + \pi {r_m}^2 \left(\lambda_p (\mu_{p0} + \Delta P \beta P_p\right) + \lambda_p (1 - q_{p)} P_{p,sleep}) \tag{3.28}$$

Where μ_{p0} and μ_{p0} are the static power expenditure of the MBSs and PBSs , and Δm, and Δp are the slope of the load-dependent power consumption in MBSs and PBS, respectively. β is the power control coefficient of MBS and PBS.

The spectral efficiency of the networks for BS cooperation

$$\mathbf{SE} = (1 - p_C) \times (\lambda_m \log_2(1 + SINR_m) + \lambda_p \log_2(1 + SINR_P) \tag{3.29}$$

Chapter Four

Simulation Result and Discussion

4.1 Simulation parameters and assumption

Since the simulations are standard compliant, all parameters and assumptions relevant to HetNets are made. Simulation metrics is selected based on the literature of 5G and HetNets evaluation metrics recommendation [15]. The assumed parameter is listed in the following table and the other assumed values are showed when different assumption are used to measure the performance of the two-tier HetNets model, a macro tier overlaid with Pico tier with the densities of the MBSs and PBSs.

Table 4.1: Simulation Parameters value

Parameters	**Abbreviations**	**Value**
Area		$10 \times 10\ km^2$
$\boldsymbol{f_c}$	Carrier frequency	4 GHz
B	Bandwidth	100 MHz
$\boldsymbol{\alpha}$	Path Loss exponent	4
$\boldsymbol{\mu_m}$	The transmit power of MBS	40 Watt
$\boldsymbol{\mu_p}$	The transmit power of PBS	6 Watt
$\boldsymbol{r_m}$	The distance between MU and served MBS	40 m
$\boldsymbol{r_p}$	The distance between PU and served PBS	10 m
$\boldsymbol{\lambda_m}$	The density of MBSs	$8 \times 10^{-4}\ MBSs\ /m^2$
$\boldsymbol{\lambda_p}$	The density of MBSs	$8 \times 10^{-4}\ PBSs\ /m^2$
$\boldsymbol{\bar{c}}$	The average number of points per cluster	20
$\boldsymbol{P_{m,sleep}}$	The sleeping power of MBS	30 Watt
$\boldsymbol{P_{p,sleep}}$	The sleeping power of MBS	4 Watt

$\Delta \boldsymbol{m}$	Slope of MBS	4.2
$\Delta \boldsymbol{p}$	Slope of PBS	5.4
$\boldsymbol{\mu_{m0}}$	Static power MBS	25 Watt
$\boldsymbol{\mu_{p0}}$	Static power PBS	3 Watt
$\mathbf{T}_{\boldsymbol{m}}$	SINR threshold for MU	8 dB
$\mathbf{T}_{\boldsymbol{p}}$	SINR threshold for PU	5 dB
$\boldsymbol{\theta}_{\mathbf{m}}$	SIR threshold for MU	6 dB
$\boldsymbol{\theta}_{\mathbf{p}}$	SIR threshold for MU	4 dB

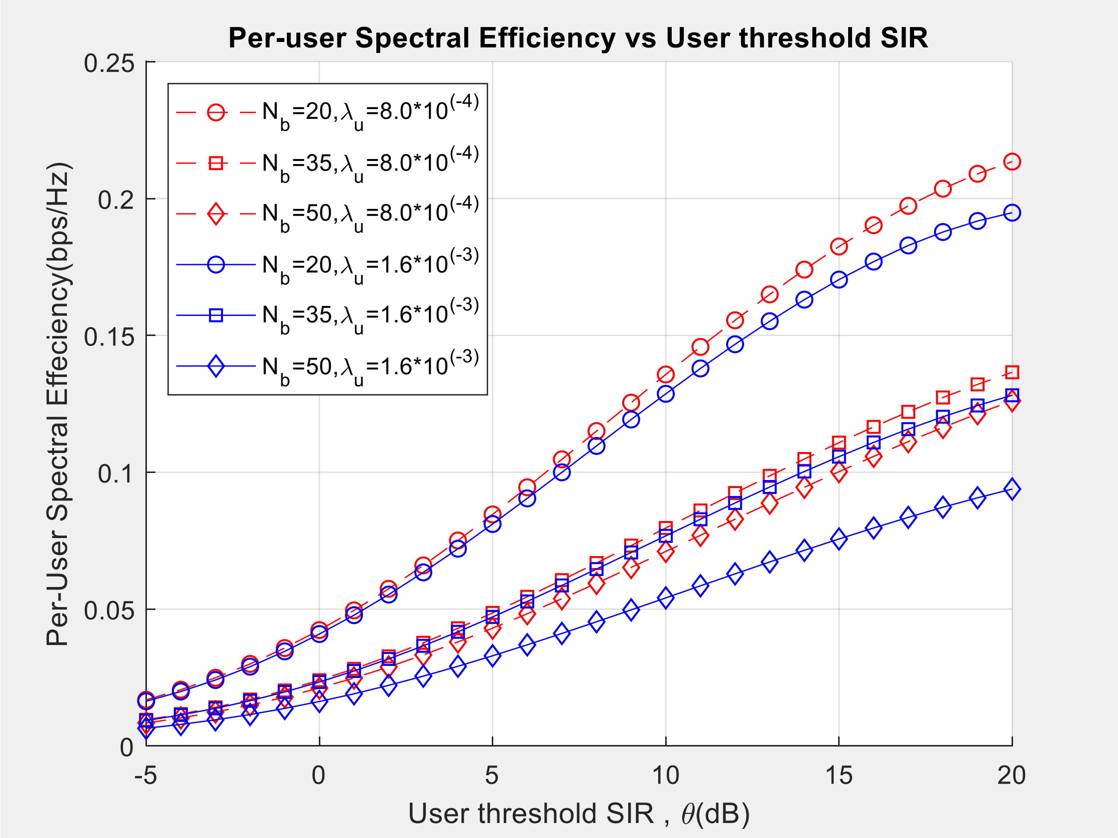


Figure 4.1: Per-user Spectral Efficiency vs user threshold SIR, where $\theta_m = \theta_p = \theta$

Figure 4.1 shows the relationship between the per-user capacity and the user SIR threshold ($\theta_m = \theta_p = \theta$) for different number of radio resources, N_b and user densities λ_u. From this figure, we observe that when a smaller λ_u the higher per-user capacity due to the sufficient available resources relative to the user density. As N_b increases the per-user capacity decreases because the available spectrum resource is allocated to each UE.

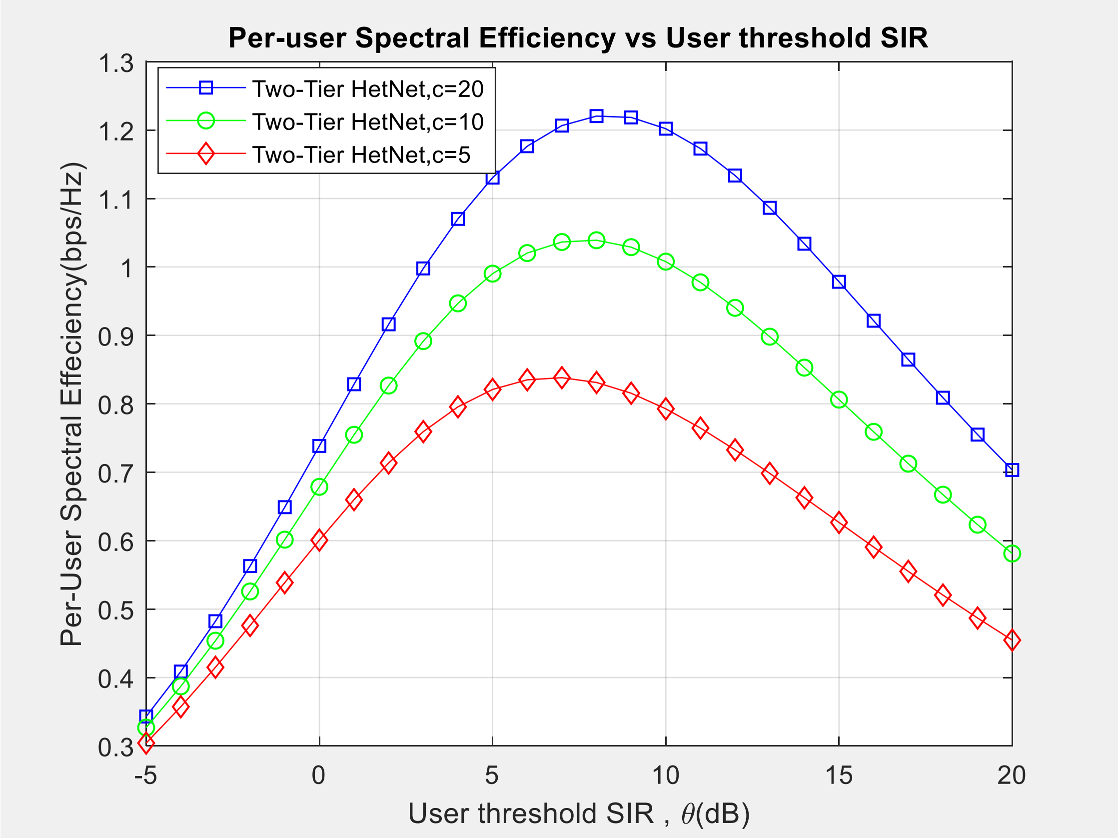


Figure 4.2: Per-user Spectral Efficiency vs user SIR threshold, where $\theta_m = \theta_p = \theta$

Figure 4.2 depicts the relationship between the per-user capacity and SIR user threshold $\left(\theta_m = \theta_p = \theta\right)$ for different average numbers of PBSs per cluster $\bar{c}$ .From the figure we observe that two-tier HetNets model with large $\bar{c}$ has higher per-user capacity because the larger $\bar{c}$ means the larger number of PBSs per cluster, reducing the distance between the PU and its serving PBSs and thus increasing the desired signal strength in spite of the fact that the interference from PBS may increase slightly at the same time.

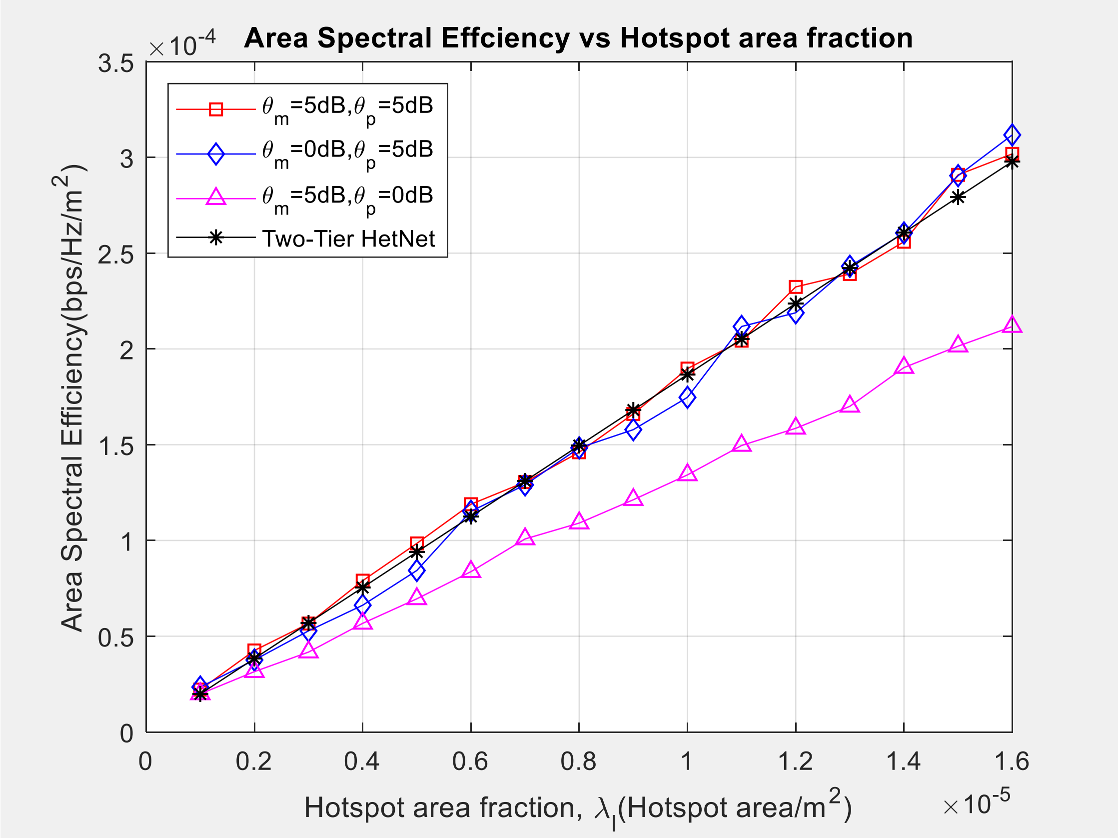


Figure 4.3: Area Spectral Efficiency vs hotspot area fraction, where, $\theta_m = \theta_p = 5\ dB$

Figure 4.3 shows that how the ASE changes with the hotspot area fraction for different SIR thresholds of both MUs and PUs. Let $\lambda_m + \lambda_p = 1.6 \times 10^{-3}$,then changing λ_l can be viewed as changing the ratio of the hotspot area to the whole network. From the figure depicts that ASE increases with λ_l.Because, as λ_l increases the hotspot area takes more proportion in the network and the capacity provided by the PBSs increases, leading to the rise of the ASE.

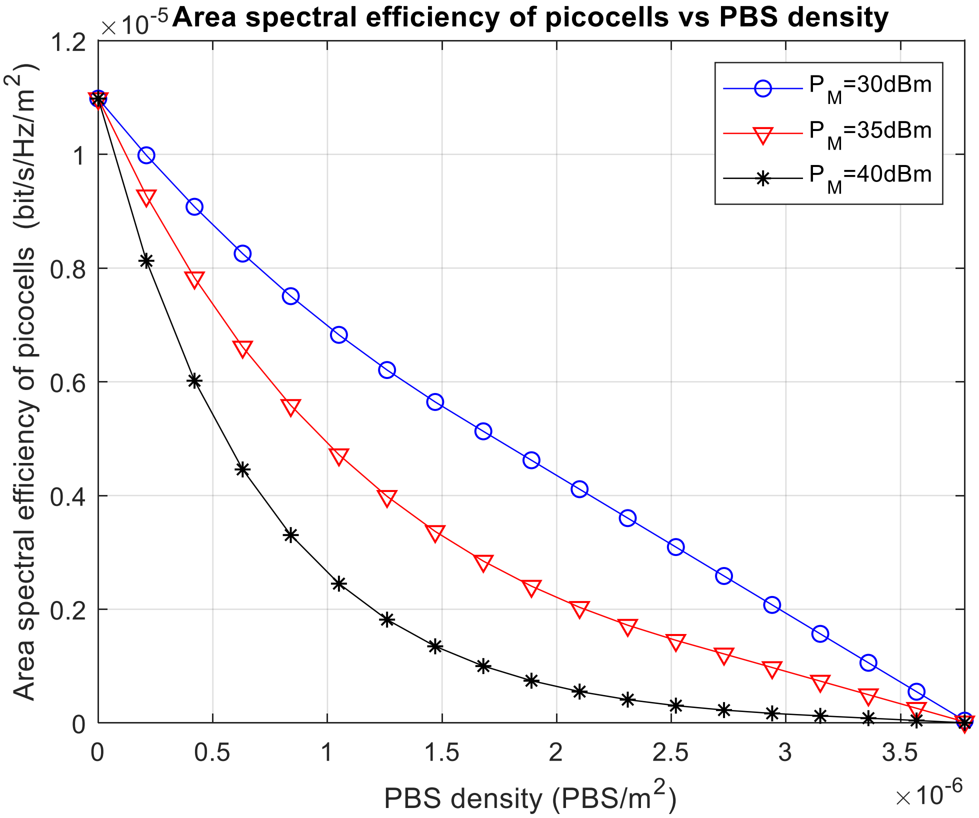


Figure 4.4: ASE Vs PBS density

Figure 4.4 illustrates the relationship between the area spectral efficiency of picocells and PBS density. From the figure observe that area spectral efficiency of picocells is decreasing as PBS density increases. Again the figure shows that high MU power also causes more interference to picocells. The area spectral efficiency of picocells is lower while the MU power is high. In addition, the increment in PBSs density, the constraints to picocells become strict, which makes the optimal PBS density to get only the boundary value of the feasible region. Then, the maximum area spectral efficiency of picocells decreases linearly.

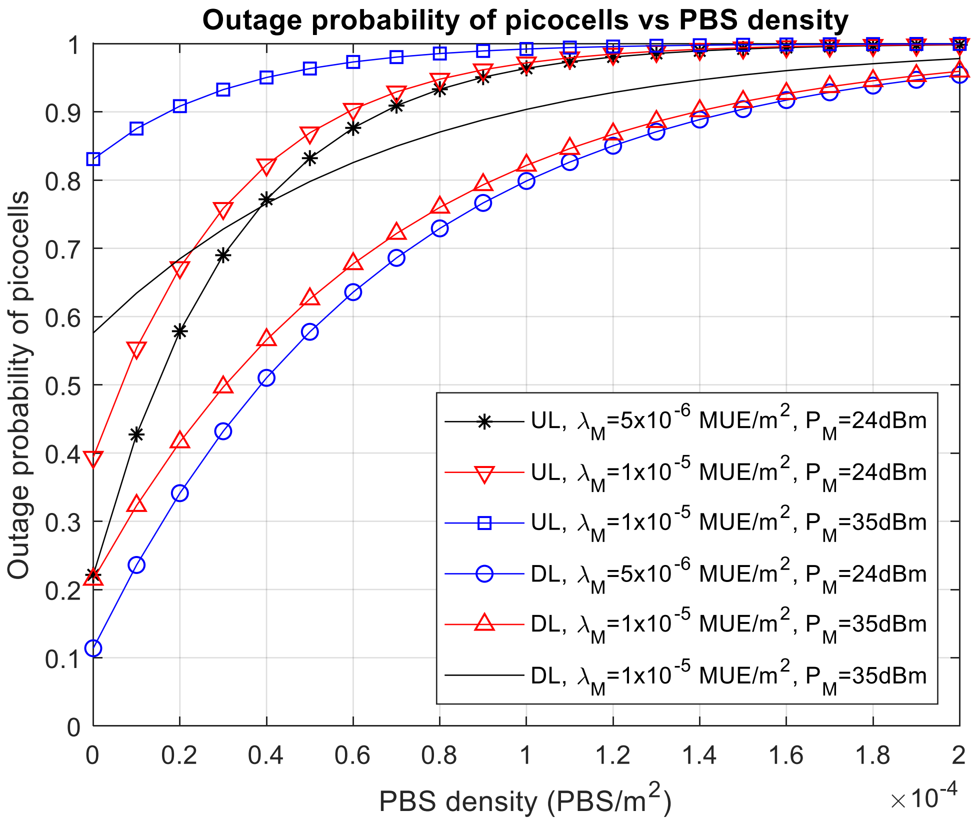


Figure 4.5: Outage probabilities of Picocells Vs PBS density

Figure 4.5 shows the outage probability of picocells with different densities of PBS. Initially, the outage probability of both uplink and downlink transmissions are increasing as PBS density increases. This is due to the fact that high PBS density causes more interference to the overall network and with higher MU density, the outage probabilities for picocells is high. The reason is that high MU density can generate high interference to the picocells, leading to more strict constraints in the transmission of picocells. Similarly, the outage probability is increased when we enlarge the transmission power of MU, which can cause more interference to the picocells.

Moreover, the uplink transmission power is smaller than the downlink transmission power in picocells, showing that the PUs can suffer more interference as receivers in downlink transmission. Therefore, the outage probability of downlink transmission is smaller than that of uplink transmission. In addition, the probabilities of uplink and downlink transmissions in picocells are set as 0.6 and 0.4, respectively, the uplink transmission in picocells causes more interference ina HetNets as the PBS density increases. Thus, the outage probabilities of uplink transmission rise faster as compare to that of downlink transmission.

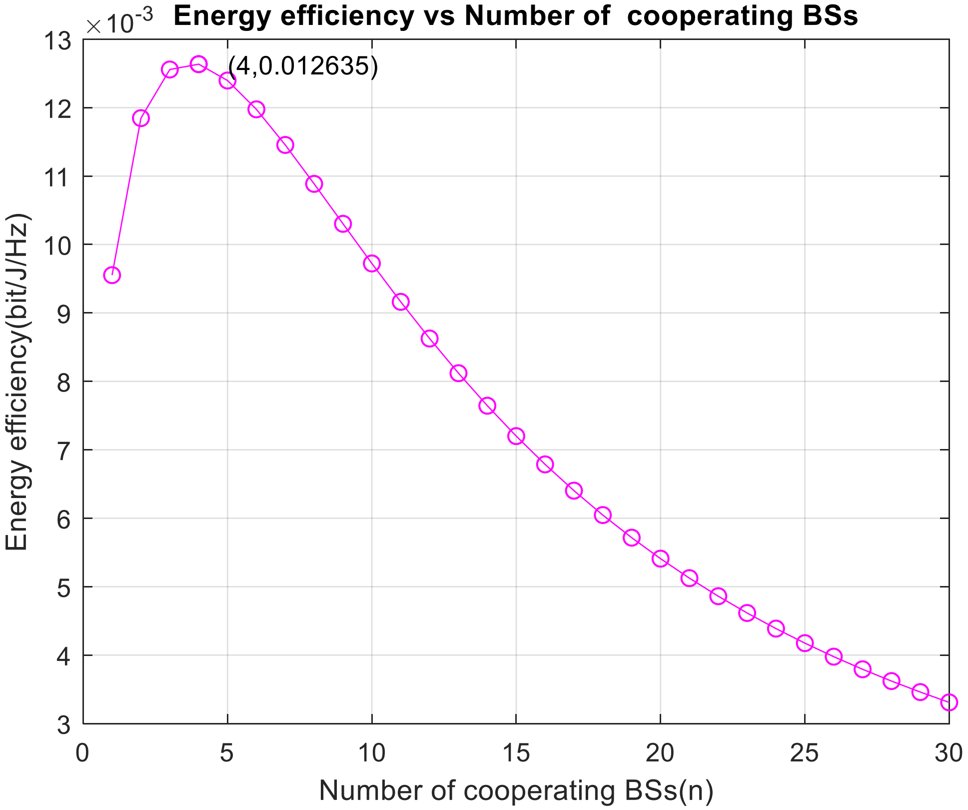


Figure 4.6: Energy efficiency vs Number of cooperating BSs.

Figure 4.6 depicts that when the number of cooperating BSs increases the energy efficiency of the HetNets is decrease. It can be seen that the energy efficiency remains high for values at 0.012607 bit/J/Hz at the number of cooperating BSs is 4.This can be explained the fact when increasing the number of cooperating BSs, more energy is needed.

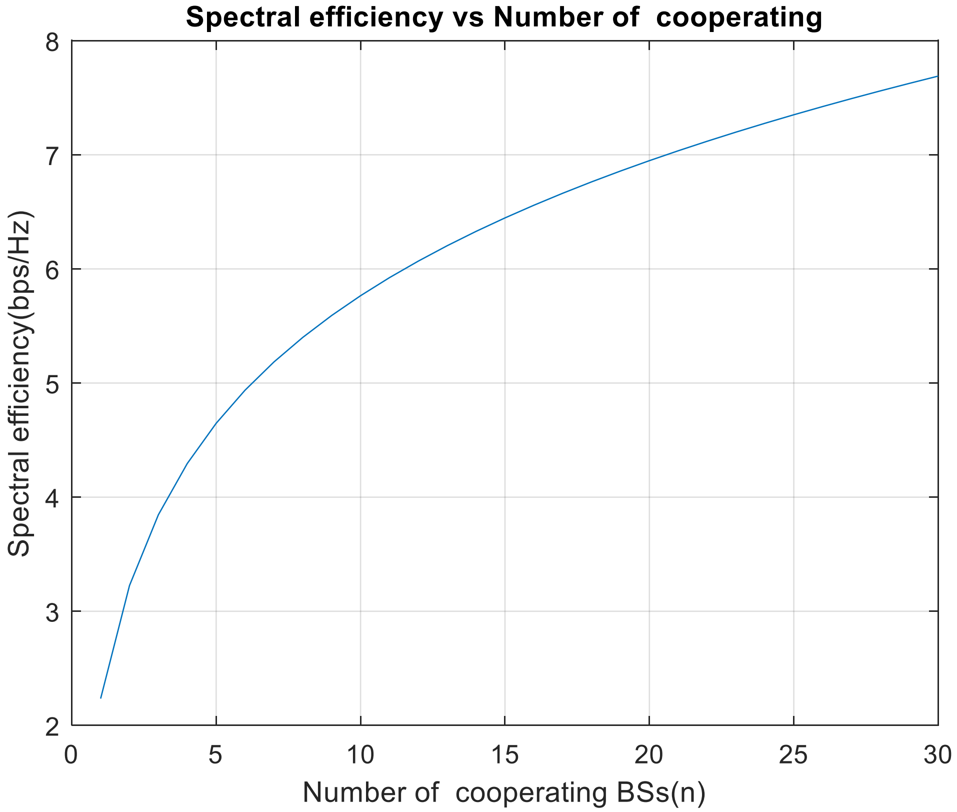


Figure 4.7: Spectral efficiency vs Number of cooperating BSs.

Figure 4.7 shows that when the number of cooperating BSs versus the spectral efficiency of the HetNets is increased. It can be seen that the spectral efficiency remains high when the number of cooperating BSs is increased. This can be explained the fact when increasing the number of cooperating BSs, more spectral efficiency is gained. This implies that the coordinated BSs improve the interference in HetNets.

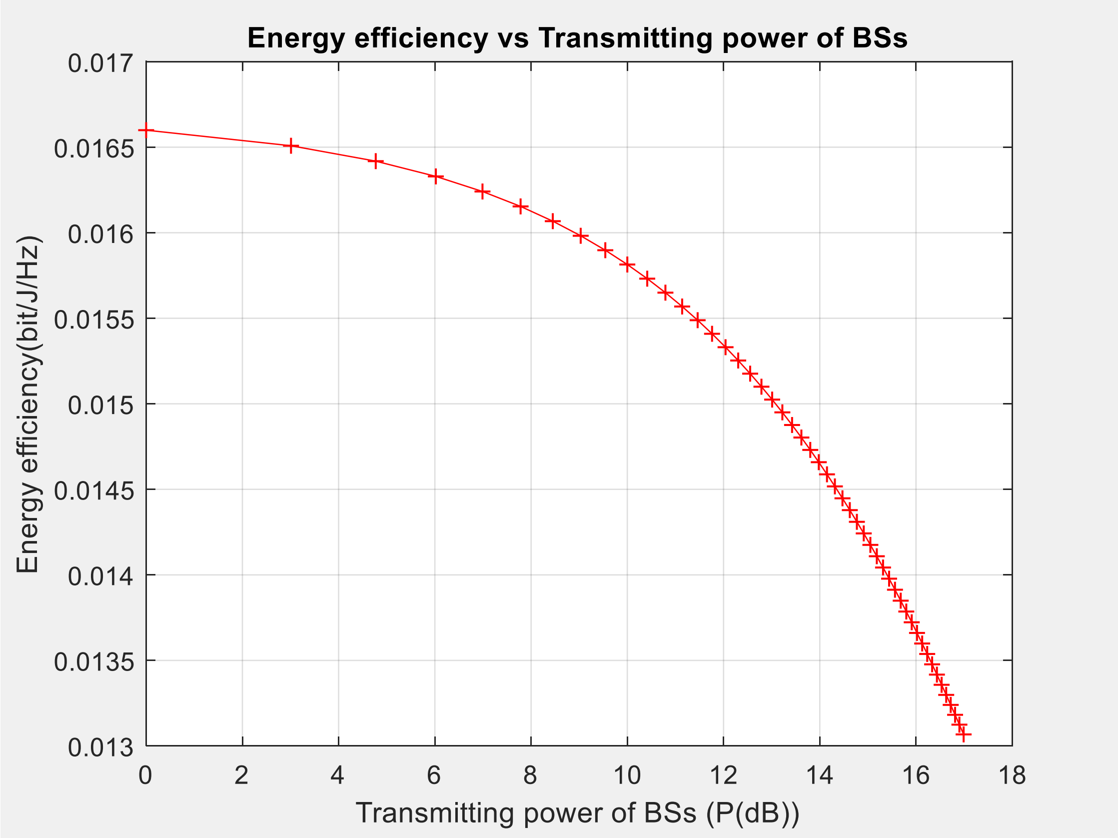


Figure 4.8: Energy efficiency vs transmitting power of BSs.

Figure 4.9 depicts that the transmit power of BSs vs energy efficiency in the HetNets. It can be seen that the energy efficiency remains high for values at 0.01653 bit/J/Hz at the transmit power is 0 dB. This can be explained the fact when increasing the number of the transmit power of BSs is increases, more energy is needed.

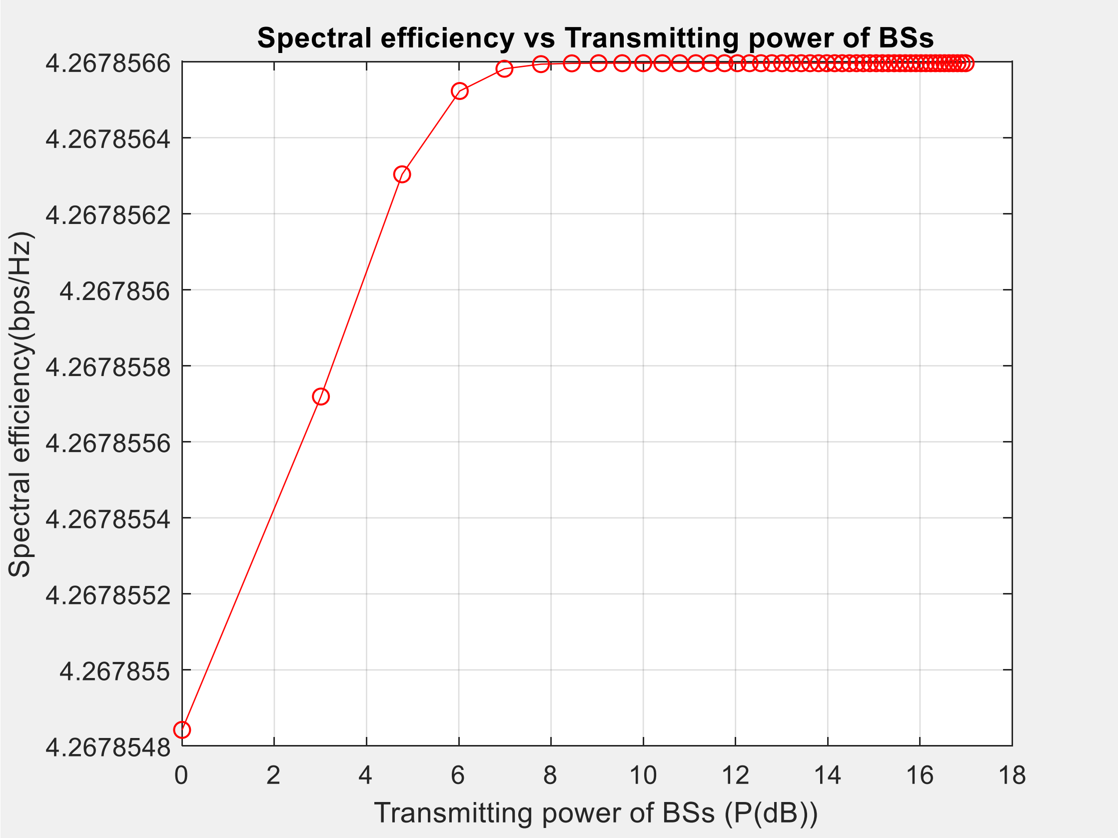


Figure 4.9: Spectral efficiency vs transmitting power of BSs.

Figure 4.10 depicts that the transmit power of BSs versus spectral efficiency of the HetNets.It can be seen that the spectral efficiency remains constant values at 4.2678566 bps/Hz when the number transmit power of BSs is greater than 8 dB. This can be explained the fact when increasing the transmit power of BSs is greater than 8dB, constant spectral efficiency is gained. This implies that the transmit power of BSs improve the interference in HetNets.

Chapter Five

Conclusion and Future Work

5.1 conclusion

In this thesis a two-tier 5G HetNets model with intra-tier dependencies between MBSs and PBSs has been studied; deployment scenario follows a PPP and MHCPP, respectively. From the simulation, result concludes that the smaller user densities have higher per-user capacity due to the sufficient available resources relative to the user density and smaller interference is resulting from the smaller probability that a given sub-channel is occupied. The area spectral efficiency of picocells is lower while the MU power is high.

With higher average number of points per cluster the higher per-user capacity due to reducing the distance between the PU and its serving PBSs. Thus, increasing the desired signal strength in spite of the fact that the interference from PBS may increase slightly at the same time. ASE increases with the density of potential PBSs and the user density but decreases with the number of channels, it implied that a better ASE comes from the proper matching between the network deployment as well as channel resource allocation, the user density, and small cells improves the ASE.

The increment in PBS density causes more interference between picocells, and the constraints to picocells become stricter. When PBS density is high enough, the receivers in picocells severely suffer interference from neighboring receivers. The area spectral efficiency of picocells is lower while the MU power is high. The outage probability of both uplink and downlink transmissions are increasing as PBS density increases. This is due to the fact that high PBS density causes more interference to the overall network and with higher MU density, the outage probabilities for picocells is high.

Finally, when the number of cooperating BSs and transmit power of BSs increases the energy efficiency of the HetNets is decreased while the number of cooperating BSs and transmit power of BSs increases the spectral efficiency of the HetNets is increased.

5.2 Future work

In this thesis, has been addressed the problem of interference in 5G HetNets using stochastic geometry BSs deployment. The main focus of the thesis was the intra-dependence interference between MBSs and PBSs. However, much different HetNets interference characterizations and management scheme have been left for future work due to lack of time. For the future the following ideas could be recommended:

1. It could be interesting to consider the coverage regions in the model depending on the mobility of UE and software-defined resource allocation approach to evaluating interference in the HetNets.
2. The way the model is constructed could be also changed: instead of using one typical path-loss model and estimation of the coverage area of BSs, in order to provide better information among the edge of BSs deployment region.

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