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RITAYAN BISWAS

PERFORMANCE EVALUATION OF COORDINATED MULTIPOINT TECHNIQUES AT MILLIMETER WAVE FREQUENCIES

Master of Science Thesis

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ABSTRACT

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Current cellular technologies operate in the microwave frequencies below 6 GHz. The spectrum below 6 GHz has become congested due to the various technologies that use this frequency band. This has led to a shortage in spectrum. The millimeter wave (mmWave) band offers a solution to the spectrum shortage and thus has been suggested by researchers as a technology enabling the fifth generation (5G) of cellular communications. There are large bandwidths available within the mmWave band which enables high throughput for end users. Coordinated multipoint (CoMP) is a technology that uses the coordination between two or more base stations. As a result subscribes enjoy higher throughput values. In addition, an improvement in the spectral efficiency is also achieved.

The performance of systems utilizing CoMP at mmWave frequencies is evaluated in this thesis. The simulation environment is considered in order to reflect the dense urban environment where 5G is the most likely to be deployed. Various scenarios for the coordination between cells from one or more base stations are formulated. The simulations for these CoMP scenarios are carried out at 2.1 GHz and 28 GHz frequencies with the channel bandwidth of 20 MHz. The bandwidth is increased ten times to 200 MHz and the evaluation of the system performance is carried out in order to offer a comparison as to how CoMP scenarios perform at different bandwidths at mmWave frequencies. Parameters such as received signal strength, signal-to-interference-plus-noise-ratio (SINR), spectral efficiency, area spectral efficiency and throughput are calculated. An analysis of the system performance is carried out based on these parameters.

The results indicate that the use of mmWave frequencies improves the performance of the system by improving the throughput when 200 MHz is the bandwidth used. However, the spectral efficiency decreases when the same bandwidth is used. CoMP improves the system performance with the increase in the number of coordinating points. The scenario where the most number of sectors coordinate provides the best SINR, throughput and spectral efficiency among the scenarios considered. The use of CoMP at mmWaves provides high throughput for users. The locations of the evolved NodeBs (eNBs) in practical deployments can be different in comparison with the simulation environment, which may change the performance of the systems.

PREFACE

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I would also like to say that I am taking much more than a degree from Finland. Coming to Finland to study helped me grow as an individual and for that I will be forever grateful to this beautiful country.

Tampere, 22.03.2016

Ritayan Biswas

“*Don’t bury your thoughts, put your vision to reality. Wake up and live!*”

-Robert Nesta Marley

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

Abbreviations

1G	First generation
2G	Second generation
3D	Three-dimensional
3G	Third generation
3GPP	Third generation partnership project
3GPP2	Third generation partnership project 2
4G	Fourth generation
4K	4K resolution
5G	Fifth generation
5GPPP	5G infrastructure public private partnership
AMC	Adaptive modulation and coding
AMPS	Advanced mobile phone service
AoA	Angle of arrival
AoD	Angle of departure
CDF	Cumulative distribution function
CDMA	Code division multiple access
CIR	Carrier-to-interference ratio
CMOS	Complementary metal-oxide semiconductor
CN	Core network
CoMP	Coordinated multipoint
CS/CB	Coordinated scheduling and coordinated beamforming
CSI	Channel state information
D2D	Device-to-device
DAS	Distributed antenna systems
dB	Decibel
DoA	Direction of arrival
DoD	Direction of departure
DPS	Dynamic point selection
DSL	Digital subscriber loop
E-DCH	Enhanced dedicated channel
eNB	Evolved NodeBs
ETACS	Extended total access communication systems
ETSI	European telecommunications standards institute
EVDO	Evolution, data only
FBR	Front-to-back ratio
FCC	Federal communications commission
FDD	Frequency division duplex
FDMA	Frequency division multiple access
FM	Frequency modulation
FSK	Frequency shift keying
GMSK	Gaussian minimum shift keying
GPRS	GSM packet radio systems
GSM	Global system for mobile communication
HDMI	High definition multimedia interface
HetNet	Heterogeneous network

HPBW	Half power beamwidth
HSDPA	High-speed downlink packet access
HS-DSCH	High-speed downlink shared channel
HSPA	High-speed packet access
HSUPA	High-speed uplink packet access
IEEE	Institute of electrical and electronics engineers
IMT-2000	International mobile telecommunications for the year 2000
IoT	Internet of things
IR	Infrared
ITU	International telecommunications union
JT	Joint transmission
LOS	Line-of-sight
LTE	Long term evolution
LTE-A	Long term evolution advanced
M2M	Machine-to-machine communications
MIMO	Multiple input multiple output
mmWave	Millimeter wave
MTC	Machine type communications
MU-MIMO	Multi-user MIMO
NF	Noise figure
NLOS	Non-line-of-sight
NMT-400	Nordic mobile telephone
NTACS	Narrowband total access communication systems
NTT	Nippon telephone and telegraph company
OFDMA	Orthogonal frequency division multiple access
PAPR	Peak-to-average power ratio
QAM	Quadrature amplitude modulation
QoS	Quality of service
QPSK	Quadrature phase shift keying
RAN	Radio access network
RF	Radio frequency
RRH	Remote radio head
SBR	Shoot and bouncing ray
SC-FDMA	Single carrier frequency division multiple access
SCH	Supplemental code channel
SINR	Signal-to-interference-plus-noise-ratio
SIR	Signal-to-interference ratio
SLL	Side lobe level
SMS	Short messaging service
SNR	Signal-to-noise ratio
TDD	Time division duplex
TDMA	Time division multiple access
TIA	Telecommunications industry association
TP	Transmission point
UDN	Ultra-dense networks
UE	User equipment
UMTS	Universal mobile telephone service
UTRAN	UMTS terrestrial radio access network
UWB	Ultra-wideband
VNI	Visual network index

VoIP	Voice over IP
WAP	Wireless access protocol
WCDMA	Wideband CDMA
WiMAX	Worldwide interoperability for microwave access
WLAN	Wireless local area network
WMAN	Wireless metropolitan area network
WPAN	Wireless personal area network

Symbols

$\langle \cdot \rangle$	Average
G_{h}	Gain in the azimuth plane
G_{m}	Maximum antenna gain
G_{v}	Gain in the elevation plane
R_{ref}	Throughput of reference scenario
R_{s}	Throughput for a scenario
η_{area}	Area spectral efficiency
ρ_{cell}	Cell density
B	Noise bandwidth
d	Distance
F	Noise factor
k	Boltzmann constant
L	Free space path loss
N	Thermal noise power
R	Throughput
T	Temperature
λ	Wavelength
C	Shannon capacity
G	Total antenna gain
W	Channel bandwidth
Γ	SINR (linear scale)
η	Spectral efficiency
θ	Angle of departure
φ	Direction of departure

1 INTRODUCTION

In the modern society, wireless communication devices like smartphones or in general mobile phones play an important role in our day-to-day lives. Communication can take place among two or more users. Cellular systems have evolved from the time when the first generation (1G) of cellular systems were launched. In those days, the communication was analog, as the primary objective was to deliver voice services. Building on voice services the future cellular systems were standardized by international standardizing bodies. As the systems evolved digital communication was made possible. Introducing data services for users brought a revolution in the field of telecommunications. Mobile phone manufacturing companies introduced mobile phones capable of handling large amounts of data and therefore the need for mobile broadband arose. The current technologies such as long term evolution (LTE) and LTE-Advanced (LTE-A) provides high data for users.

With the advancement in the field of multimedia, and the growing number of devices for each user it is imperative that new technologies are thought of which are capable of ensuring good quality capacity and coverage for the network to meet the demands. Research indicates that there is going to be a significant increase in the number of devices capable of handling wireless data in the near future. The fifth generation (5G) of cellular communication is currently under research where new technologies are being studied which are capable of providing a thousand times data rates compared with today's standards. International bodies such as METIS, 5GNOW and 5G infrastructure public private partnership (5GPPP) have been formed in order to study the fifth generation of mobile communications.

The spectrum currently used for cellular communications below 6 GHz is utilized by existing standards. However, there is plenty of spectrum available in the millimeter wave (mmWave) frequency band. Due to unfavorable propagation characteristics, this band was not considered earlier for cellular communications. The advancement in semiconductor technologies will allow radio network planning engineers to overcome these propagation issues. Due to the small wavelength of mmWaves, a large number of antenna arrays can be placed at both the transmitting and receiving ends. Large amount of bandwidth are available at mmWave frequencies. The 28 GHz band has been previously suggested as the likely band where mmWave systems are likely to be deployed.

In cellular communications only one cell from a evolved NodeB (eNB) serves a user at a given point of time. One of the technologies that enable higher data rates for each user is coordinating multipoint (CoMP). Here the coordination between different base stations or eNBs helps in ensuring better data rates for the users. The CoMP technology was introduced as part of the LTE Release 11. One of the key aspects of CoMP technology is the method by which some of the signals causing interference are converted into useful signals. This results in the increase in the signal-to-interference-plus-noise-ratio (SINR) and the throughput of the systems deployed using CoMP technology. The coordination exists between cells from the same eNB and between cells belonging to different eNBs.

The purpose of this thesis is to study the performance of the system for different CoMP scenarios at 28 GHz frequency band. Simulations are carried out in environments resembling the dense urban environment where 5G is the most likely to be deployed. Performance evaluations are also carried out at 2.1 GHz band. The coordination between cells from same/different eNBs is analyzed with different parameters defining the system performance. The millimeter wave band (28 GHz) is also examined with the help of these parameters. The mmWave band also enables the use of greater bandwidths and therefore performance is evaluated and analyzed with different bandwidths.

2 THE EVOLUTION OF CELLULAR NETWORKS

During the past 30, years there has been an impressive growth in wireless communication services. The first successful commercial cellular telephone system was set up in late 1983 by Ameritech in the Chicago area of the United States. It was an analog service known as advanced mobile phone service (AMPS) [1]. Digital cellular telephone services, as of today, are available all over the world and have eclipsed fixed-line telephone services both in terms of users as well as availability. Wireless technologies have been embraced much more in comparison to wired technologies in developing countries. For example, wireless technologies are four times more predominant than fixed line in India [1].

The number of mobile users have grown from zero to over a billion worldwide in less than 20 years [1]. This growth can not only be attributed to the eagerness of users to be able to share information and be connected on the go but also to the enormous advances in technology that has made such an evolution possible. Improvement in miniaturization techniques (which decreases the size of the antenna) in addition to advancements in radio frequency (RF) circuit fabrication and digital signal processing have made the deployment of wireless communication circuits plausible to the extent that we observe them today.

In contrast to the growth which was previously attributed to voice telephony it is safe to say that future growth in the field of wireless communications will be driven by the data centric wireless applications. The internet has grown alongside wireless communications and is a fundamental source of information worldwide. It provides a variety of services such as e-mail, social networking and more predominantly entertainment. High speed data is one of the precursors in obtaining a smooth internet experience. Providing high speed data for mobile users has become one of the primary objectives of wireless communications, and LTE which is a part of the fourth generation (4G) of cellular systems is a key enabling technology that aim to fulfil these goals. In this chapter, the evolution of cellular systems is outlined from the initial deployments to the current standards.

2.1 First Generation

Distributing voice services was the main objective of the 1G of cellular systems and was characterized by analog modulation techniques. Development of the first generation of cellular systems was led by the United States, Japan and some European countries. Nippon telephone and telegraph company (NTT) in 1979, deployed the first commercial cellular system in Japan. In Europe, the Nordic mobile telephone (NMT-400) system which supported international roaming and automatic handover was implemented in the year 1981. Finland, Denmark, Sweden, Norway, Spain and Austria were the European countries where NMT-400 was first deployed. However, AMPS in the United States along with its variants extended total access communication systems (ETACS) and narrowband total access communication systems (NTACS) in Europe and Japan respectively, were the systems which were the most successful among the first generation systems. [1]

All the three aforementioned systems employed frequency division multiple access (FDMA) as a Multiple Access Scheme and used frequency modulation (FM) as the Voice Modulation technique. The systems were built with the channel bandwidths of 30 kHz, 25 kHz and 12.5 kHz for AMPS, ETACS and NTACS respectively. [1]

AT&T Bell Labs were responsible for the development of AMPS towards the latter part of the 1970s. The Chicago area was where the system was first set up in 1983. It utilized omni-directional base station antennas and usually covered large areas with a very limited number of base stations with antenna heights ranging from 150 feet to 550 feet. [1] These systems aimed to achieve a decent voice quality and hence were designed with a carrier-to-interference ratio (CIR) of 18 dB. They were set up with a 7-cell frequency reuse pattern with each cell consisting of three sectors [1]. For the deployment of AMPS in the United States, the federal communications commission (FCC) allocated a spectrum of 20 MHz which supported a total of 416 AMPS channels. 395 out of these channels were allocated for carrying voice traffic and the remaining 21 channels were assigned to carry control information. Voice traffic was carried by the FM technique and frequency shift keying (FSK) was used for the control channels. [1]

AMPS was also deployed in certain other countries in Asia and South America. After the second generation (2G) systems were deployed AMPS ensured backward compatibility. AMPS also provided roaming facilities between operator networks who set up 2G systems which were incompatible. [1]

2.2 Second Generation

Unlike the first generation cellular systems, the 2G cellular systems employed digital modulation techniques which brought about significant improvements with respect to the performance of the system. The use of digital codecs which had high spectral efficiency, multiplexing a number of subscribers on the same frequency channel by various multiplexing techniques such as time division or code division and the efficient reutilization of frequency bands resulted in the improvement of system capacity [2]. Link level signal processing helped in improving the voice quality. Security, which was one of the major drawbacks of 1G was alleviated by the use of encryption, which prevented eavesdropping and fraud. [2]

2.2.1 GSM

The global system for mobile communication (GSM) introduced in the year 1990 is a 2G digital cellular system which has been widely deployed. GSM today has a global market share of 90% and has been deployed in more than 220 countries which culminates in having 4.2 billion subscribers worldwide. Such a global adoption of the technology has enabled smooth international roaming.

In addition to better voice quality and security, 2G systems supported new applications such as short messaging service (SMS) which became very popular especially among the young generation. GSM also provided support for wireless applications with a low data rate. Initially, 2G systems were designed to support circuit switched data services but later developed so that packet data services could also be supported [1]. The wireless applications in the beginning had restraints with regard to data rates and were mostly limited to news delivery, the weather, stock market updates to name a few. Wireless access protocol (WAP) was developed in order to overcome these limitations and deliver content to mobile devices [2].

GSM uses time division multiple access (TDMA) as its air-interface scheme. It is based on multiplexing eight users by providing each of them different time slots on a single 200 kHz wide frequency channel. The modulation scheme that is used in GSM is Gaussian minimum shift keying (GMSK) which is an alternative to FSK. GMSK was chosen as it provided satisfying power and spectral efficiency due to constant envelope modulation. [2]

The European telecommunications standards institute (ETSI) introduced GSM packet radio systems (GPRS) by the mid 90’s as advancement to circuit switched data (providing a data rate of 9.6 kbps) which was part of the original GSM standard. GPRS was a progression towards higher data rates for GSM systems. GSM and GPRS systems share the same time slots, frequency bands and links used for signaling. Four different channel coding schemes were described by GPRS, each supporting 8 kbps to 20 kbps. Theoretically, during suitable conditions, with a peak rate of 20 kbps and with all the eight channels in the GSM TDM transmitting data, a data rate of 160 kbps can be achieved [2]. However, in practical implementations a rate of about 20–40 kbps is achieved [2].

2.2.2 CDMA

Code division multiple access (CDMA) was projected as a more competent and higher quality wireless technology in comparison to GSM by Qualcomm in 1989. In 1993, telecommunications industry association (TIA) adopted Qualcomm's proposal for adopting CDMA as a standard for Interim Standard 95 (IS-95). IS-95 CDMA systems allowed multiple users to use the same frequency channel simultaneously [1]. Each user was assigned distinct spreading codes orthogonal to each other in order to isolate different signals at the receiver. The codes were put into use by multiplying the user data symbols with a code sequence of higher rate that led to the spreading of the signals over a larger bandwidth. The effects of multipath fading and interference were mitigated by the spreading of the signals. Transmission of 9.2 kbps or lower voice signals was made possible by the use of a 1.25 MHz bandwidth in IS-95 CDMA [3].

CDMA provided notable advantages over the GSM technology. Frequency reuse, whereby each frequency channel could be used by each one of the cells was made possible. This resulted in an increase in capacity and frequency planning was also simplified [1]. The use of RAKE receiver helped in the reduction of transmitted power as it combined several multipath signals in order to produce a stronger signal. The introduction of soft handover where a mobile device was able to make a connection with a new base station before disconnecting the existing connection enhanced the handover performance. System capacity was further improved by turning off transmissions during inactive periods. This in turn also helped in reducing the overall interference level. However, slow frequency hopping helped in enabling frequency reuse in GSM systems.

There was always a dispute between the TDMA and CDMA technologies as to which technology administered better coverage and capacity but practical deployments suggested that IS-95 CDMA offered better coverage and capacity in comparison to GSM. However, CDMA systems did not have a global acceptance in comparison to GSM systems. North America, South Korea, Brazil and India were the only parts of the world which had CDMA subscribers.

The initial system (IS-95A) had support for a channel that was dedicated to data transmission in addition to the voice channel providing a data rate of 9.6 kbps. An improvement in efficiency occurred due to the introduction of the supplemental code channel (SCH). SCH provided a data rate of 14.4 kbps. A peak data rate of 115.2 kbps could be obtained by combining 7 SCH channels. [3]

2.3 Third Generation

Even though the second generation of cellular systems helped in improving voice quality and initiated data support for applications the 2G systems provided very low data rates and hence were very inefficient for data. This was due to the fact that 2G systems were built on circuit switching and provided the data rates of a few kilobits per second with inadequate capacity.

Third generation (3G) systems supported much higher data rates in addition to providing higher voice capacity and better voice quality. Providing better quality of service (QoS) was also expected of 3G systems for both voice communication and web browsing. The international telecommunications union (ITU) started inviting ideas for 3G and subsequently determining a possible spectrum. This was formally known as International Mobile Telecommunications for the year 2000 (IMT-2000) and was responsible for developing standards that were globally interoperable. ITU proposed certain data rate specifications for IMT-2000. In building and fixed environments a data rate of 2 Mbps. A data rate of 384 kbps in urban environments and in vehicular environments a data rate of 144 kbps.

2.3.1 CDMA2000 and EVDO

The evolution of the IS-95 standards led to the formation of the CDMA2000. The third generation partnership project 2 (3GPP2) was formed in the year 1999 in order to have the official standardization process under a single standards body. The first development of the IS-95 standard used the same bandwidth (1.25 MHz) as IS-95 and hence it was termed as the CDMA2000-1X. By adding logical channels, the data rates were enhanced in this iteration. CDMA2000-1X did not meet the specifications that 3G provided and due to this it could only be attributed as a 2.5G system. However, with the use of multiple carriers the data rate could be raised as was the case in CDMA2000-3X. By adding 64 channels orthogonally to the existing 64 channels the theoretical data rate could be doubled in comparison to IS-95 [4]. The use of better modulation techniques and power control helped in improving the data rate of both the uplink and the downlink channels.

To achieve an overall increase in system performance and obtain data rates close to the 2 Mbps as specified by IMT-2000, the CDMA2000-1X evolved into CDMA2000-1X-EVDO (evolution, data only). This standard had no support for anything other than data traffic. Therefore, a single carrier had to be assigned by operators for providing data services. The original development of EV-DO by Qualcomm was aimed at providing 2 Mbps data rate for fixed applications as was specified by the IMT-2000. However, complete mobility requirements were incorporated in the later iterations. Consequently, that led EV-DO to being the first standard that provided data rates comparable to broadband for users using mobile devices and applications.

EV-DO consisted of multiplexing users in time into a TDMA link thus providing data rates of 2.4 Mbps theoretically in the downlink. The data rates for uplink were about 153 kbps thus making the whole system very asymmetric [4]. EVDO used quadrature phase shift keying (QPSK) and quadrature amplitude modulation (QAM) as modulation techniques and the link conditions had the capability to determine the modulation and coding rates.

2.3.2 UMTS WCDMA

As part of the development for GSM, ETSI developed the universal mobile telephone service (UMTS) according to the specifications provided by the IMT-2000 for 3G systems. The third generation partnership project (3GPP) was formed in order to develop the UMTS standards. In 1999, the first UMTS standard for 3G systems known as UMTS Release 99 was presented and it was met with success worldwide.

The architecture of UMTS was hinged on being backward compatible with the GSM/GPRS architecture. It consists of a core network (CN) that is responsible for the routing, switching and managing users. Also part of the UMTS architecture is the UMTS terrestrial radio access network (UTRAN) and user equipment (UE). However, the air interface for 3G systems is completely different in compared with 2G systems. The benefits of IS-95 motivated the design of the wideband CDMA (WCDMA) as the air interface for 3G systems. Frequency division duplex (FDD) operation for WCDMA is certainly most widely deployed even though WCDMA states both FDD and time division duplex (TDD) operation [1]. The UMTS WCDMA standard is capable of supporting a large number of voice calls in addition to providing peak data rates between 384 kbps and 2048 kbps due to the fact that it is based on a larger bandwidth of 5 MHz in comparison with CDMA2000 [4].

2.3.3 HSPA

The aggregation of two most important 3G protocols namely high-speed downlink packet access (HSDPA) and high-speed uplink packet access (HSUPA) led to the fabrication of the high-speed packet access (HSPA). The development of 3GPP UMTS was focused primarily on the downlink channels due to the greater download throughput necessity of various applications. Achieving a theoretical data rate of 14.4 Mbps was specified by HSDPA with the use of a separate downlink channel. High-speed downlink shared channel (HS-DSCH) uses time division multiplexing with a restricted use of code division multiplexing. [5]

Walsh codes help in separating users on the downlink channel. 15 out of 16 Walsh codes in HSDPA are used for user traffic. Though the UE restricts the number of Walsh codes a single user is allowed to use, a better throughput is obtained by using more number of codes [5]. HSDPA produced data rates between 500 kbps and 2 Mbps for real life scenarios [5]. Adaptive modulation and coding (AMC) was one technique used by HSDPA in order to obtain high data rates where the modulation and coding method is altered for every user depending upon the condition of the downlink channel at a particular instant.

The enhanced dedicated channel (E-DCH) which is another uplink channel was introduced by HSUPA to the UMTS WCDMA. Some of the advanced characteristics that were used in HSDPA was incorporated into HSUPA. The peak data rate that HSUPA was able to provide theoretically was up to 5.8 Mbps. Low latency and data rates between 500 kbps and 1 Mbps was achievable for real life applications which enabled uploading large files and the use of real time communication applications such as the voice over IP (VoIP). [4]

2.3.4 HSPA+

Release 7 HSPA, also known as HSPA+, brought about improvements in latency, throughput and system capacity in comparison to HSPA systems. The use of 64QAM and 16QAM as additional modulation schemes in downlink and uplink, supplementing the existing modulation schemes outlined in Release 6 HSPA helped increase the peak downlink and uplink data rates to 21.1 Mbps and 11.5 Mbps respectively.

HSPA+ also supports the use of two transmitting and receiving antennas for multiple input multiple output (MIMO). The use of 2 x 2 MIMO enables efficient techniques such as beamforming, spatial multiplexing and transmission diversity. The use of 64QAM and MIMO is not permitted by Release 7. However, Release 8 allows this and therefore enables a theoretical peak downlink rate of 42 Mbps [6]. Release 8 also described the dual-carrier operation in the downlink of adjacent carriers. When multiple carriers are present in a single cell, the use of dual-carriers helps in achieving very high data rates. In contrast to MIMO, this technique does not incur additional implementation challenges, in addition to providing higher cell capacity.

An improvement in battery life is achieved by allowing uplink transmissions to be discontinuous in contrast to Release 6 HSPA, which required the transmission of the physical control channel even in the absence of data transmission. Even on the downlink, discontinuous reception was supported where the mobile device would only wake up in the event of a part of a data frame being received. Discontinuous transmissions in the uplink and downlink enabled an improvement in battery life for data applications such as web browsing. The discontinuous uplink transmissions helped in avoiding interference and resulted in an increase in capacity for VoIP applications.

2.4 Fourth Generation

The massive growth of the internet over the past decade led to the requirement of mobile broadband. The internet has become a fundamental technology that is required in order to communicate, gather information and serve as a mode of entertainment for users. The internet is rich in multimedia content and the access to fixed line broadband has enabled users to use the internet seamlessly. The introduction of smartphones, capable of handling applications requiring high bandwidth such as video streaming and the popularity of video sharing websites such as YouTube has led to the requirements of high data rates. Present-day smartphones have technologies such as GPS navigation systems incorporated into them. This gives rise to a wide variety of applications requiring high data rates. In addition, smartphones being able to handle full web browsing, email and video playback has enabled users to use a lot of wireless data. The fourth generation of cellular communications aims to provide users with access to the multimedia rich content of the internet everywhere and even while the user is mobile.

The ITU defines the requirements for 4G systems with IMT-Advanced. IMT-Advanced aims to achieve the peak data rates of 100 Mbps in environments where the users are mobile and 1 Gbps in environments with low mobility [43]. IMT-Advanced also requires for a peak spectral efficiency of 15 bps/Hz, the average spectral efficiency of 2.6 bps/Hz and 0.075 bps/Hz spectral efficiency at the cell edge for each user in the downlink [43]. The spectral efficiency requirements can be achieved by the utilization of higher order modulation and MIMO techniques.

2.4.1 Mobile WiMAX

The institute of electrical and electronics engineers (IEEE) created a group in 1998 to standardize the wireless metropolitan area network (WMAN). This group was known as 802.16 which primarily aimed at standardizing fixed wireless applications. In 2005, a revision was made in order to support devices which were mobile and this group was termed as the IEEE 802.16e. It was formally known as mobile worldwide interoperability for microwave access (WiMAX) and was based on the air-interface standards specified by IEEE 802.16. ITU accepted mobile WiMAX as a radio access technology based on orthogonal frequency division multiple access (OFDMA) in 2007. [1]

WiMAX network is constructed using IP protocols. Voice services are not supported as the network employs packet switching technology. However, the use VoIP enables subscribers to utilize voice services. WiMAX was an alternative to LTE for operators who intended to make mobile broadband available to users. Though WiMAX was not as successful as LTE in the mobile broadband market features such as the use of OFDM/OFDMA technology in LTE were influenced from their use in WiMAX. The use of OFDM in the physical layer allows WiMAX to function with large bandwidths in non-line-of-sight (NLOS) environments. OFDM offers a robust technique to reduce the effects of multipath propagation. [1]

WiMAX aimed at providing mobile broadband for users, therefore peak data rates of 74 Mbps was achieved in the 20 MHz operating frequency. Data rates of 18 Mbps were achieved when 5 MHz was the operating frequency. These data rates were observed when the modulation technique used was 64QAM. The use of advanced antenna techniques helps in improving the spectral efficiency and the capacity of the system by employing multi antenna techniques such as beamforming and spatial multiplexing. The architecture of WiMAX is IP based and requires all services to be delivered over an IP framework based on IP protocols.

2.4.2 Long term evolution

The evolution of GSM/UMTS/HSPA+ networks by the 3GPP led to the development of LTE networks. Release 8 specified the OFDMA based LTE radio interface in 2009. LTE can be deployed on the existing spectrum which helps in the reuse of frequency and transmission equipment used in previous generations. LTE aimed to provide seamless internet coverage and achieve internet browsing experience comparable to fixed line broadband. LTE also aimed to achieve high throughput and reduced latency during communications.

Multi-antenna techniques are supported by the LTE standard in order to provide for a robust link and improving the spectral efficiency and capacity of the system. Multi-antenna techniques enable transmission diversity which helps in nullifying the effects of multipath fading. In order to improve the signal-to-interference ratio (SIR), beamforming can be used which focusses the transmitted beam from multiple antennas in the direction of the receiver [6]. The use of multi-user MIMO (MU-MIMO) enables spatial multiplexing in LTE systems. MU-MIMO allows each user to transmit simultaneously on the same frequency channel.

In comparison to UMTS/HSPA+ which uses TDMA/CDMA as the multiple access technology, LTE makes use of OFDMA for its downlink channels and single carrier frequency division multiple access (SC-FDMA) for its uplink channels. SC-FDMA is used in the uplink as it provides better power efficiency in the uplink due to the low peak-to-average power ratio (PAPR) which reduces the size and power consumption of the power amplifier in the user equipment. LTE can make a flexible usage of the spectrum as operators can deploy LTE in any of 700 MHz, 900 MHz, 1800 MHz and 2.6 GHz bands [7]. This flexibility in the usage of the spectrum will make LTE a global standard. The Channel bandwidths of 1.4, 3, 5, 10, 15 and 20 MHz can be supported by LTE networks with the user equipment being able to operate at channel bandwidths that are lower than the maximum supported value [7]. Therefore a user equipment supporting a maximum cannel bandwidth of 15 MHz can operate at the 3 MHz and 10 MHz bands in addition to others.

Theoretically, LTE networks aim to provide the peak data rates of 300 Mbps on the downlink and 75 Mbps on the uplink channels. These data rates are a significant increase in comparison to the 3G systems. Only a few handful users (near the base stations) are able to experience the peak data rates. The LTE network design targets at providing the average user with an increase in a data rate of 3-4 times on the downlink and 2-3 times on the uplink in comparison to the original deployment of HSPA [7]. Voice centric and video streaming applications in addition to applications like interactive real time gaming are sensitive to delays and LTE helps at diminishing the network latency. The round trip delay in fixed line broadband systems such as digital subscriber loop (DSL) systems is about 20-40 ms [7]. However, LTE systems aim at providing a delay of less than 5 ms for one way radio communication. LTE networks apart from providing performances comparable to fixed line broadband also aims to achieve requirements such as high quality connections and handover in mobile environments. These requirements are to be met in mobile environments with the speed of 15 km/h with only small performance deteriorations at the speed of 120 km/h and low quality support at the speed of 350 km/h [7].

2.4.3 Long term evolution advanced

LTE Release 10 also known as LTE-A brought about a major improvement to LTE in the year 2011. Even though much of the industry refers to LTE as a 4G system, strictly speaking it does not adhere to the requisites laid forward by the ITU as part of the IMT-Advanced. LTE-A is not a new radio access technology as it is an improvement over the existing LTE systems. An evolution of LTE was the right way forward for operators as LTE-A systems remain backward compatible with existing systems. LTE-A brings about advancements such as carrier aggregation, support for heterogeneous networks, CoMP transmission in the downlink and evolved multi-antenna techniques in comparison to LTE.

LTE Release 8 supported the deployment of systems with the bandwidth varying from 1.4 MHz to 20 MHz. However, LTE Release 10 specifies that the transmission bandwidth can be enlarged with the help of a technique termed as carrier aggregation. In carrier aggregation, multiple component carriers can be combined and used collectively in order for the transmissions to take place to and from a user equipment [7]. A maximum of five component carriers can be combined, therefore, enabling a transmission bandwidth of nearly 100 MHz. Combining the carriers helps in obtaining high data rates which are part of the requirements of IMT-Advanced. The downlink peak throughput target is about 1 Gbps and peak rates of about 500 Mbps are targeted in the uplink.

LTE Release 10 supports the spatial multiplexing of eight transmission layers on the downlink with an improvement in the reference signal design and four layers on the uplink where codebook-based precoding is used [8]. The primary purpose of CoMP (which was released as part of Release 11) is to provide an air interface for the cooperation among different eNBs in the downlink. This enables the eNBs to decide on the scheduling, parameters used during transmission and weights for the transmit antenna for an individual mobile terminal. CoMP aims to achieve a reduction in the interference for a single mobile terminal which is situated near multiple eNBs.

An improvement in capacity and coverage can be attained by the deployment of low power nodes in a homogeneous environment like in macro-cells. These low power nodes can be relays, micro-cells, pico-cells, femto-cells and distributed antenna systems (DAS) which are installed in varying surroundings such as hotspots in order to achieve system optimization [7]. A relay or a repeater node is a low powered node which can help in increasing the system coverage by amplifying and forwarding the received waves. Nevertheless, this is not always an advantage as these nodes are unable to differentiate between signals and noise.

Release 12 aims to provide improvements with respect to capacity, coverage, coordination between cells and cost. These improvements are achieved due to technologies such as machine type communications (MTC), 3D-MIMO, the development of carrier aggregation and small cell and macro cell enhancements [9]. Release 12 was functionally frozen in March 2015.

A large number of small cells are to be deployed in dense environments. This will increase the traffic arising due to signaling, in the core network as users move between cells. Separating the control channel in the radio access network (RAN) will enable the macro-cells to handle the signaling while the small-cells take care of the high data traffic [9]. Carrier aggregation between different sites is an interesting technique for heterogeneous networks (HetNets) whereby the signaling is handled by the macro-cell and the combining of small cells help in providing high data rates and capacity improvements. This technique combines the advantages of macro-cell coverage and small cell capacity and are used together with carrier aggregation in order to achieve a gain of 50% on the cell edge even when there are many subscribers using the network simultaneously [10].

The growth in network traffic requires the enhancement in the network capacity and coverage of macro cells by utilizing techniques such as multi-antennas, state of the art receivers and fresh spectrum. The utilization of more transmitting and receiving antennas at the base station increases the network capacity. The use of MU-MIMO further increases the capacity of the network. Sector and cell edge capacity can be improved by making use of both the azimuth and elevation of the multipath channel at the same time by a using the 3D-MIMO technique. Release 12 also improves the support for MTC applications for LTE-A systems. The RF equipment in a terminal, utilizing a single receiving antenna and operating in the half-duplex mode can lead to major savings regarding the cost. By using a single antenna for receiving, curtailing the bandwidth usage and having a lower peak throughput ensures a cost saving of about 60% [10].

2.4.4 LTE-Advanced pro

Release 13 which is set to be standardized during March 2016 aims at building on the technologies introduced with Release 12 while introducing new technologies. The use of active antenna systems leads to enhancement in the performance of the system due to adaptable cell splitting and beamforming [11]. This is made possible due to the fact that base stations deploying active antenna systems can alter the radiation pattern due to the presence of multiple transceivers on the antenna array.

Signaling for Inter-eNB CoMP is another focus area of Release 13 whereby the objective is to decrease the interference between eNBs by introducing a method by which coordination between a pair of eNBs can be achieved. Better system coverage and an increase in the cell edge and overall system throughput are thought to be some of the advantages of using Inter-eNB CoMP technology [11]. Release 13 discusses the improvements regarding public safety functionalities such as LTE device-to-device (D2D) communications in environments with full network coverage to environments where there is little or no coverage. To allow for better coverage and low power consumption in mobile terminals, in comparison to existing standards, Release 13 introduces a new concept for MTC [11]. Dedicated core networks bring about enhancements like routing which helps core networks to keep mobile terminals in specific networks thus assisting the dedicated core networks to isolate individual mobile terminals by supplying particular functions and/or characteristics [11]. High latency communication aims to support devices that are inaccessible for long time periods with 3GPP IP connectivity without contradicting the network performance.

Enhancements in carrier aggregation are also considered in Release 13 whereby the combining of up to 32 carriers will be possible by the structure. License assisted access utilizes carrier aggregation in order to combine low power secondary cells, functioning in the unlicensed spectrum. This works either in the downlink or in both the downlink and uplink. License assisted access and the unlicensed spectrum are closely coupled with the licensed spectrum in LTE in order to provide a good user experience. [11]

3 FIFTH GENERATION

The fourth generation of wireless communications has been set up and has reached its prime thus the question on researchers' mind is "what's next?" [12]. As per the visual network index (VNI) reports published by Cisco, the IP data handled by wireless devices is set to increase from 3 exabytes in 2010 to more than 500 exabytes by 2020 [13]. This explosion of IP data can be attributed to smartphones, tablets and high-definition video streaming to name a few. In addition, there may be various different unforeseen applications consuming large amounts of data introduced by the time 2020 is reached. Apart from the data consumed the number of connected devices is also set to increase. Therefore, there is a need to develop methods by which such huge amount of data can be handled and a large number of connected devices can be catered to.

The need for communications, especially wireless communications is very predominant in the modern society. As per current analysis the number of connected devices in the world is estimated to double by the year 2020. However, with present technologies it would be really difficult to support such an array of devices.

3.1 Requirements

It is estimated that there will be 10,000 times data traffic in comparison with the present-day scenario, before 2030. There is a growing belief among network operators and researchers that communications will be composed of emerging technologies in addition to technologies currently in use [14]. Using technologies such as Wi-Fi and LTE-A in coherence with emerging technologies which fulfils the requirements set by 5G will help in driving future communication systems beyond 2020. The evolutions of each of the cellular system generations were driven by key factors. The first generation of cellular communication used analogue transmission channels and was mainly concerned with providing voice services. The second generation implemented the digital technology which helped in obtaining better voice quality and services such as text messaging were introduced. The requirement for fast data services and more voice capacity was the driving factor behind the third generation of cellular systems. 4G systems such as LTE were developed in order to provide topmost data rates for multimedia applications and improving the capacity. The fifth generation of cellular systems is expected to provide the data rates of the order of gigabits along with zero latency [14].

High data rates reaching the values of gigabits per second are expected in both the uplink and downlink but that does not necessarily indicate the need for the installation of high capacity networks in all places. Densely populated urban areas are the places of prime importance where the need for new networks capable of supporting high capacity is the most prevalent. Even though the maximum data rate for 5G systems is expected to be of the order of 10 Gbps, the data rates at the cell boundaries should reach 100 Mbps [14]. This generally ensures mobile internet to be a viable replacement for fixed-line broadband.

It is also expected that communications between humans will not be the only use case for the next generation of mobile communication. Machine-to-machine communications (M2M) which can also be attributed as the ‘Internet of Things’ (IoT) will be one major use case, as huge advancement in machine to machine communications are expected. This basically indicates that in addition to machines being supervised by humans they will also be communicating among each other. Thus stable links and lower delays in transmission (latencies) are desired as machines can process information much faster than human beings.

3.2 Use cases

Mobile broadband is one major use case, as data is likely to be the primary driver for the fifth generation of cellular communications. Voice services are to be managed as applications as there is a presumption that a dedicated voice service may be absent in 5G [14]. Data traffic has observed a yearly growth between 25% and 50% and this increase is likely to be sustained till the year 2030 and can be mainly attributed to bandwidth hungry applications as well as the volume of the data being handled as illustrated in Figure 3.1 [14]. The announcement of 4K resolution (4K) which has led to a rise in screen resolution and camera resolution along with the evolution of technologies such as 3D video are some of the main causes for the increase in data traffic. In addition, applications requiring real time information, high definition audio and video streaming and interactive video will facilitate the rise in data traffic. There has also been a very quick development of cloud storage and this has led to the increase in the data rates for uplink whereas in the past the downlink was mostly used for data downloads. The current technologies in place are equipped to cope with this rise in data traffic but they will probably be exhausted by the time 2020 is reached. With further advancements expected in the field of technology it is safe to say that new technologies such as 5G will be required.

A good quality connection enabling high data rates in moving environments (such as vehicles) is seen as an important factor for future users. Vehicular communication is envisioned for the future whereby cars will be able to communicate among themselves. Driver assistance with the help of 3D imaging and the installation of various different sensors is already being provisioned by car manufacturers [14]. METIS has focused its research on various different aspects of traffic safety whereby cars are able to communicate among themselves in addition to communicating with the pedestrians with the help of wireless modules. Dangerous and risky situations leading to accidents can be bypassed by cars being able to identify such situations. Self-driving cars are seen as a viable option for automobile users in the foreseeable future. Such cars are able to take care of the normal driving activities, thereby enabling the driver to use the travelling time for other purposes and only calling the attention of the driver in the scenario of an irregularity which cannot be handled by the car. Such cars would require contact with other cars and other supporting framework. Very high reliability based on almost negligible latency is one of the technical constraints of self-driving cars.

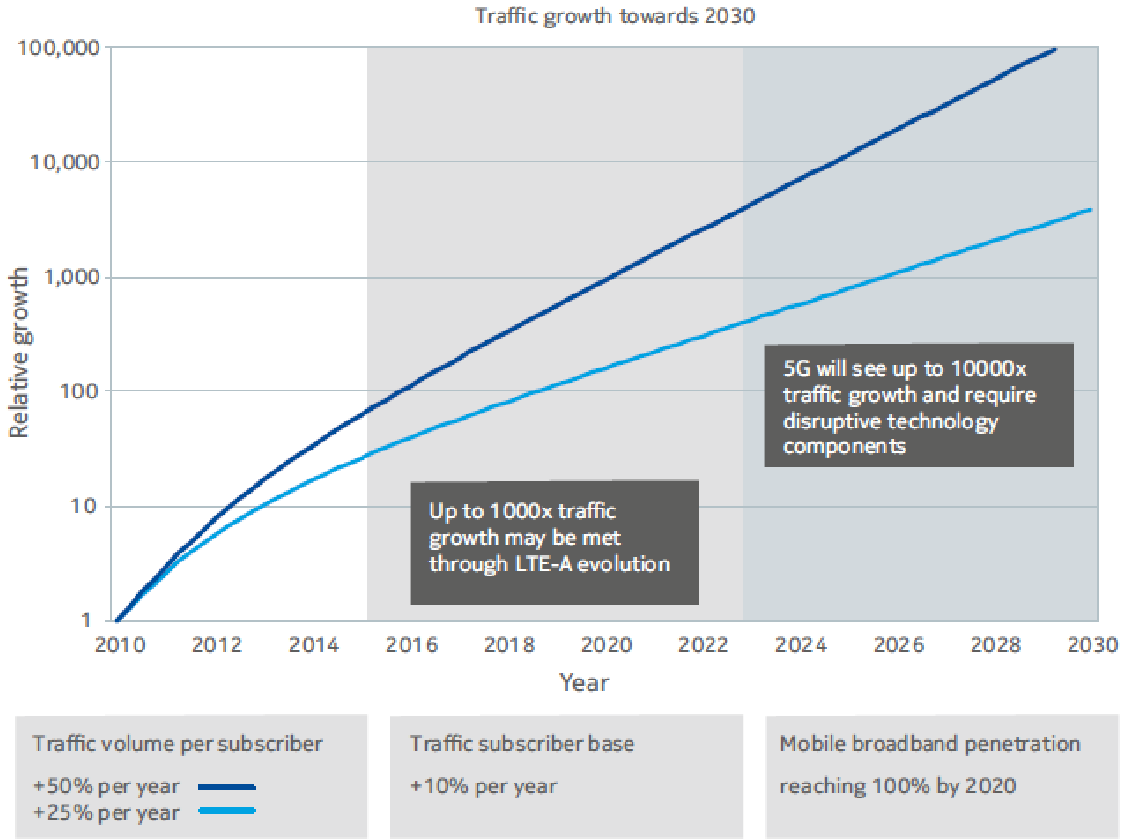

Figure 3.1. *Anticipated growth of mobile traffic till 2030 [14].*

3.3 Design principles

The various different scenarios for 5G deployment require for the architectures of the systems to be adaptable. Plenty of resource allocation will be required for large data transmissions. Quick adjustment due to data traffic variation in the uplink and downlink will also be one of the design goals of 5G. In use cases such as the streaming of audio and video, the overall latency should also complement the data rate. The deployment of 5G should also ensure that all subsequent use cases that emerge due to technological advancements are managed till 2030 at the earliest, by when the sixth generation of cellular communications is expected to be standardized.

Reliability is also an important design principle for 5G systems and is closely related to the other design principle that requires the architecture of the system to be adaptable. This does not indicate only about the dependability of various components. It points to the idea of extensive capacity and coverage which are the major requirements of 5G. Data needs to be reliably delivered for varying use cases and huge number of users within a particular time frame. The usage of mobile communications for safety and control demands that the communication is reliable [14]. If a packet of data is correctly deciphered within a specific time span then that communication can be termed as reliable, even if retransmissions are required.

3.4 Enabling technologies

There are a number of technologies currently under research that may prove to be essential for developing the future cellular communications. The next generation of cellular technology is expected to operate in the mmWave frequency band as most of the microwave band of the electromagnetic (EM) spectrum is occupied by current technologies. In addition, it is also expected that the transmission bandwidth in 5G systems will be extended due to this shift in operating frequency [15]. The use of massive multiple input multiple output (massive MIMO) antennas are presumed to improve the spectral efficiency in 5G systems [16]. The deployment of small cells helps in achieving a greater throughput and low power consumption [17]. The dense deployment of small cells which is also termed as ultra-dense networks (UDN), will thus ensure uninterrupted coverage. M2M communications and D2D communications are also suggested as technologies which can be used to improve the coverage and capacity demands in 5G systems. In the next sections some of the technologies currently under research for 5G will be briefly reviewed.

3.4.1 Small cells and ultra-dense networks

A technique by which operators can resolve the requirement for high data rates is by decreasing the size of the cell. The reduction in the area covered by a cell leads to an increase in spectral efficiency that is achieved due to better frequency reuse. Additionally, the transmission power is saved due to lower power required for propagation purposes [18]. The use of small cells for indoor coverage will also help in alleviating some of the load on the macro cells. The localized use of small cells can also be extended to scenarios such as stadiums, stations, airports, city centers and other densely populated urban areas. Such a move by the operators will help in resolving some of the capacity and coverage related needs that are encountered by current cellular technologies. The advancement of technologies which has led to the miniaturization of hardware and the added reduction in cost will enable the utilization of small cells [18].

The dense deployments of small cells form an ultra-dense network. The METIS project identifies the UDNs as suitable means for increasing the capacity of the network and providing end users with high data rates. This is accomplished due to the fact that the distances between the sites are small and interference during communications minor. The distance between access nodes varies from around 50 meters in outdoor scenarios to about a few meters indoors [19]. This basically points to the fact that ultra-dense networks are typically envisioned to provide the coverage in localized environments. In addition, UDNs should be combined accurately with cellular systems to provide coverage on a wider scale [18].

3.4.2 Massive MIMO

To provide for the diversity and compensate the path loss, a technology termed as massive MIMO, which utilizes a large array of antenna elements, is envisioned as an enabling technology for future cellular communications. The large beamforming gains for a significant number of antennas render inter-cell and inter-stream interference negligible. Values for spectral efficiency can reach as high as 100 bits/s/Hz [21].

MIMO makes use of multiple transmit and receive antennas to improve the capacity of a system by utilizing the features of multipath propagation. More than one data signal can be sent simultaneously on an individual radio propagation channel and is made possible due to the presence of parallel sub channels distributed in space. If these subchannels are considered uncorrelated, then antenna diversity is achieved [20]. Massive MIMO aims to achieve the benefits that systems employing simple MIMO provide but on a much larger scale.

The spacing of the antenna elements and correlation of multipath components between a pair of transceivers restricts the capacity of a channel in MIMO. Therefore, to determine the coefficient of the MIMO channel and the channel capacity between a mobile station and base station proper network modeling will be required [20]. The base station may comprise numerous electrically steerable antennas which is feasible due to the smaller wavelength of millimeter waves [21]. The simulations carried out by the authors of [22] shows a marked increase in the energy efficiency of MIMO systems in comparison with present-day technologies. This is of particular importance as base stations around the world utilize huge amounts of energy. The deployment of base stations with MIMO technology would be possible in remote areas of the earth, void of any electricity as the energy efficiency of MIMO systems enables such base stations to be powered by renewable energy sources such and wind.

3.4.3 Device-to-device communication

Another possible way by which the coverage in 5G systems can be improved is by the utilization of D2D communications. Generally in cellular communication, devices are prohibited to communicate between each other in the band licensed for cellular communications. However, using an architecture where devices can communicate between themselves (as well as any base station) these intermediate devices can act as relay networks. This phenomenon by which the transmitted packets can be routed (through relay networks) aid in decreasing the load on the base station [23] as well as saving both bandwidth and energy in addition to increasing the coverage of the network.

The primary purpose of using D2D communication is to establish a connection among nearby devices either directly or additionally with connections to a central node or eNB [24]. QoS and reduction in latency are the main reasons as to why D2D has been advocated for cellular networks. Devices connected by two separate links (device–BS and device–device) results in an increase in latency when compared with devices connected directly, which consequentially leads to low energy consumption. This is because a lot of resource has to be allocated and separate uplink and downlink channels need to be deployed for two separate links instead of one radio link between devices. Thus, in addition to improved coverage, higher data rates, reduction in latency and power utilization, spectral efficiency and energy efficiency can be attained by D2D communication. The authors in [25] demonstrate a marked increase in transmission bandwidth (about 65%) if devices near each other support D2D communication.

3.4.4 Machine-to-machine communications

M2M signifies a broad technology which enables devices connected to a network to transfer data and information among each other without the help of any human assistance. The concept of IoT is based on the ability of machines to communicate among each other. M2M is a key technology in remote monitoring, warehouse management and traffic control [26].

Some of the key constituent elements for M2M communications are sensors, RFID and computing software which is autonomous. In addition it should have data communication which enables the machines to communicate among each other based on the decisions taken by the computing software. For example, a sensor installed in the traffic light posts can sense a vehicle approaching and immediately make a decision based on the state which it is currently in and inform the other traffic lights of the decision it made. For public safety, this represents a very critical application. Therefore, in order to avoid mishaps, errors should be avoided.

3.4.5 Millimeter waves

The increase in bandwidth is an approach by which the throughput of the system can be improved. However, the spectrum below 6 GHz is occupied by existing technologies, therefore, making it unsuitable for future cellular communications. The use of higher frequencies has been proposed by researchers and academia. The propagation at these higher frequencies was thought to suffer from losses due to attenuation caused by the atmosphere and rain, especially around 60 GHz frequency. The advancement of semi-conductor technology has helped in overcoming the propagation loss related problems [42].

The millimeter wave band is situated between 30 GHz and 300 GHz frequency band of the EM spectrum. The large unlicensed bandwidth present in the millimeter wave frequency has attracted the attention of the industry and academicians. The features of millimeter wave frequencies and some of the research carried out in this field are discussed in detail in Chapter 4.

4 COORDINATED MULTIPOINT TECHNIQUES AT MILLIMETER WAVE FREQUENCIES

Systems operating at the millimeter wave frequency band experiences attenuation in the atmosphere as the propagation is adversely affected due to various factors. Irrespective of these, the mmWave band has been proclaimed by the academia and industry as the frequency band where future cellular communications will take place. Coordinated multipoint which was introduced as part of LTE Release 11 is a concept where the performance of the system is improved by the coordination of two or more base stations/eNBs. In this chapter, millimeter waves and coordinated multipoint is studied extensively and this provides a foundation on which the simulation is carried out in order to evaluate the performance of systems using coordinated multipoint at millimeter wave frequencies.

4.1 Millimeter waves

One of the key requirements of fifth generation (5G) research is the need to implement systems which are capable of supporting a thousand times data rates compared with the current standards. To achieve such data rates one of the major factors under consideration is the increase in bandwidth. The commercial cellular communications have just been focused on the range of frequencies below 6 GHz of the EM spectrum to date. The frequencies occupied by the most existing cellular standards, especially during peak hours, lie between a few hundred MHz to a few GHz, corresponding to the wavelengths from a few centimeters to a meter.

The millimeter wave spectrum corresponds to frequencies in the range of 30 GHz to about 300 GHz of the EM spectrum. The wavelength (λ) is in 10 mm to 1 mm range. They are present between the microwaves (1 GHz and 30 GHz) and infrared (IR) waves (300 GHz to 430 THz). The mmWave band has largely remained unused to date due to the fact that it has unfavorable propagation characteristics. High path loss, absorption due to rain, lower diffraction properties around obstructions along with low penetration characteristics have been stated as the main reasons as to why the frequency bands in the order of 30 GHz to 300 GHz have largely remained underutilized. NLOS links in dense urban environment deployments are of particular concern due to the propagation characteristics of mmWaves. Until recently, the notion was that mmWaves could only be used for communications which addressed short range transmissions, especially in 60 GHz unlicensed band [40].

Large unlicensed bandwidth (up to 7 GHz) present in the mmWave spectrum is one of the primary reasons as to why there is so much interest from the industry, academia and researchers as this available bandwidth becomes useful for future cellular communications. The size of this unlicensed bandwidth (which is continuous) is comparable to the bandwidth assigned for ultra-wideband (UWB) purposes [39], in addition to having minimal restrictions regarding power limits. Gigabit wireless communications are also enabled due to the high capacity and flexibility features provided by the utilization of the massive bandwidth. 60 GHz regulation allows for the use of greater transmit power in comparison to existing wireless technologies such as the wireless personal area network (WPAN) and wireless local area network (WLAN). This higher transmit power in turn helps to overcome the effects of higher path loss at 60 GHz. [40]

The use of mmWaves opens up a lot of possibilities for spectrum usage. The spectrum below 30 GHz has just about been used up due to government agencies allocating most of the available usable spectrum therefore causing shortages in spectrum. Cellular services with 4G technologies such as LTE are dependent on the availability of usable spectrum which is very scarce. mmWaves solves this problem by providing room for expansion.

Millimeter wave communications provide high data rates when compared with present-day technologies. The data rates in the microwave frequency range are limited to about 1 Gbps. At mmWave frequencies data rates can reach 10 Gbps and more thus facilitating the use of applications which were technically constrained at lower frequencies. Applications like the high definition multimedia interface (HDMI), uncompressed high definition video streaming, mobile distributed computing, fast transfer of large files, wireless gigabit Ethernet and so on are the conceived application scenarios for mmWave communications.

A major limitation of mmWave technology is its limited range. As per the general physics of radio RF signals, the shorter the wavelength, the shorter is the transmission range for a particular transmission power [41]. The free space path loss (L) (in dB) can be expressed by [33]

$$L = 92.4 + 20\log(f) + 20\log(d), \tag{1}$$

where f represents the frequency in GHz and d represents the line-of-sight (LOS) distance between the transmitter and receiver in kilometers. For example, the loss is 88 dB at 10 meters and 60 GHz. This limitation, however, can be surmounted by good sensitivity at the receiver, high transmit power and high antenna gains. Performance of the system can also be improved by improving the SINR.

In mmWaves, antenna gain can be calculated by using antenna arrays for both the transmitting and receiving antennas. The decrease in the wavelength results in the size of the antennas decreasing thus reducing the antenna aperture size. From the Friis free space path loss equation [33], it is seen that mmWave signals at 30 GHz experience 20 dB larger path loss than signals at 3 GHz. However, it is possible to form an antenna array at the mmWave transceivers by arranging multiple antenna elements in a small space. This design is made possible due to the small wavelength of mmWaves. The size of antennas for mmWave systems is roughly 140 times smaller than 5 GHz systems [40], and thus can be placed in electronic devices used by the end users. The use of antenna arrays helps in improving the efficiency of the transmitted power per bit due to the fact that antenna arrays possess high directivity. Beamforming at the transmitter and receiver can result in antenna gains and is enabled due to the use of large antenna arrays. Antenna gain helps in compensating for the path loss, reducing out-of-cell interference in addition to overcoming the additional noise power [34].

The range of mmWaves is also affected due to absorption in the atmosphere. Any type of moisture in the atmosphere such as rain or fog makes the signal attenuation very high, thus reducing transmission distances. However, with the advancement of technologies, especially semi-conductors, it is thought that the hindrances arising due to propagation could be overcome. A large number of miniaturized antennas (greater than or equal to 32 elements) can be placed in small dimensions with the advancement in the low power complementary metal-oxide semiconductor (CMOS) radio frequency circuits [42]. These antenna elements can in turn produce high gain and electrically steerable antennas. The smaller wavelength of mmWaves allows large antenna arrays to be present at both the transmitter and receiver side resulting in a fairly decent signal-to-noise ratio (SNR) in addition to also improving the transmission range [42].

Radio wave propagation in wireless networks is influenced due to diverse propagation characteristics. The radio frequencies and scenarios determine the degree to which signal attenuation and distortion influences the radio wave propagation mechanisms. The free space path loss [33] varies as the square of the distance between the links and the carrier frequency. Therefore, a signal at 60 GHz experiences nearly 36 dB higher attenuation on the same path to the receiver when contrasted with a signal at 1 GHz. Atmospheric impacts principally include oxygen absorption (the highest at 60 GHz), water vapor absorption (the highest at 183 GHz), precipitation and fog. They scale exponentially with the distance between the links. These become significant for mmWave links greater than 100 meters and decisive for longer links. The increase in frequency greatly increases penetration losses. Although it is possible to have good coverage indoors up to several GHz, penetrating buildings is practically improbable for mmWave signals. With the increase in frequency, the effects of diffraction decrease swiftly. Thus, diffraction in the mmWave range is relevant only when the obstruction is very small (the order of a few centimeters), therefore, even the human body causes prominent losses [36].

Directional beam forming maximizes the rate of transmission by choosing the direction of the best beam produced by multiple antenna elements. Beamforming also helps in overcoming the effects of the unfavorable path loss by aiming the transmitted or received signal in a particular direction. Beamforming can be implemented either in the digital or analog domain based on the beamforming architecture and the beamforming weights [38].

Digital beamforming is accomplished by multiplying the modulated baseband signal by a particular coefficient, similar to digital precoding. The performance is improved but there is a trade-off as complexity and cost is increased due to the fact that separate blocks are required for each RF chain. Analog beamforming achieves high beamforming gains in an efficient and straightforward manner by applying complex coefficients in order to modify the RF signals by the utilization of variable gain amplifiers and phase shifters. However, beamforming in the digital domain is much more flexible than performing it in the analog domain. In [38], the authors propose a hybrid beamforming architecture for mmWave bands by utilizing the analog beamforming to overcome the effects of the path loss and utilizing the digital beamforming to facilitate the use of multi-antenna techniques such as multi-beam MIMO.

4.1.1 Past research on mmWaves

The authors in [27] propose a clustering algorithm based on measurements carried out at 28 GHz and 73 GHz in New York City, in order to develop statistical channel models for initial mmWave system deployment. The urban, dense environment was chosen so as to reflect the likely scenario for mmWave deployment. 28 GHz frequency was chosen due to its lower frequency in the mmWave range. The E-band (71–76 GHz and 81–86 GHz) [30] has ample free spectrum available and is suitable for urban, dense deployments. Microcell deployment was used in street level measurements up to 500 meters from the transmitters, which were placed on the rooftops at a height of 7 meters and 17 meters from the ground. In addition, highly directional horn antennas were used to perform the measurements in order to indicate the spatial structure of the channels along with the bulk path loss.

The results display that even though LOS component was absent, signals at those frequencies could be observed at 100–200 meters from the transmitter. Due to reflections from buildings, signals followed multiple paths before reaching the location thus supporting spatial multiplexing and diversity. Straightforward measurable models, like those in current cellular standards [28], for example, give a solid match to these perceptions. These models, based on capacity evaluations anticipate a stark increase in capacity in comparison with the modern 4G systems based on the antenna, beamforming and bandwidth related criteria. These discoveries give a solid confirmation of the practicality of small cell outdoor mmWave systems even in difficult urban canyon situations such as New York City.

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The analysis demonstrated the way that the measurements and the models obtained from those measurements were in view of outdoor street-level sites. For indoor propagation, penetration losses through various common building materials were carried out by placing the transmitter and receiver on the opposite sides of the material that was to be tested. The reference measurement that was considered was a path loss in free space with a separation of 5 meters between the transmitter and receiver. Tinted glass, brick, clear glass and drywall were the materials that were tested for penetration losses. Tinted glass and brick (usual building materials) showed reasonably high penetration losses in comparison to the clear glass and drywall (generally present indoors) [37]. This demonstrates that mmWaves will have difficulty penetrating buildings thus segregating the indoor and outdoor networks.

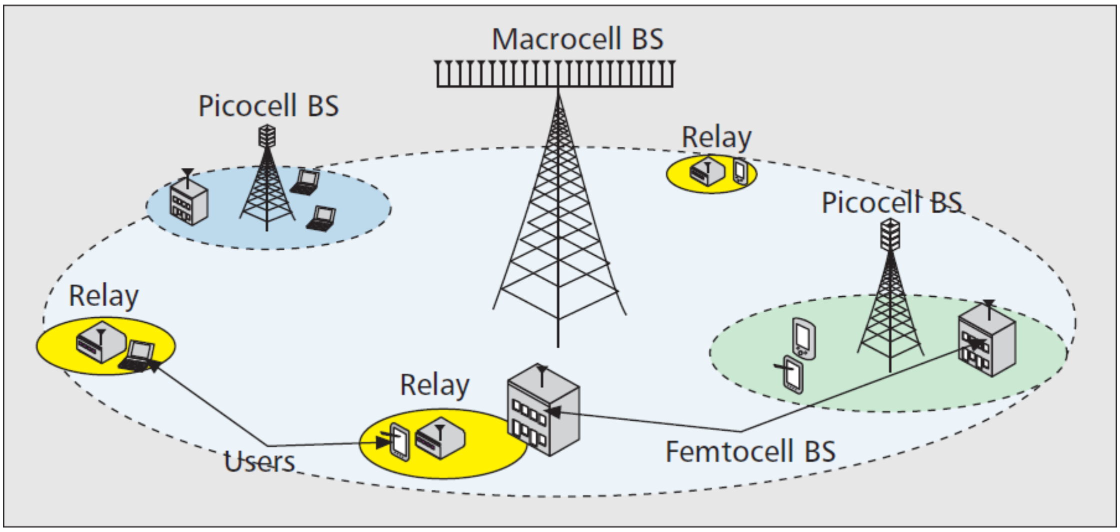


Figure 4.1. *A typical HetNet with a macrocell BS with relays supporting the picocell and femtocell BSs.*

However, regular urban cell evaluations put a substantial part of mobiles indoors, where mmWave signals will probably not enter. Therefore, indoor sites have to be considered in order to attain a complete cellular evaluation which can probably be achieved by using microwave systems in coherence with mmWave systems thus forming a HetNet.

HetNets (Figure 4.1), by the virtue of effective utilization of network resources enhance the bandwidth efficiency and throughput of wireless networks. However, the significant inter-user interference which arises due to the higher density of users and access points needs to be diminished [29]. The authors in [29] introduce a concept referred to as hybrid HetNets which addresses the reduction of interference in heterogeneous networks.

The E-band or the 70–80 GHz spectrum has much lower atmospheric absorption (approximately 16 dB) in comparison with the 60 GHz spectrum (V-band) as illustrated in Figure 4.2. Furthermore, as per FCC regulations the allowed transmission power of E-band (3 W) is higher than that of the V-band (0.5 W). [30] The bandwidth of 7 GHz in the V-band can be utilized to set up extremely high speed wireless links without causing interference to neighboring networks and devices due to high antenna directivity and a large attenuation factor [29]. These characteristics form the base of the hybrid HetNet concept which enhances bandwidth efficiency in addition to minimizing interference in mmWave systems. The large bandwidth of the V-band is utilized to set up short range high speed point-to-point links. Interference in these links will not particular concern due to the strong attenuation of radio signals and high antenna directivity. The authors in [29] propose the utilization of the E-band for long distance communication links and for interconnecting HetNet base stations in order to overcome the drawback of the V-band. As an example, the connections between the macrocell and picocell BSs can work in the E-band while the V-band can be utilized by femtocell BSs.

Using both the E-band and the V-band in hybrid HetNets demonstrates significant advantages in the simulation results. The throughput of mmWave systems is greatly improved by utilizing the characteristics of both bands.

In order to decrease signal outage in heterogeneous mmWave cellular systems, the authors in [31] explore the possibility of base station cooperation in the downlink of mmWave cellular systems. In order to address the demand for higher data rates, the authors propose cooperation between various base stations. This cooperation allows the users a uniform broadband experience across the network. Inter-cell interference can be restricted by the effective coordination of base stations, termed as coordinated multipoint, consequently enhancing performance at cell borders in addition to obtaining an increase in throughput [32]. CoMP is discussed in further detail in the following section.

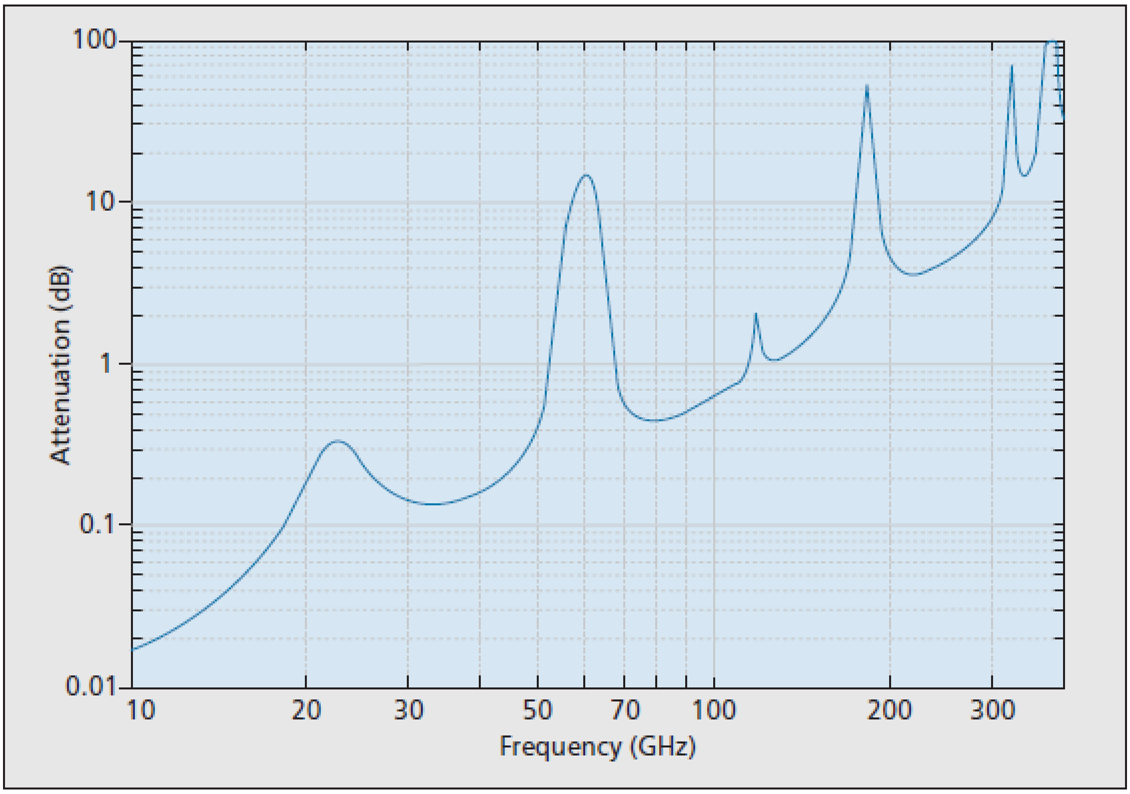


Figure 4.2. *Attenuation due to the atmosphere vs frequency of operation. [30]*

4.2 Coordinated Multipoint

To enable the coordination among multiple points (cell sites) 3GPP introduced the concept of coordinated multipoint for LTE-Advanced systems as one of the major features in its Release 11 [1]. CoMP operating principle is based in such a way that signals to/from various points are not subject to interference and in some cases the interference can even be used as a meaningful signal. The primary purpose of CoMP is to address the demand for high quality service at the mobile terminal by reducing the interference caused by neighboring cells, in turn helping to raise the throughput at the edge of the cell [2]. In addition, an increase in the average throughput of the system was also targeted. Before the specification was stated a study was carried out, which indicated that coordination between multiple points can actually help in increasing the system performance in comparison to conventional cellular networks [46].

Traditionally in cellular networks, the reuse of network resources such as frequency and timeslots, often referred to as spatial reuse, forms a key element in network planning as signal strength decreases due to the effects of path loss and shadowing. Cellular systems such as 3G and 4G employ frequency reuse which consequently results in interference between cells. Network coordination has been presented in literature [47] as a technique by which interference from adjoining cells can be reduced thus helping in achieving an improvement in spectral efficiency and achieving an increase in the peak and average data rates at the cell borders by completely eliminating the interference or using the interference in a useful way.

LTE Release 11 aimed to specify the support for coordinated transmission and reception in the downlink and uplink respectively. The purpose of coordinated transmission in the downlink was to improve the signal strength that was received at the user equipment by coordinating the multiple transmission points [1]. The use of CoMP also helped in alleviating the interference caused by neighboring cells. The objective of coordinated reception was to make sure that the network was capable of receiving signals from the user equipment, without any interference in the uplink [44].

The specification by Release 11 targeted at providing support for CoMP in various environments thus creating distinct deployment scenarios. One of the scenarios that were considered for CoMP deployment were similar or homogeneous environments, where coordinating points were from different cells or from different sectors of the same cell [45]. Another scenario that was considered was the deployment of such systems in a dissimilar or heterogeneous environment. Aforementioned environments included low power points such as pico-cells and femto-cells together with macro-cells in the same geographical area [44]. The scenarios considered for CoMP are discussed in more detail in the following section.

4.2.1 Scenarios for the deployment of CoMP

The deployment of CoMP is based on the backhaul characteristics such as capacity and latency. 3GPP in its feasibility study of CoMP has focused on the following four scenarios so as to take into consideration the diverse backhaul characteristics and network topologies [45]. These four scenarios are shown in Figure 4.3.

For similar or homogenous environments

Scenario 1: Cells (or sectors) under the coverage of the same macro-cell base station coordinating among each other without the need for any backhaul connection.

Scenario 2: Cells coordinating among each other but under the coverage of different macro-cell base stations.

For different or heterogeneous environment

Scenario 3: Coordination among low power cells such as pico-cells and macro-cells within the coverage of the macro-cell.

Scenario 4: Coordinating low power cells such as remote radio heads (RRH), existing within the macro cell coverage area.

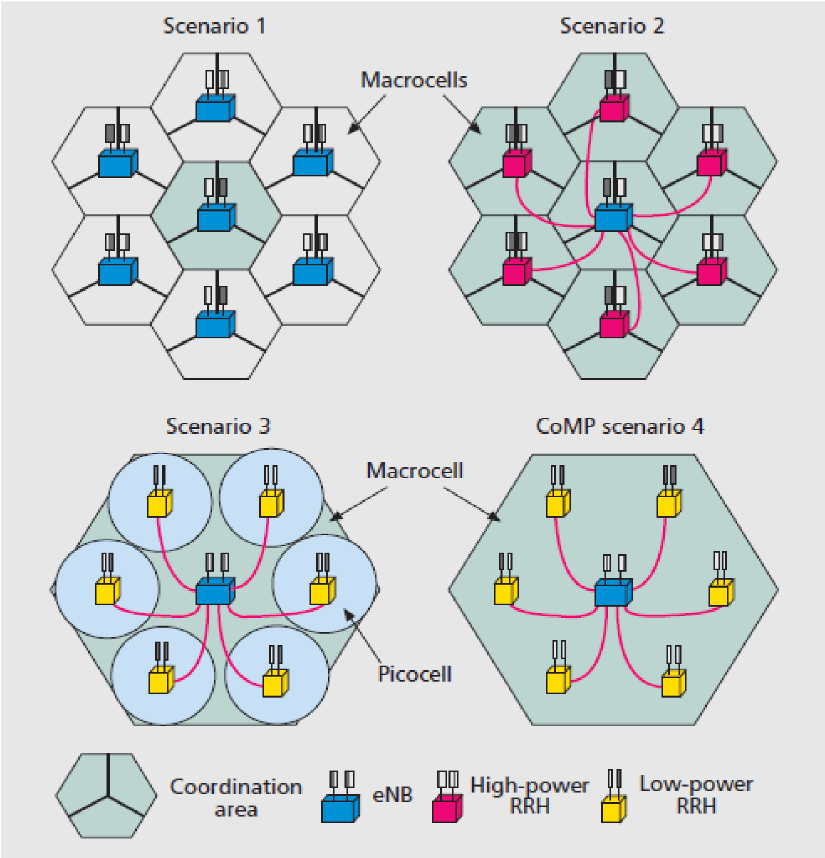


Figure 4.3. *The scenarios proposed by 3GPP for the deployment of CoMP. [44]*

The first scenario for CoMP is for homogenous networks, where the area under which the coordination takes place is served by a single base station. The coordination in this scenario can take place between cells (or sectors) whose coverage is provided by the same eNB. Although the area of coordination is restricted, unlike other scenarios for CoMP deployment, connections between various sites are non-essential. Therefore, this is one of the most practical scenarios for CoMP deployment.

Also intended for homogeneous networks, the second CoMP scenario extends the area of coordination. The increase in the area of coordination is done so that cells from different sites are also included. This scenario can consist of a single eNB which controls the RRHs of different sites in order to serve the coordinating cells. Also, a situation where eNBs from different sites coordinate among each other can be foreseen. Figure 4.3 shows high power RRHs at different locations being controlled by the same eNB. Scenario 2 can obtain an increase in performance over Scenario 1 based on the deployment of the network which determines the number of coordinating cells and the latency that exists due to the connection between the sites.

The third scenario is considered for heterogeneous networks includes both macro-cells and pico-cells. Marco-cells are typically characterized by high transmission power and pico-cells with low transmission power. CoMP Scenario 3 can be realized in two ways.

Firstly, a network where the eNBs for macro-cells and pico-cells are different but coordination exists among them. Secondly, as depicted in Figure 4.3, a single eNB controls the low power RRHs at different sites within the macro-cell coverage area. Coordination can occur among a single macro-cell and multiple pico-cells that are located within the coverage area of the macro-cell.

The final scenario for CoMP is also intended for heterogeneous networks and primarily focusses on the low power RRHs being located in the same coverage area as that of the macro-cell. A distinct feature of this scenario is that the low power RRH forms a set of distributed antennas, as they possess the same physical identity of the macro-cell [44]. Mobility support such as handovers are not required as the coordination is performed within the same cell. Furthermore, as the RRH does not from different cells, a backhaul connection is necessary between RRHs and the macro cell sites. The third and fourth scenario are very practical in densely populated urban areas where RRH with different power levels exists.

4.2.2 CoMP techniques

A cell is comprised of sectors from the same or different antennas which are located close to each other geographically. Based on the signal strength received at the user equipment, the cell providing the strongest signal generally acts as the serving cell. The various different configurations and scenarios that CoMP offer corresponds to situations where the antennas that are configured together as a cell may not be located geographically close to each other. Collocated antennas can be specified by the term transmission point (TP) where a cell can be associated with one or more TPs. A particular site can consist of more than one TP when sectors are considered where each TP corresponds to a sector. The CoMP techniques can be thought of as the coordination between TPs. [45]

After performing studies on CoMP, 3GPP concluded that CoMP techniques could be categorized into three major categories. These categories are dependent on the backhaul link present between the coordinating points and the complication that is experienced due to scheduling [48]. CoMP techniques are categorized as coordinated scheduling and coordinated beamforming (CS/CB), dynamic point selection (DPS) and joint transmission (JT) [44]. These CoMP techniques are briefly discussed in the following sections.

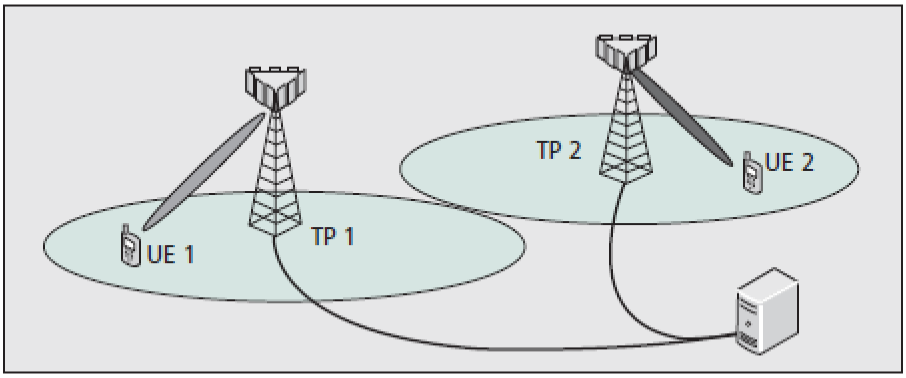


Figure 4.4. *CS/CB between two TPs. [44]*

Coordinated Scheduling and Coordinated Beamforming

CS/CB consists of various TPs that distribute only the channel state information (CSI) for multiple UEs even though the concerned data packet is located at a single TP [45]. The TP that transfers data to the UE is chosen in a semi-static way (radio resource control signaling is used instead of dynamic control) [44]. CS/CB helps in decreasing the level of interference that a user equipment encounters by choosing suitable beamforming weights [45]. An example of coordinated scheduling would be dynamic point blanking (DPB) where the interference handling is carried out by switching the TP on/off based on the effect the TP has on the overall performance of the system [44]. Another example of the CS/CB is shown in Figure 4.4 where in order to decrease the interference the network co-schedules two UE terminals inversely to form nulls for opposite TPs [44]. Scenarios which have imperfect backhaul links generally employ CS/CB compared with other CoMP techniques as the CS/CB functionality can be carried out in a less dynamic manner [44].

Dynamic point selection

DPS is a relatively straightforward CoMP technique where the TP that serves a UE can be altered every millisecond based on the CSI and the resources available [44]. An example of DPS is shown in Figure 4.5a where the TP is changed dynamically in order to serve a particular UE. The characteristics of the wireless channel helps in obtaining beamforming gain. In practical conditions, DPS utilizes the fast backhaul link in the network that exists within the TPs and the central scheduler to coordinate scheduling [44]. For the coordination to take place the data to be transmitted should be accessible at each TP [44].

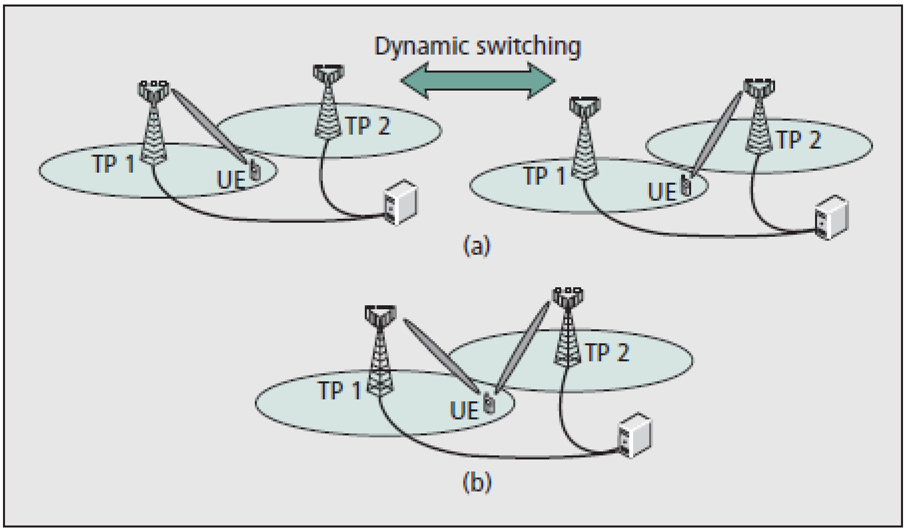


Figure 4.5. *a) DPS, b) JT. [44]*

Joint transmission

As illustrated in Figure 4.5b the same data is transmitted from different coordinating TPs with suitable beamforming weights. From the perspective of the UE, one or more neighboring TPs can transmit the required signal instead of the signals that cause interference [45]. The purpose of JT is to improve the overall throughput of the system which is a measure for the system performance. The modification of the signals causing interference into signals relevant to the UE aids in improving the performance at the edge of the cell. The transmission in the JT CoMP technique can be coherent or non-coherent. [45] In coherent transmission, the signals from multiple TPs are precoded together to obtain an understandable combining on the wireless channel [44]. Precoding is done individually for non-coherent transmissions [44].

A combination of the aforementioned methods may be used in order to contend with the different types of interference. The complexity for processing and scheduling grows with the number of coordinating TPs. A trade-off needs to be reached between the gain in performance and the cost for network upgradation. [48]

The performance evaluations carried out by the authors of [45] and [48] show that the use of CoMP techniques improve the spectral efficiency of systems. The cell edge data rates are also improved due to coordination among cells. Using CoMP techniques for both homogeneous and heterogeneous networks illustrates the performance of the system when compared with traditional networks. One of the major stumbling blocks that are faced by traditional cellular networks are the interferences that are caused by signals. CoMP techniques can help in avoiding these interfering signals or use them in a productive manner.

A major disadvantage of using the CoMP technology is the large amount of information that need to be transferred between coordinating eNBs. In order to support large amounts of information, robust backhaul networks have to be deployed. The effects of information duplication can be alleviated with the use of CS/CB technique.

4.3 Antenna modeling

The antenna is modelled to obtain antenna patterns for both the horizontal plane (azimuth) and the vertical plane (elevation). A commonly deployed antenna that is used for system performance evaluation is Kathrein 742215 [54]. The model used in this work follows traits similar to Kathrein 742215. This model is a variation of the model proposed by the authors of [55] which generally forms the vertical and the horizontal antenna patterns [55]. The antenna model is explained in the remainder of this section.

The horizontal antenna pattern has a maximum antenna gain of G_{m} = 18.26 dBi. The gain, $G_{\mathrm{h}}(\varphi)$ in the azimuth plane is obtained by using the mathematical expression

$$G_{\mathrm{h}}(\varphi) = -\min\left(12 \cdot \left(\frac{\varphi}{HPBW_{\mathrm{h}}}\right)^2, FBR_{\mathrm{h}}\right) + G_{\mathrm{m}}, \quad -180° \leq \varphi \leq 180°. \qquad (2)$$

The half power beamwidth is represented by the parameter $HPBW_{\mathrm{h}}$ (in degrees). The value considered for $HPBW_{\mathrm{h}}$ is 65°. The value for the front-to-back ratio (FBR_{h}) is 30 dB. FBR_{h} depicts the ratio of the signal strength in the forward direction to that of the signal strength in the backward direction. The horizontal angle pointing in the mainlobe direction is parameterized by the angle φ. The value of φ is expressed in degrees. The value of φ in the model used for this work is evaluated as the difference between the direction of departure (*DoD*) and the azimuth reference ($azimuth_{\mathrm{ref}}$) for a particular cell of a eNB as shown in equation (3). Three cells are considered for each eNB therefore for 10 eNBs there are 30 cells and there is a value for the azimuth reference corresponding to each of these cells. *DoD* is obtained from the simulations and represents the angle between the receiver and transmitter from the perspective of the receiver in the azimuth plane. The value of φ is represented by the (3) and is used as the φ value for (2)

$$\varphi = DoD - azimuth_{\mathrm{ref}}, \quad -180° \leq \varphi \leq 180°. \qquad (3)$$

The formulation of the vertical antenna pattern results in a gain for the elevation plane. This gain, $G_{\mathrm{v}}(\varphi)$ is stated using the formula

$$G_{\mathrm{v}}(\theta) = \max\left(-12 \cdot \left(\frac{(\theta - \theta_{\mathrm{tilt}})}{HPBW_{\mathrm{v}}}\right)^2, SLL_{\mathrm{v}}\right), \ -90° \leq \theta \leq 90°. \qquad (4)$$

$HPBW_{\mathrm{v}}$ (in degrees) represents the half power beamwidth in the vertical direction. $HPBW_{\mathrm{v}}$ of 6.2° is used for formulating the vertical antenna pattern. The electrical tilting for an antenna is used in macro-cellular environments to improve the cell coverage. An electrical tilt (θ_{tilt}) of 9° is used for the simulations. Sidelobe level (SLL_{v}) measured in decibels is the power of the sidelobe relative to the peak of the mainlobe. The value of SLL_{v} is considered as −18 dB. The angle θ is represented by the angle of departure (*AoD*), which is the angle in the vertical plane between the receiver and transmitter from the perspective of the base station. The horizontal plane is characterized by θ of 0°. The value of the angle θ is −90° upwards and 90° downwards.

The horizontal and vertical patterns represent the antenna patterns in the azimuth and elevation plane respectively. In order for the pattern to be observed in a general direction the horizontal and vertical gain components are added with unity weights. The gain, $G(\varphi, \theta)$ in any general direction is represented by

$$G(\varphi, \theta) = G_{\mathrm{h}}(\varphi) + G_{\mathrm{v}}(\theta). \quad (5)$$

The values for the different parameters are summarized in the Table 4.1. These values are generally considered by Kathrein 742215 for antenna modeling.

Table 4.1. *Summary of antenna modelling parameters.*

$HPBW_{\mathrm{h}}$	FBR_{h}	G_{m}	$HPBW_{\mathrm{v}}$	SLL_{v}	θ_{tilt}
65°	30 dB	18.26 dBi	6.2°	–18 dB	9°

4.4 System performance metrics

The metrics which helps in determining the system performance are discussed in this section. The first metric that helps in evaluating the system performance is the received signal strength for a particular user. The reference scenario considers the strongest received signal strength for a particular user. The received signal strength for CoMP with the 2-sectors of the same eNB is calculated by finding the sector with the strongest signal for a particular user from a particular eNB. The strongest signal from the remaining sectors of the eNB is added with the strongest signal which was found initially. The total corresponds to the maximum signal strength for that user in this scenario. In the scenario where the CoMP with the 3-sectors of the same eNB is considered, the eNB whose sector provides the strongest received signal is identified. The powers from the remaining two sectors of that same eNB are added to the strongest signal in order to achieve the received signal strength for a particular user in this scenario. The received signal strength for CoMP where 2-sectors are chosen dynamically is obtained by finding two sectors with the strongest received signal strengths and then computing their sum for each user. For the scenarios where 3-sectors and 4-sectors are chosen dynamically for CoMP, the three strongest and the four strongest signals are identified following which their sum is computed in order to determine the received signal strength for each user. The received signal strength is expressed in the logarithmic scale with respect to 1 milliwatt (dBm).

One key metric for the performance evaluation of the system is the SINR. The SINR helps in calculating the theoretical upper bounds for channel capacity. Radio network planning engineers aim to achieve high SINR values as that represents good system performance. The mathematical expression for calculating the *SINR* is:

$$SINR = \frac{S}{I + N}. \tag{6}$$

The signal *(S)* in this case is the received signal strength for each of the users in the simulation environment. The interference *(I)* is evaluated by considering all the received powers for each user apart from the signal. For example, in the scenario where 3-sectors are chosen dynamically, the signal consists of the sum of the powers from the three strongest sectors. The interference is constituted of the sum of all the other powers for each user. The noise *(N)* is evaluated at the temperature (*T*) of 290 Kelvin (K). A bandwidth (*B*) of 20 MHz is considered as for calculating the noise. The noise is evaluated using the formula

$$N = 10 \cdot \log_{10}(\mathrm{k} \cdot T \cdot B) + NF. \tag{7}$$

Boltzmann's constant (k) has a value of $1.38064852 \times 10^{-23}$ and a noise figure (*NF*) of 8 dB is used for the simulations. The *SINR* is expressed in decibels.

The maximum capacity of the system also termed as the Shannon capacity (*C*) is defined by the mathematical expression

$$C = W \cdot (\log_2(1 + \langle \Gamma \rangle). \tag{8}$$

The capacity is expressed in bits/second/hertz. The bandwidth of the channel is represented by *W*, which is considered 20 MHz for our simulations. Simulations are also carried out for 28 GHz with 200 MHz bandwidth. In these cases, the value of the bandwidth for the noise is increased to 200 MHz. The *SINR* of the system is represented by the term, Γ which is in the linear scale. The mean/average $\langle \cdot \rangle$ of the *SINR* values, are calculated for evaluating the system capacity. The capacity of the system is directly proportional to the bandwidth. Inadequate spectrum is allocated for cellular operators hence increasing the system bandwidth is not a very viable option [50]. However, the increase in the SINR can help in achieving greater system capacity.

The spectral efficiency (η) is a measure of the amount of services that can be supported in a given environment concurrently for a particular frequency band. The average spectral efficiency, $\langle \eta \rangle$ [50] of the channel is expressed in bits/second/hertz and can be calculated by dividing the Shannon capacity with the system bandwidth defined by the mathematical expression

$$\langle \eta \rangle = \frac{C}{W}. \tag{9}$$

The area spectral efficiency (η_{area}) is evaluated by obtaining the product of the average spectral efficiency, $\langle \eta \rangle$ with the cell density (ρ_{cell}). The area spectral efficiency is expressed in bits/second/Hertz/area and is illustrated by the mathematical expression

$$\eta_{\text{area}} = \langle \eta \rangle \cdot \rho_{\text{cell}}. \tag{10}$$

The final metric that is used for system performance evaluation is the system throughput (R). Throughput is generally measured in bits/second and is the sum of all the data rates for all the users in the simulation environment. Throughput is defined by the mathematical expression

$$R = W \cdot \langle \eta \rangle. \tag{11}$$

The gain (g) in the throughput for all the scenarios are evaluated based on the reference scenario. The gains for the other scenarios are calculated by subtracting the value of the reference throughput (R_{ref}) from the throughput of that particular scenario (R_{s}). The value is expressed as a percentile relative to R_{ref}. The gain in the throughput is calculated for both the frequency bands.

$$g = R_{\text{s}} - R_{\text{ref}}. \tag{12}$$

These parameters are calculated to evaluate the performance of the CoMP techniques at mmWave frequencies. The simulations that were carried out as part of this work are discussed in the next chapter.

5 SIMULATION PROCEDURE

Radio network planning generally utilizes empirical or semi-empirical propagation models such as the Okamura-Hata, Cost-231-Hata and Cost-231-Walfisch-Ikegami in order to predict the coverage of base stations for particular cells [49]. These propagation models are beneficial for network planning purposes as they are simple and often have very low computing time. In addition, the detailed description of the environment is not required. These models provide precise predictions for environments which are similar. Minor adjustments of the parameters are required for environments with different characteristics [49]. However, even after these adjustments are made, the propagation models are generally unsuccessful in predicting the signal propagation accurately [50].

To predict the signal propagation correctly, ray tracing techniques based on algorithms like the shoot and bouncing ray (SBR) and image theory can be utilized for obtaining multipath components with a fixed number of reflections and diffractions between every transmitter and receiver [50]. The estimation of the multiple ray paths between the transmitter and receiver can be done with the help of a 3D map of the environment. Ray tracing tools have been widely used to define the radio propagation environments. Computing the received power is dependent on the multipath components that exist between the transmitter and receiver [51]. Parameters such as building penetration losses, the permittivity of the ground and building materials, the accurate locations of the antennas with respective heights and the operating frequency need to be defined along with a high accuracy of obstacles such as buildings in order to achieve precise results from the simulated environment [50]. Even though it is complex and time consuming, ray tracing helps in developing a clear perception of the signal propagation.

5.1 Simulation tool

Ray tracing algorithms such as SBR and image theory can be used in developing ray tracing techniques. For the SBR algorithm, a large number of rays are sent from the transmitter with constant angular separation between the neighboring rays. The angular separation plays a vital role in determining the preciseness of the SBR algorithm [51]. To verify the valid rays existing between the transmitter and receiver each ray is subjected to intersection and reception tests.

MATLAB is the programming environment that was used to develop a ray tracing tool which is used for simulations in this work. The tool uses 3D maps for predicting the coverage in simulated environments. The 3D ray tracing tool, “sAGA”, uses image theory to predict the various different paths that the ray traverses from the transmitter to the receiver. The image theory algorithm is chosen ahead of the SBR algorithm as it provides a much more detailed and definitive description of the traversed ray paths. The image theory algorithm can determine all the multipath components without any repetition and reception tests are also not necessary [52]. The image theory algorithm uses a lot of time for computation as the children of images have to be computed and the increase in the number of reflections and diffractions increase the computation time [52]. Diffracted ray paths and ground reflected paths are found out by the ray tracing tool for macro-cellular simulations where the antenna is located above the rooftop. The field strength of each propagation path is calculated using propagation theory based on the number of diffractions and reflections that are considered. Although image theory gives an accurate prediction of the propagation model, the total accuracy of the system hinges on the data that is provided for the environment. [51]

Each propagation path is characterized by the power, time delay, the direction of arrival (DoA), the direction of departure, the angle of arrival (AoA) and the angle of departure. The angle between the receiver and the base station in the horizontal plane (azimuth plane), is represented by DoA. DoD depicts the angle of the mobile station with respect to the base station. AoA represents the angle between the base station and mobile station with respect to the mobile station in the vertical plane (elevation plane). AoD also represents the same but from the perspective of the base station. These are the parameters that are computed by the ray tracing tool and these act as the inputs to the simulation scenarios that are considered in this work. The simulation environment and the scenarios are discussed in the following sections.

5.2 Simulation environment

The environment considered for this work is a locality in the capital area of Finland. This locality in Helsinki is chosen as the simulation environment to represent the dense urban environment where the fifth generation of cellular communications is the most likely to be deployed. There are 10 transmitting antennas located above the level of the rooftop as this is a macro-cellular environment. Each transmitting antenna is at a height of 30 meters above the rooftop level. Figure 5.1 illustrates the location of the transmitting antennas in the environment that is considered for the simulation scenarios. There are 884 users that are present in this locality located both outdoors and indoors. The users located inside the buildings are located at the heights of 1.5 m (ground floor), 7.5 m (second floor), 16.5 m (fifth floor) and 22.5 m (seventh floor) respectively. Figure 5.2 gives a figurative illustration of the location of the users.

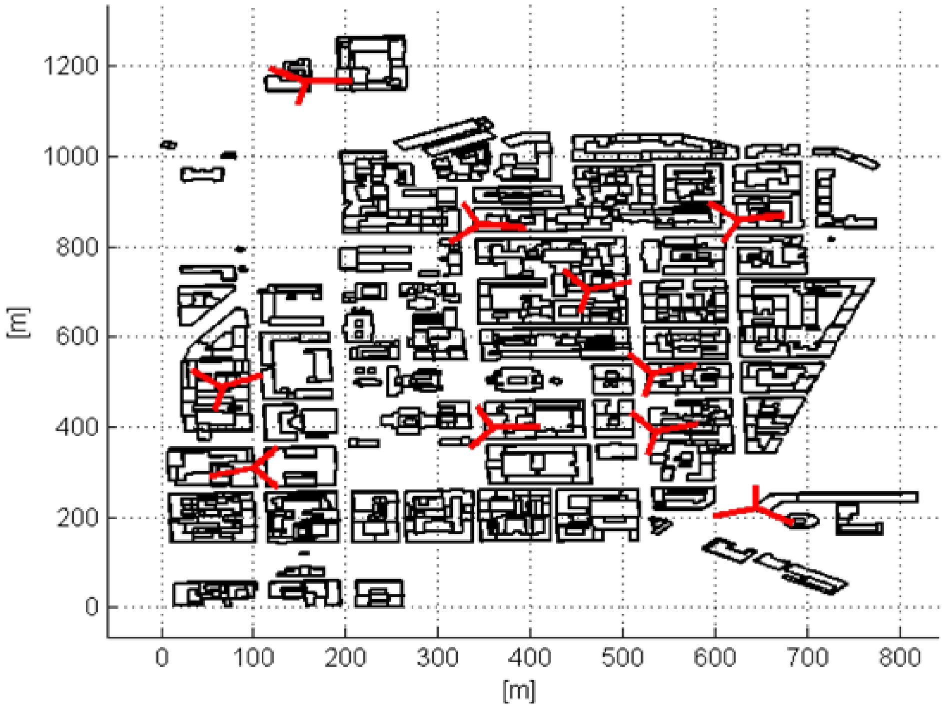


Figure 5.1. *Location of the 3-sectored base stations for our simulation environment.*

Figure 5.2. *Figurative positions of the users.*

5.3 Scenarios

In this work, the system performance is evaluated for different scenarios at 2.1 GHz and 28 GHz frequency bands. The frequency band of 28 GHz is chosen as it is close to the millimeter wave frequency band thus illustrating similar properties. For the 28 GHz band bandwidth values of 20 MHz and 200 MHz are used. System performance is evaluated based on the received signal strength, SINR, spectral efficiency, area spectral efficiency, throughput for each user. Here, the signal with the strongest power is considered the carrier signal, all the other remaining received powers at the user are considered as the interference. This would be the reference case for both of the frequency bands.

CoMP is considered for all other scenarios where two or more base stations/eNBs coordinate to affect the system performance. Three sector eNBs were considered when the simulations were carried out. Therefore, scenarios where coordination between the sectors of the same eNB exists, are formulated. The coordination between the sectors of different eNBs is also formulated. These are discussed in the following sections.

5.3.1 CoMP for 2-sectors from the same eNB

The first scenario considers the coordination between the two strongest sectors from the same eNB. Firstly, the sector and the node are identified from where a particular user receives the strongest power. Then the strongest among the remaining two sectors is found. These two received signal powers are added to determine the carrier signal for that user. The interference is the sum of all the other received powers for that particular user.

5.3.2 CoMP for 3-sectors from the same eNB

Similar steps are followed for evaluating the performance of the system for the CoMP between the three sectors of the same eNB. The node with the strongest power from a single sector for a particular user is identified. Subsequently, the powers of the remaining sectors of that node are added to the signal received from the strongest sector to obtain the carrier signal. Powers received at the user from all other sectors forms the interference signal. This constitutes our second scenario.

5.3.3 CoMP for 2-sectors chosen dynamically

The third scenario is the case where the two strongest signals received at a particular user are considered, constituting the carrier signal, irrespective of the eNB the signals are coming from. Two sectors from where the received signal strength is the strongest is chosen dynamically and all the other sectors from where a particular user receives power is considered the interference signal.

5.3.4 CoMP for 3-sectors chosen dynamically

The three sectors from which a particular user receives the three strongest powers are considered for the third scenario. The sum of these three powers form the carrier signal. This is irrespective of the eNB the sectors belong to. The remaining received signals form the interference to the carrier signal.

5.3.5 CoMP for 4-sectors chosen dynamically

In the final scenario, the sum of the four strongest signals from the sectors constitute the carrier signal with the remaining received signal strengths adding up to form the interference.

5.4 Simulation parameters

This section describes the parameters that are considered for the evaluation of the system performance. The transmission power for each antenna is 40 watts. The building penetration losses of 15 dB and 26.5 dB are considered for 2.1 GHz and 28 GHz bands respectively. There are 10 eNBs present in the simulation environment, each consisting of 3-sectors. These sectors are considered as cells therefore there are 30 cells in the simulation environment, each having its own antenna. These sectors are described by the reference angles in the azimuth plane. The power from each sector of each eNB is considered after the antenna modeling phase, which is described in Chapter 4. The simulations are carried out for both 2.1 GHz and 28 GHz frequency band. An additional gain of 16.5 dB is considered for the simulations in 28 GHz frequency band. This gain is used due to the large number of antenna arrays that can be placed on a single antenna operating at 28 GHz.

For the performance evaluation of the system, parameters like received signal strength, SINR, spectral efficiency, area spectral efficiency and throughput are calculated for all the CoMP scenarios at both frequency bands. The results are discussed in the next chapter.

6 SYSTEM PERFORMANCE ANALYSIS

Modern cellular systems operate around 2 GHz frequency band especially in urban environments like cities. For example, UMTS operates at 2.1 GHz. The system performance is evaluated based on certain parameters which clearly define how the system works based on different scenarios where the systems are deployed. Analysis of the system performance is carried out for different scenarios which are defined by the coordination between two or more points from the same or different eNB. The performance for each of the CoMP scenarios is studied at 28 GHz frequency band. Evaluation of the performance of CoMP scenarios at 2.1 GHz is also carried out to formulate a comparison between the frequency bands that cellular networks traditionally use and the millimeter wave (28 GHz) band. For 28 GHz, 20 MHz and 200 MHz bandwidths are studied. The parameters that are studied include the signal strength received by each user, the SINR for the whole system, the SINR for the users located near the cell edges, the spectral efficiency, the area spectral efficiency and the throughput.

This chapter discusses all of these parameters in detail with the help of graphs and tables that were obtained after the simulation was carried out. Cumulative distribution function (CDF) plots are developed for the received signal strength and SINR. The other parameters are discussed with the help of tables and illustrative graphs.

6.1 Received signal strength

The received signal strength is the measure of the power received by a particular user. For cellular communications, the unit of measurement is dBm. By definition, the higher the value of the received signal strength the stronger is the signal for a particular user. Radio network planning engineers generally strive to provide strong signals for each user which ensures a high performance for the system. The minimum received signal strength for the simulations was fixed at –110 dBm in order to exclude users with very low received signal strength.

Figure 6.1 illustrates the power received by each user for all the considered CoMP scenarios at 28 GHz. The CoMP scenario where there are four cells (TPs) coordinating (to determine the total signal strength for a particular user), has the largest received signal strength. The average value for the received signal strength for this case is –65.53 dBm. The reference scenario, where the power from only the strongest cell makes up the received signal strength, has an average signal strength of –69.26 dBm. This represents the lowest signal strength among all the scenarios. The average received signal strength for all the other scenarios ranges between these values. Therefore, there is not much of a difference in the received signal strength for the scenarios.

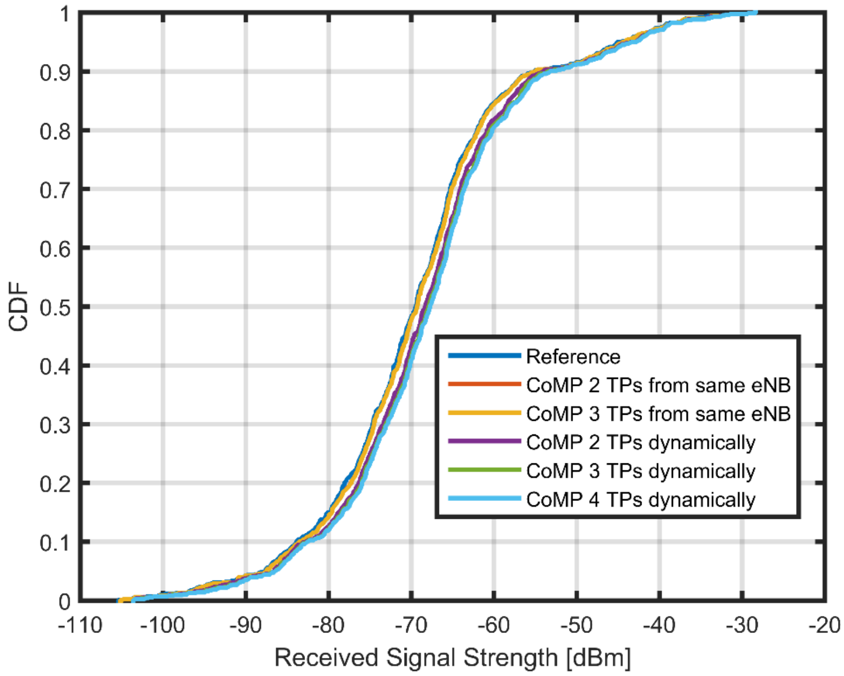


Figure 6.1. *CDF of Received signal strength for all the scenarios at 28 GHz.*

The mean and median values for the received signal strength are summarized in Table 6.1. The difference between the largest and smallest received signal strength is very low. The use of CoMP does not improve the received signal strength greatly.

Table 6.1. *Received signal strength (mean and median) at 28 GHz.*

Scenarios	Reference	2TP same	3TP same	2TP dynamic	3TP dynamic	4TP dynamic
Mean (dB)	–69.25	–69.01	–69.00	–68.06	–67.69	–67.53
Median (dB)	–69.45	–69.31	–69.30	–68.31	–67.89	–67.73

Table 6.2. *Received signal strength (mean and median) at 2.1 GHz.*

Scenarios	Reference	2TP same	3TP same	2TP dynamic	3TP dynamic	4TP dynamic
Mean (dB)	–62.06	–61.83	–61.82	–60.80	–60.37	–60.18
Median (dB)	–62.81	–62.64	–62.63	–61.46	–60.92	–60.81

The received signal strengths are also evaluated at 2.1 GHz. There is a similar pattern observed for the received signal strength, compared with 28 GHz band. The received signal strength for the scenario where the coordination takes place among 4 TPs is the strongest. The reference scenario has the weakest received signal strength. The mean and median values for the received signal strength are summarized in Table 6.2. Figure 6.2 shows the signal strength received by each user at 2.1 GHz band.

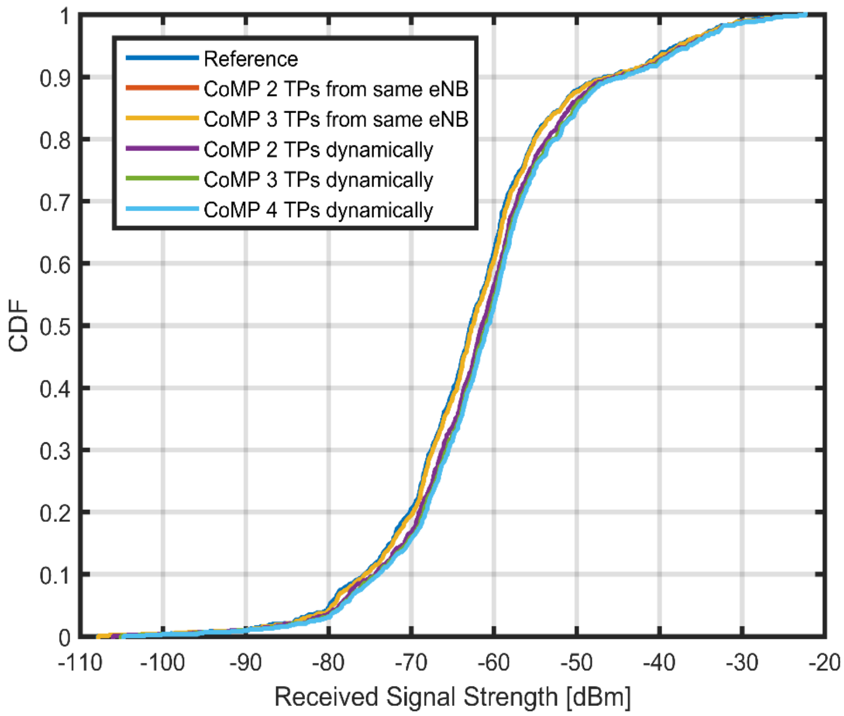
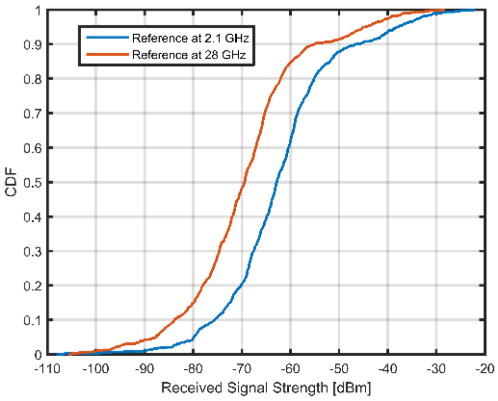
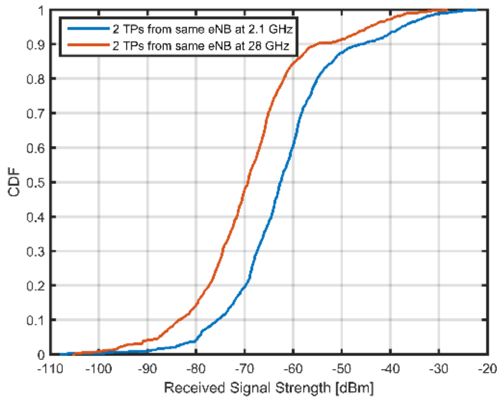


Figure 6.2. *CDF of Received signal strength for all the scenarios at 2.1 GHz.*

The received signal strength values for the different CoMP scenarios appear to have better signal strength at 2.1 GHz. Millimeter wave frequencies are characterized by low building penetration losses. The simulation environment considers users located both outdoors and indoors. Therefore, the average signal strength for each scenario is better at 2.1 GHz. From Table 6.1 and Table 6.2 it can be seen that for both of the frequency bands, the CoMP scenario where there are 4 TPs coordinating has the highest received signal strength. The reference scenario where only the strongest TP determines the received signal strength has the least received power. Table 6.1 and Table 6.2 shows that there is not much difference in the received signal strength for the scenarios where 2 TPs and 3 TPs are chosen from the same eNB. There is a difference of 0.01 dBm in both the frequency bands. However, by choosing the TPs dynamically, i.e. irrespective of the eNB helps in improving the received signal strength for each user.



(a)



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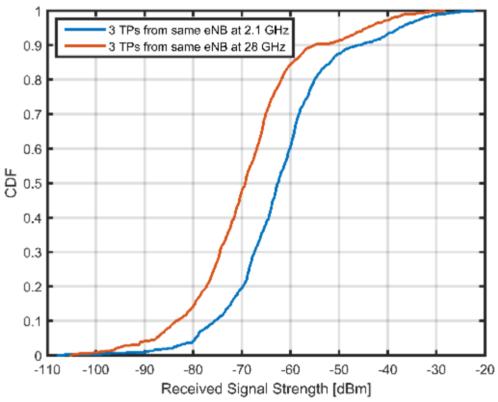

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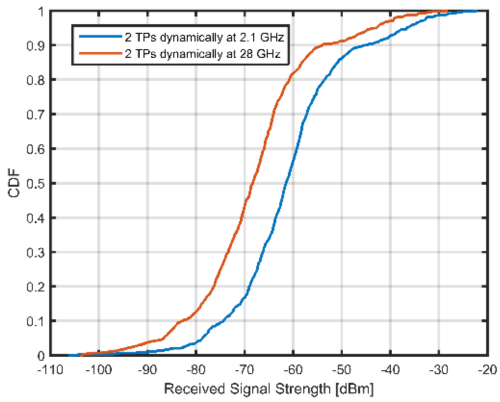

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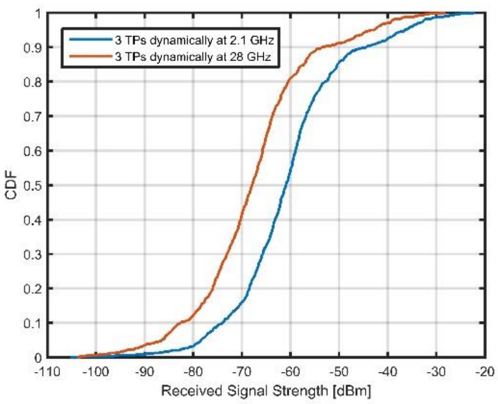

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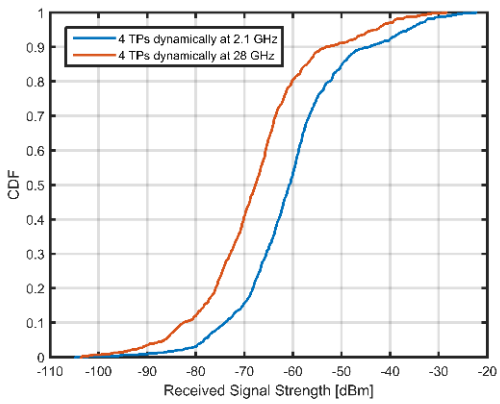


(f)

Figure 6.3. *Corresponding CDF of received signal strength for each CoMP scenario. (a) Reference, (b) 2 TPs from the same eNB, (c) 3 TPs from the same eNB, (d) 2 TPs chosen dynamically, (d) 3 TPs chosen dynamically, (d) 4 TPs chosen dynamically.*

Figure 6.3 (a)–(f) shows the comparison of the received signal strength for the different coordinating scenarios at 2.1 GHz and 28 GHz respectively. It can be observed that strength of the signal at 2.1 GHz is stronger for all the scenarios. Systems utilizing the millimeter wave frequency band experience larger building penetration losses, hence the signals at 2.1 GHz are stronger than the signals at 28 GHz. Thus, it can be concluded that the received signal strength is reduced for 28 GHz due to building penetration losses incurred in providing coverage for indoor users.

6.2 Signal-to-interference-plus-noise-ratio

The SINR is defined as the sum of all useful signals received by the user divided by the sum of all interfering signals and noise. The bandwidths used for the simulations at 28 GHz are 20 MHz and 200 MHz respectively. The simulations at 2.1 GHz have a bandwidth of 20 MHz. By definition, larger the value of the SINR, better is the performance of the system. The SINR is calculated in dB.

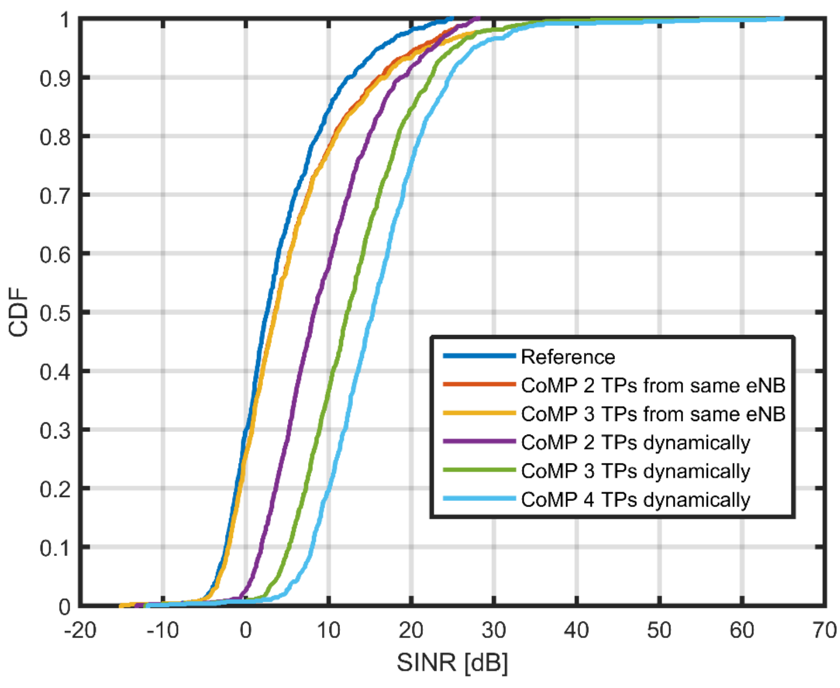


Figure 6.4. *CDF of SINR for all the scenarios at 2.1 GHz.*

Figure 6.4 illustrates the CDF plot of all the scenarios that were considered for the simulations. These values were obtained by utilizing 2.1 GHz frequency band. The scenario where 4 TPs are coordinating has the best SINR. The mean SINR value for this scenario is 15.97 dB. The scenario where 3 TPs were chosen dynamically (from all of the eNBs in the simulation environment) has a mean SINR of 13.14 dB and is the scenario with the second highest SINR values. The third highest SINR values are obtained from the scenario where 3 TPs chosen dynamically coordinate. The mean SINR value for this scenario is 9.42 dB. The scenarios where 2 TPs and 3 TPs are chosen from the same eNB have similar median SINR values. The mean values for these two scenarios are 5.32 dB and 5.68 dB. The CDF plot in Figure 6.4 shows that for users located near the eNB, the scenario where 3 TPs coordinate has better SINR values. The reference scenario has a mean SINR of 3.93 dB and has the lowest (mean) SINR value. Hence, at 2.1 GHz it can be deduced that CoMP provides better (mean) SINR values. It is seen that the scenarios where the TPs are chosen dynamically from any eNB in the simulation environment produces better SINR values than the scenario where the coordination is between the TPs of the same eNB. Furthermore, when chosen dynamically the more the number of TPs the better is the SINR value.

Table 6.3. *SINR (mean and median) at 2.1 GHz.*

Scenarios	Reference	2TP same	3TP same	2TP dynamic	3TP dynamic	4TP dynamic
Mean (dB)	3.93	5.32	5.68	9.42	13.14	15.97
Median (dB)	2.57	3.57	3.59	8.27	12.27	15.35

Table 6.3 summarizes the mean and median values of the SINR for all the scenarios. It can be seen that for the scenarios where the coordination between the TPs are dynamic, the mean SINR values are better than the reference scenario.

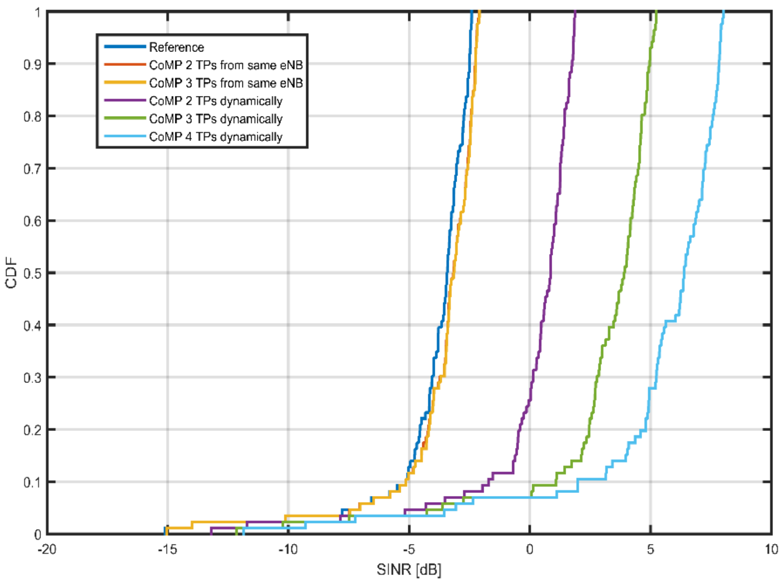


Figure 6.5. *CDF of SINR (cell edge) for all the scenarios at 2.1 GHz.*

Figure 6.5 illustrates the SINR values for the users located at the cell edges for all the scenarios. The cell edge is defined as the users with the worst 10% SINR values for the simulations. It can be observed that the scenario where there are 4 TPs coordinating has the best SINR when the TPs are chosen dynamically from the environment. The other scenarios follow traits similar to when all the users are considered as shown in Figure 6.4. The scenarios where the 2 TPs and 3 TPs are chosen from the same antenna have identical SINR values. The values are close to the reference scenario. However, it can be concluded that at 2.1 GHz, for cell edge users CoMP provides better SINR values when compared with the reference scenario where no coordination among TPs is considered.

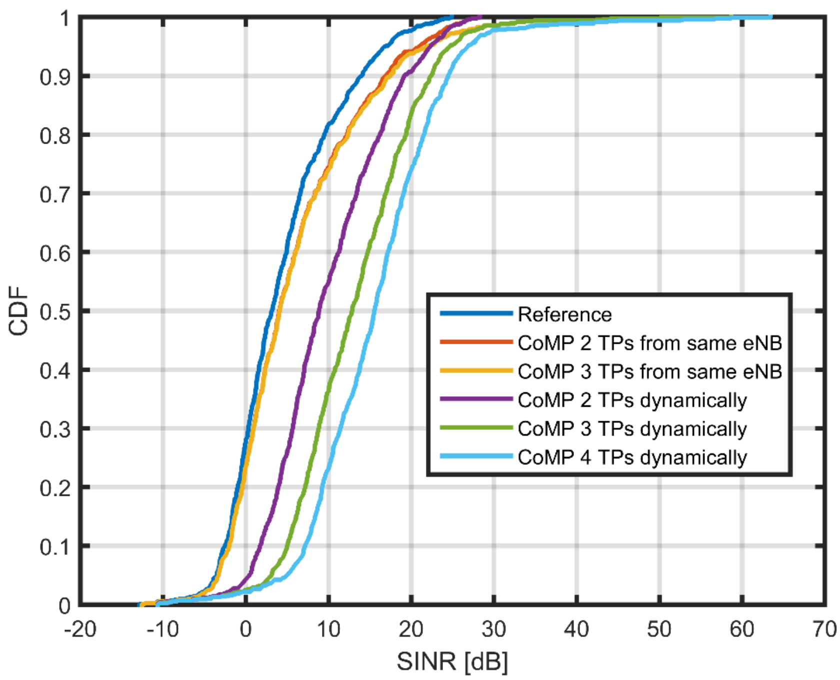


Figure 6.6. *CDF of SINR for all the scenarios at 28 GHz (20 MHz bandwidth).*

The CDF plot of the SINR values for the simulations at 28 GHz with 20 MHz bandwidth is shown in Figure 6.6. CoMP for 4 TPs chosen dynamically is the scenario which has the highest SINR value. The mean SINR for this scenario is 15.64 dB. The scenario with the second highest SINR value is the one where 3 TPs are chosen dynamically for coordination. This scenario has a mean SINR of 13.2 dB. The third strongest SINR is obtained from the scenario where CoMP between two TPs are considered dynamically and this scenario has a mean SINR of 9.82 dB. Scenarios where the coordination exists between TPs from different eNBs produces better SINR compared with the reference scenario or the scenarios where the coordination between TPs from the same eNB is considered. The scenarios where the coordination between 2 TPs and 3 TPs from the same eNB exists, the mean SINR values of 5.75 dB and 6.09 dB are observed. The SINR values for these two scenarios are very similar and can only be differentiated on the plot for the users that are located close to the eNB. For users located close to the eNB the scenario where 3 TPs from the same eNB are chosen has better SINR values among the two. The reference scenario has the least average SINR value of 4.36 dB.

The mean and median SINR values for all the scenarios at 28 GHz with 20 MHz bandwidth are summarized in Table 6.4. The scenario where the 4 TPs are chosen dynamically has a mean SINR which is 3.5 times greater than the reference scenario. The scenarios where CoMP takes place between the TPs dynamically generally have larger SINR values compared with the reference case. With the increase in the number of TPs the signal strength increases and the interference decreases and therefore the SINR increases.

Table 6.4. *SINR (mean and median) at 28 GHz (20 MHz bandwidth).*

Scenarios	Reference	2TP same	3TP same	2TP dynamic	3TP dynamic	4TP dynamic
Mean (dB)	4.36	5.75	6.09	9.82	13.20	15.64
Median (dB)	3.15	4.05	4.09	8.84	12.84	15.54

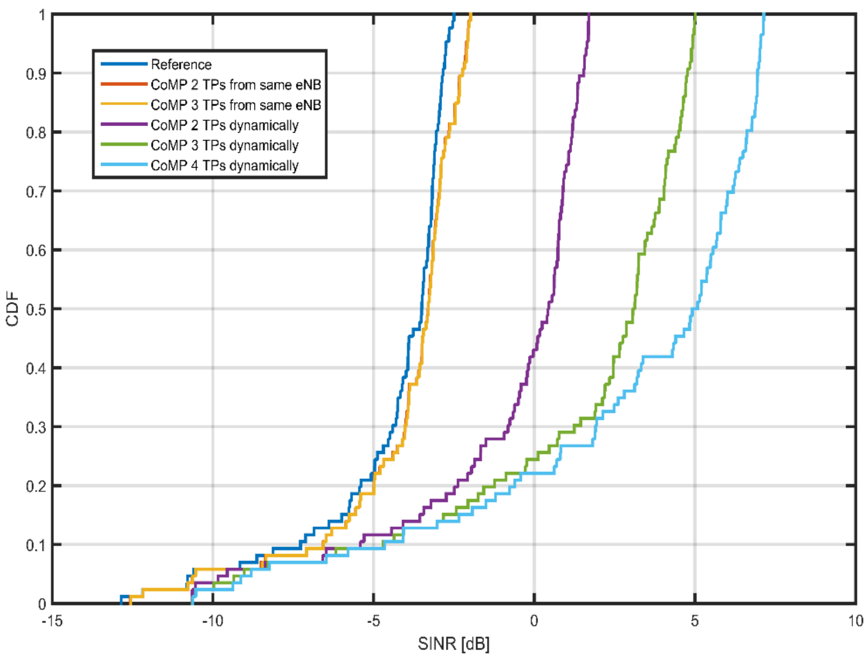
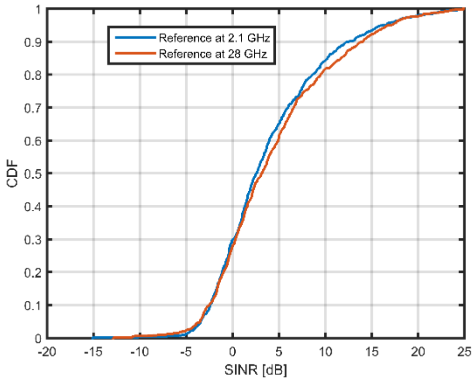
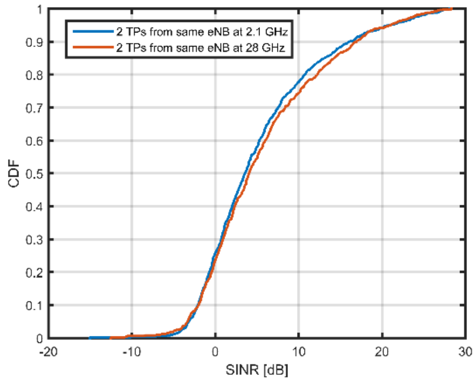


Figure 6.7. *CDF of SINR (cell edge) for all the scenarios at 28 GHz (20 MHz bandwidth).*

Figure 6.7 shows the CDF plot of the SINR for the cell edge users for all the scenarios considered for the simulation. The bandwidth used is 20 MHz and the frequency band is 28 GHz. Figure 6.7 resembles the traits of the plot in Figure 6.6. It is seen that even for the cell edge users the coordination between 4 TPs yields the best SINR. The scenarios where 3 TPs and 2 TPs are chosen dynamically have the second and the third highest SINR values. The scenarios where 2 TPs and 3 TPs from the same eNB are chosen have similar SINR values at the cell edges. The SINR values for these two scenarios are barely



(a)



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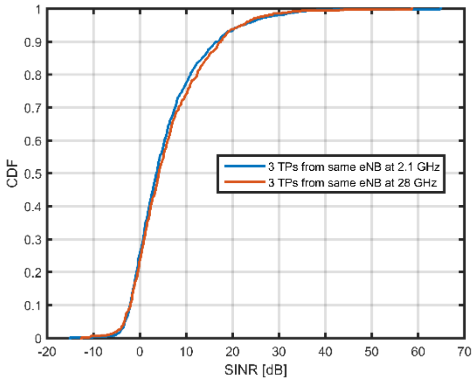

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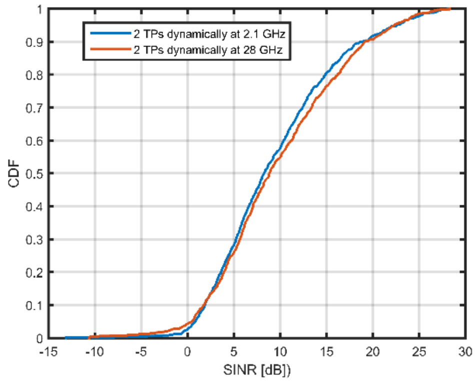

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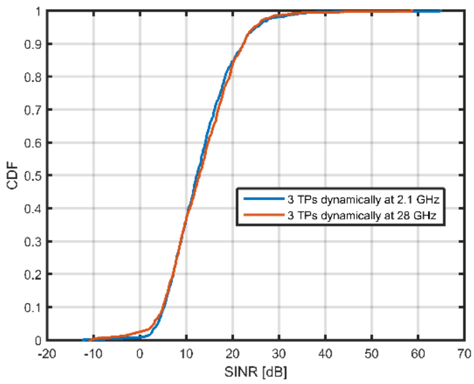

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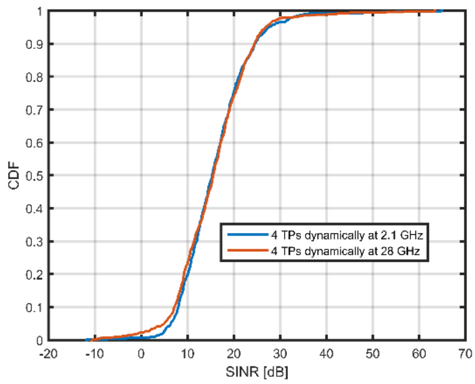

(f)

Figure 6.8. *Corresponding CDF of SINR for each CoMP scenario (20 MHz). (a) Reference; (b) 2 TPs from the same eNB, (c) 3 TPs from the same eNB, (d) 2 TPs chosen dynamically, (d) 3 TPs chosen dynamically, (d) 4 TPs chosen dynamically.*

better than the reference scenario. The reference scenario has the lowest SINR for cell edge users thus demonstrating that CoMP helps in improving the performance of the system at even the cell edges.

Figure 6.8 (a)–(f) illustrates the comparison between the corresponding scenarios at 2.1 GHz and 28 GHz. It is observed that for the scenarios in Figure 6.8 (a)–(d) the SINR values are better for 28 GHz compared with 2.1 GHz. For the scenario depicted in Figure 6.8 (e) the SINR values are marginally better at 28 GHz. Figure 6.8 (f) shows the scenarios where the SINR values are nearly identical to both of the frequency bands. The cell edge users for the scenarios depicted in Figure 6.8 (d)–(f) have SINR values which are better for 2.1 GHz compared with 28 GHz. The SINR values for 28 GHz can be further improved by using antenna arrays which are enabled due to the small wavelength of mmWaves.

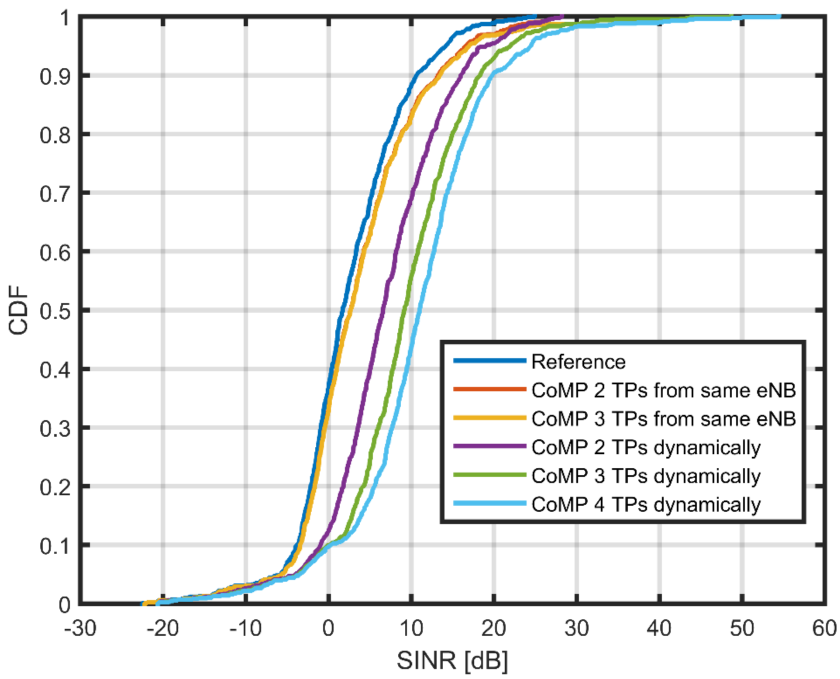

Figure 6.9. *CDF of SINR (cell edge) for all the scenarios at 28 GHz (200 MHz bandwidth).*

The bandwidth was changed from 20 MHz to 200 MHz for the plot in Figure 6.9. It is observed that the reference scenario has the lowest SINR value. A mean of 2.47 dB was observed for this scenario. For 40% of the users located away from the eNB, it is observed that the scenarios where 2 TPs and 3 TPs from the same eNB are chosen have similar SINR values with each other and the reference scenario. For the scenarios where 2 TPs and 3 TPs are coordinating the mean SINR values are 3.51 dB and 3.73 dB respectively. The scenario where 3 TPs from the same eNB are coordinating has SINR values better for the users located close to the eNB than the scenario where 2 TPs are coordinating. The best SINR is observed for the scenario where 4 TPs are coordinating dynamically within the environment. This scenario has a mean SINR of 10.9 dB. The mean SINR for the scenario where 3 TPs are chosen dynamically is 9.28 dB and provides the second highest SINR values among the scenarios. The scenario where 2 TPs are chosen dynamically has a mean SINR of 6.86 dB and has the third highest SINR values among the scenarios.

Table 6.5. *SINR (mean and median) at 28 GHz (200 MHz bandwidth).*

Scenarios	Reference	2TP same	3TP same	2TP dynamic	3TP dynamic	4TP dynamic
Mean (dB)	2.47	3.51	3.73	6.86	9.28	10.90
Median (dB)	1.72	2.65	2.67	6.58	9.16	11.02

The mean and median values for the SINR are summarized in Table 6.5. The increase in bandwidth decreases the SINR for all the scenarios compared with the results obtained by using a bandwidth of 20 MHz. There is a decrease of 4.74 dB in the SINR for the scenario where 4 TPs coordinate dynamically when the bandwidth is increased from 20 MHz to 200 MHz at 28 GHz. The mean SINR decreases with the increase in bandwidth. However, CoMP improves the SINR and therefore improves the performance of the system.

The CDF plot for the SINR at the cell edge for all the scenarios is illustrated in Figure 6.10. It is observed that there is about 4 dB difference between the scenarios having the highest and lowest SINR values. The scenarios where coordination is established dynamically among the TPs have better SINR values in comparison with the reference scenario. The scenarios where the coordination occurs between the cells/TPs of the same eNB have similar SINR values which in turn are marginally better than the reference scenario that has the lowest SINR values. The scenario where 4 TPs coordinate dynamically has the best SINR values. At the cell edge, the scenario where 3 TPs coordinates has SINR values close to the scenario which provides the best SINR. The scenario where 2 TPs coordinate dynamically also improves the SINR in comparison with the reference scenario. Thus it can be concluded CoMP increases the SINR for the cell edges of a particular environment especially when the cells are chosen dynamically. The more the number of TPs the better is the SINR, therefore the system performance at the cell edge is improved due to CoMP.

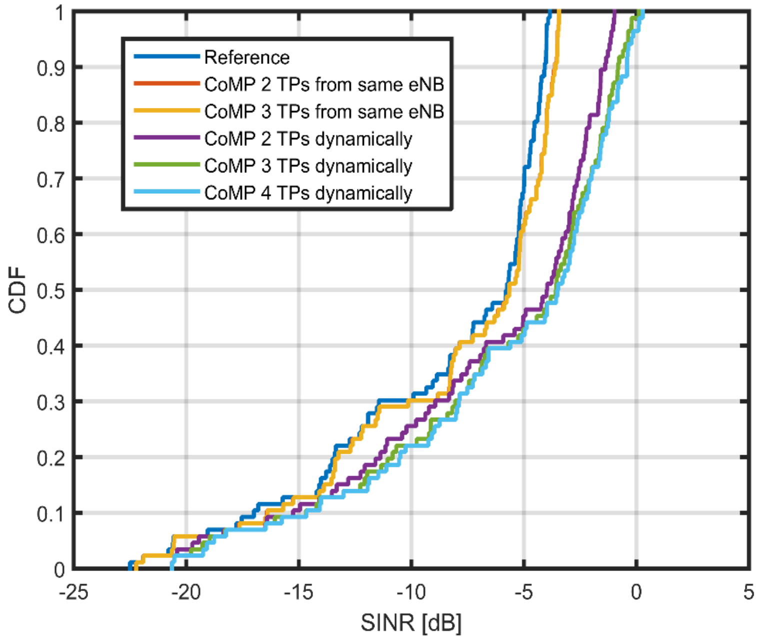

Figure 6.10. *CDF of SINR (cell edge) for all the scenarios at 28 GHz (200 MHz bandwidth).*

Figure 6.11 (a)–(f) shows the comparison of the CoMP scenarios for 28 GHz simulations with 2.1 GHz simulations when the bandwidth for 28 GHz simulations is increased from 20 MHz to 200 MHz. It is noticed that for all the scenarios the SINR at 2.1 GHz is better than the SINR at 28 GHz. Therefore, the increase in bandwidth decreases the SINR values at 28 GHz. By using antenna arrays the SINR values can be improved.

6.3 Spectral Efficiency

The spectral efficiency of a system can be defined as the measure of the number of users that can be served at the same time. This is evaluated by equation (9) as described in Chapter 5. The unit for spectral efficiency is bits/second/hertz. The performance of the system gets better with the increase in the spectral efficiency as this is a measure of the rate at which the information transfer takes place over a particular bandwidth. The spectral efficiency is evaluated for all the CoMP scenarios at 2.1 GHz and 28 GHz. The bandwidths used for 28 GHz simulations are 20 MHz and 200 MHz respectively.

Table 6.6 shows the spectral efficiency for all the CoMP scenarios at two frequency bands. The bandwidth is changed from 20 MHz to 200 MHz for 28 GHz band. It can be observed that the CoMP scenario where 4 TPs are coordinating dynamically produces the best spectral efficiency among all the considered scenarios irrespective of the bandwidth and the frequency band that are used for the simulations. When 2 TPs and 3 TPs from the same eNB coordinate the spectral efficiency increases compared with the reference scenario.

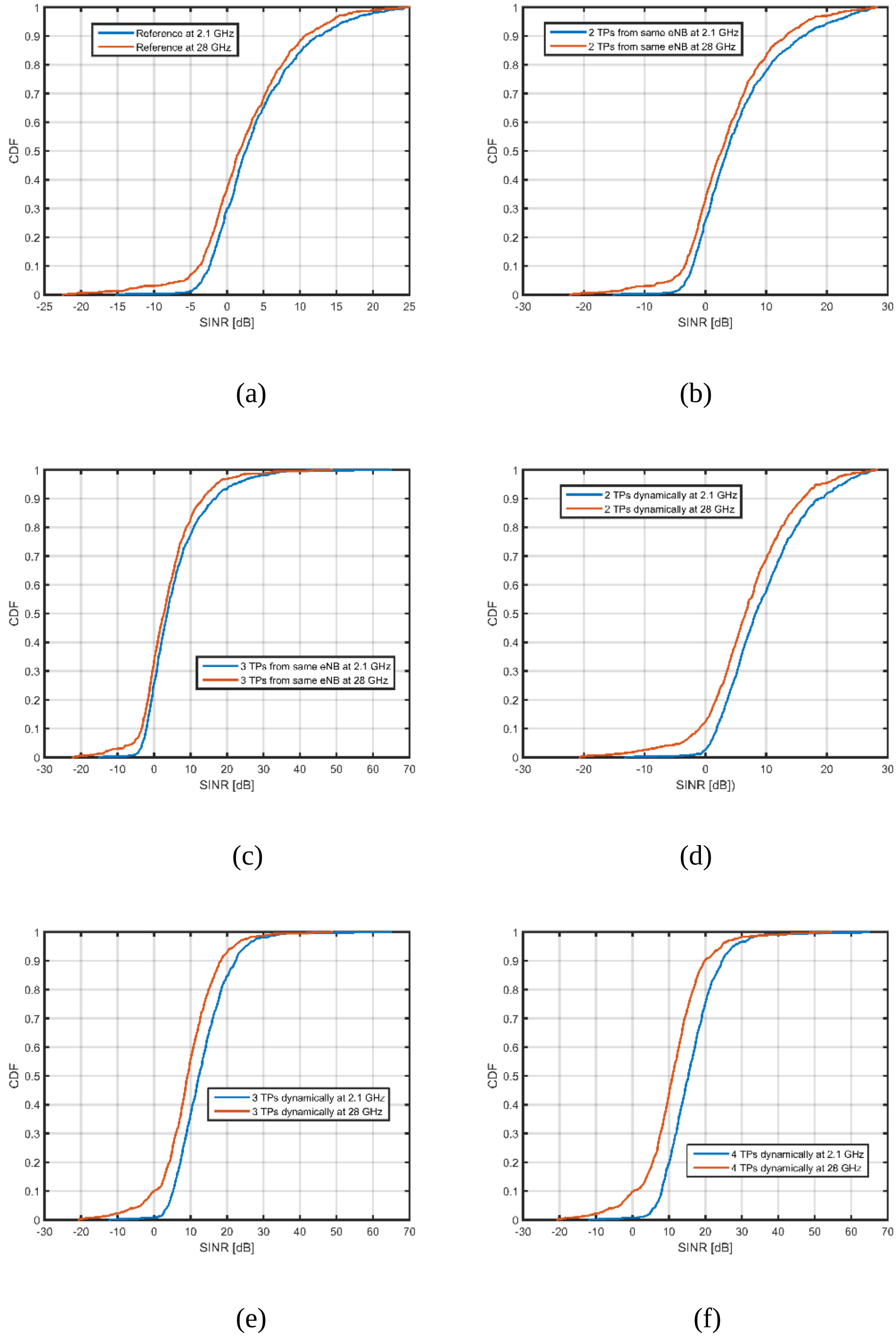

Figure 6.11. *Corresponding CDF of SINR for each CoMP scenario (200 MHz). (a) Reference, (b) 2 TPs from the same eNB, (c) 3 TPs from the same eNB, (d) 2 TPs chosen dynamically, (d) 3 TPs chosen dynamically, (d) 4 TPs chosen dynamically.*

However, when the coordinating cells are chosen dynamically the spectral efficiency increases further. The more the number of coordinating cells, the better is the spectral efficiency for the specified bandwidth at a particular frequency band.

Table 6.6. *Spectral efficiency for the CoMP scenarios at 2.1 and 28 GHz frequency.*

Frequency bands	2.1 GHz (20 MHz) [bits/second/Hz]	28 GHz (20 MHz) [bits/second/Hz]	28 GHz (200 MHz) [bits/second/Hz]
Reference	1.79	1.90	1.47
2-TPs from same eNB	2.14	2.25	1.70
3-TPs from same eNB	2.23	2.33	1.75
2-TPs dynamically	3.29	3.40	2.55
3-TPs dynamically	4.43	4.45	3.25
4-TPs dynamically	5.34	5.24	3.73

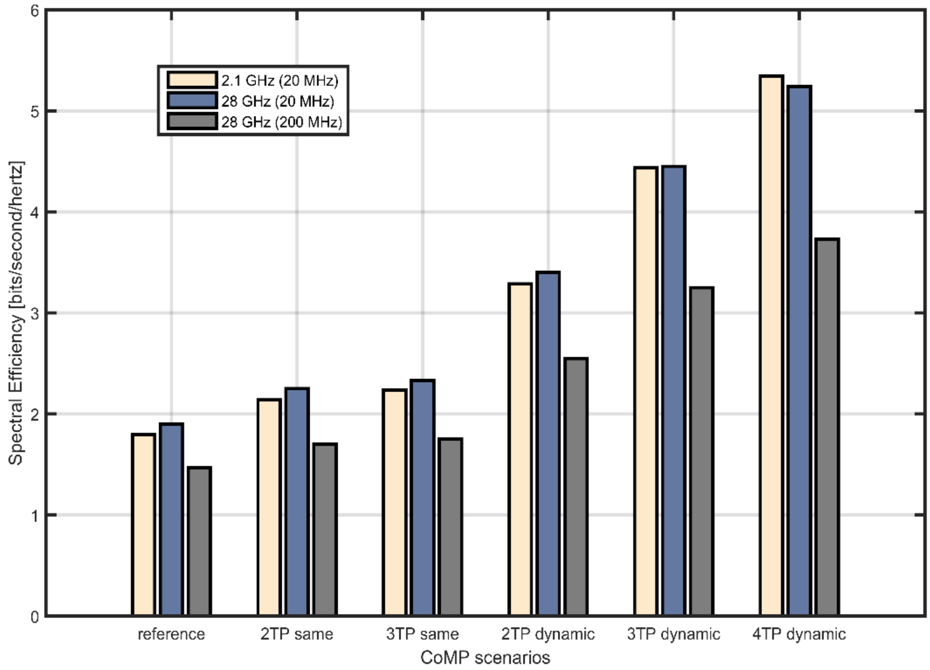

Figure 6.12. *Corresponding spectral efficiency for all the scenarios at 2.1 GHz and 28 GHz. For 28 GHz, 20 MHz and 200 MHz bandwidth are used.*

The comparison of the spectral efficiency for corresponding CoMP scenarios at two frequency bands (with 20 and 200 MHz bandwidths) are illustrated in Figure 6.12. It is observed that when the bandwidth is 20 MHz then the spectral efficiency values are similar at both of the frequency bands. There are only minor improvements in the spectral efficiency at 28 GHz for the first four scenarios including the reference scenario. For

28 GHz band, the scenarios where 3 TPs and 4 TPs are chosen dynamically from the simulation environment displays a decrease in spectral efficiency compared with 2.1 GHz. As the bandwidth for 28 GHz is increased to 200 MHz, the spectral efficiency decreases considerably for all the scenarios. The bandwidth utilized affects the spectral efficiency, therefore using a larger bandwidth reduces the spectral efficiency.

6.4 Area spectral efficiency

The area spectral efficiency describes the sum of all the information per unit bandwidth per unit area. This is expressed in bits/second/hertz per cell. It is obtained as a product of the spectral efficiency with the cell density as shown in equation (10).

It can be observed from Table 6.7 that the use of CoMP improves the area spectral efficiency. The scenario where 4 TPs coordinate dynamically has the largest area spectral efficiency for all the scenarios under study. The reference scenario has the least area spectral efficiency. For the scenarios where 2 TPs and 3 TPs are chosen dynamically, the area spectral efficiency increases for 3 TPs CoMP scenario with the addition of a coordinating TP. This increase in area spectral efficiency is also noticed when 2 TPs and 3 TPs are chosen from the same eNB. Therefore, it can be concluded that the use of CoMP increases the area spectral efficiency so the performance of the system also improves.

Table 6.7. *Area spectral efficiency for the CoMP scenarios at 2.1 and 28 GHz frequency.*

Frequency bands	2.1 GHz (20 MHz) [bits/second/Hz]	28 GHz (20 MHz) [bits/second/Hz]	28 GHz (200 MHz) [bits/second/Hz]
Reference	53.90	56.99	44.09
2-TPs from same eNB	64.18	67.54	50.98
3-TPs from same eNB	67.04	70.19	52.50
2-TPs dynamically	98.58	102.17	76.51
3-TPs dynamically	133.05	133.60	97.37
4-TPs dynamically	160.26	157.10	112.01

The study of 28 GHz frequency band when the bandwidth is 20 MHz displays an increase in the area spectral efficiency corresponding to the first five CoMP scenarios at 2.1 GHz. The area spectral efficiency decreases at 28 GHz when 4 TPs are chosen dynamically when compared with the corresponding scenario at 2.1 GHz. However, when the bandwidth is increased to 200 MHz it is observed that the area spectral efficiency decreases for all the CoMP scenarios and the reference scenario. It is observed that choosing the TPs dynamically decreases the area spectral efficiency further than when the TPs are chosen from the same eNB. It can be concluded that with the increase in bandwidth at 28 GHz the area spectral efficiency is greatly reduced. The area spectral efficiency can be improved with the use of heterogeneous networks to serve the users located indoors.

6.5 Throughput

A key parameter for measuring the performance of the system is the throughput. The throughput of a system is defined by the amount of information that can be transferred over the link in a given time. The data rate for all the users when added also gives the system throughput. The throughput is closely related with the system capacity shown in equation (8) where the capacity determines the theoretical upper bound for reliable information transfer. The results for the throughput from the simulations are expressed in Mbps.

Table 6.8. *Throughput for the CoMP scenarios at 2.1 and 28 GHz frequency.*

Frequency bands	2.1 GHz (20 MHz) [Mbps]	28 GHz (20 MHz) [Mbps]	28 GHz (200 MHz) [Mbps]
Reference	35.93	37.99	293.90
2-TPs from same eNB	42.78	45.03	339.88
3-TPs from same eNB	44.70	46.80	349.98
2-TPs dynamically	65.71	68.11	510.09
3-TPs dynamically	88.70	89.06	649.14
4-TPs dynamically	106.84	104.73	746.76

Table 6.8 shows the throughput values for all the CoMP scenarios at 2.1 GHz and 28 GHz. Similar to the other parameters the bandwidths in the 28 GHz simulations are 20 MHz and 200 MHz. The throughput of the system is closely related to the bandwidth but it can be seen from the simulations that the throughput does not increase ten times even though the bandwidth is increased by ten times for 28 GHz frequency band. The highest throughput is obtained for the scenario where the 4 TPs are chosen dynamically from the simulation environment. For this scenario, it can be observed that the throughput is better for 200 MHz compared with the 20 MHz band. Keeping the bandwidth constant at 20 MHz it is observed that the throughput value drops slightly for 28 GHz compared with 2.1 GHz. It is also observed that the use of coordination among cells helps in improving the system performance by increasing the throughput. The scenarios where the TPs are chosen dynamically typically provide the best throughput values. It is also observed that the coordination between two and three cells from the same antenna does not increase the throughput massively. The reference scenario provides the least

throughput in both the frequency bands. Therefore, it can be concluded that CoMP improves the system throughput.

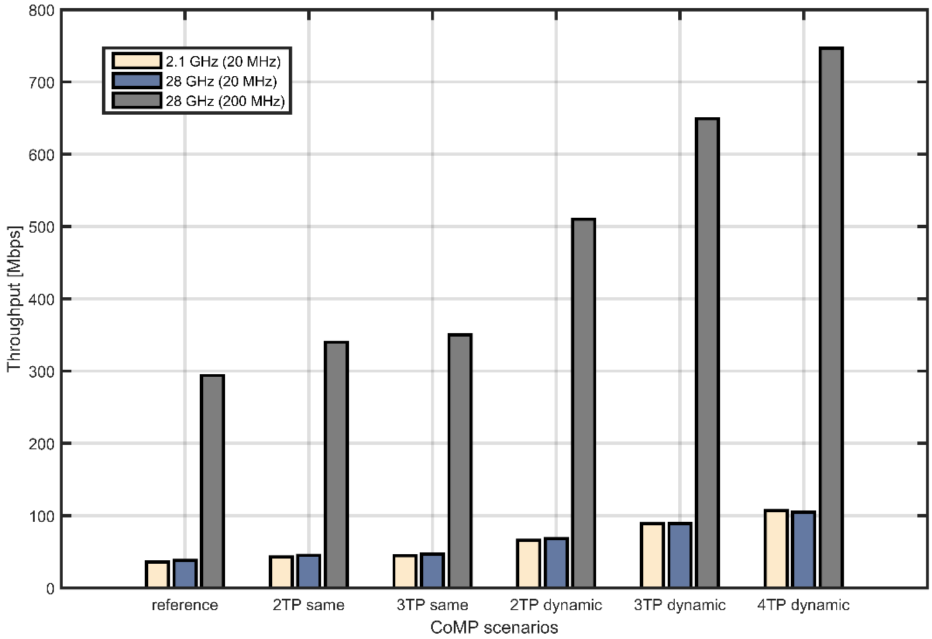

Figure 6.13. *Corresponding throughput for all the scenarios at 2.1 GHz and 28 GHz. For 28 GHz, 20 MHz and 200 MHz bandwidth are used.*

Systems utilizing the mmWave frequency band experience better throughput when the bandwidth is increased. Figure 6.13 shows the throughput for the corresponding CoMP scenarios for each frequency band. It is observed that when the bandwidth is increased ten times to 200 MHz the throughputs of all the scenarios improve considerably. The throughput however does not increase ten times. On average, the throughput values increase about 6–6.5 times for all the scenarios. This is due to the increase in noise power. Throughput values closer to ten times can be achieved by increasing the transmission power at the eNB. As discussed earlier it is also observed that the coordination of more number of transmission points increases the throughput of the system. By definition, a better throughput generally signifies a better performance of the system. 28 GHz frequency band enables ten times increase in bandwidth which enables better capacity. Therefore, it can be concluded using 28 GHz band helps in improving the performance of the system.

The gain in throughput for all the CoMP scenarios is expressed by equation (12) and is illustrated in Figure 6.14. It is observed that the throughput of the system improves when CoMP is used. Utilization of the mmWave frequency band enables the use of 200 MHz bandwidth which also helps in improving the throughput. It is seen that the gain in throughput is the highest when 2.1 GHz is used. In this band, the scenario where 4 TPs coordinates has a gain in the throughput of 197%. The second highest gain in throughput is achieved when 28 GHz frequency band is used and the bandwidth is 20 MHz. For the CoMP of 4 TPs the gain is 175%. The lowest gain in throughput among the compared frequency bands is observed when the frequency band is 28 GHz and the bandwidth is increased to 200 MHz. The gain is 154% in this band for the scenario where 4 TPs are coordinating dynamically. These values are calculated relative to the reference scenario and represent the highest gain percentage that is obtained for both the frequency bands with varying bandwidths. It can also be observed that the gain in throughput is not significant when 2 TPs and 3 TPs from the same eNB coordinate. CoMP where TPs are selected dynamically has significant gains in the throughput compared with the scenarios where the TPs are chosen from the same eNB.

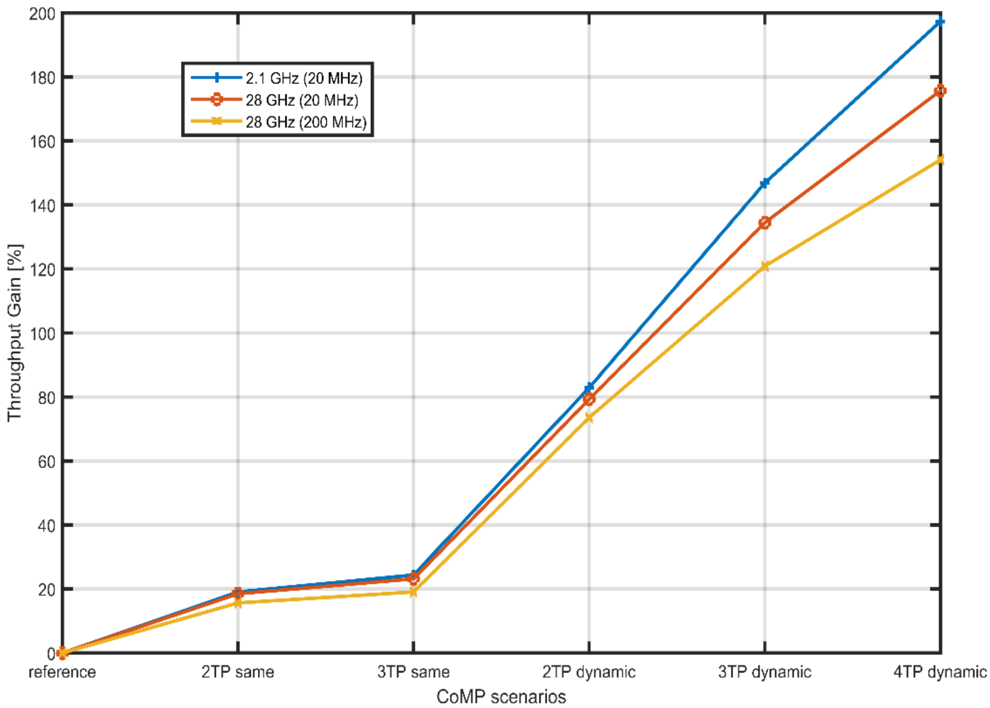

Figure 6.14. *Corresponding gain in throughput for all the scenarios at 2.1 GHz and 28 GHz. For 28 GHz, 20 MHz and 200 MHz bandwidth are used.*

7 CONCLUSION

In order to meet the growing demand for supporting numerous devices and bandwidth hungry applications, new technologies need to be developed as the current ones will not be sufficient to support such an IP data explosion. Research on 5G is focused on developing ways and means by which such issues can be mitigated. Technologies such as massive MIMO, ultra-dense networks, D2D, M2M has been under research for the last few years to determine enabling technologies for 5G. Due to the shortage of spectrum that exists below 6 GHz frequency band, an expansion in the spectrum used for cellular communications has been studied by researchers and academicians. Large unlicensed bandwidth exists in the mmWave frequency band which opens up the possibility of providing greater data rates for users in the future. The development of semiconductor technologies will help in alleviating the poor propagation characteristics that mmWave systems suffer from. Coordination among eNBs leads to better system throughput and SINR. Thus the utilization of CoMP can help in providing high data rates which is a primary requirement of 5G.

The motive of this thesis was to study the performance of systems utilizing the CoMP technology. Various simulation scenarios utilizing CoMP in homogeneous and heterogeneous environments are formulated. The frequency bands of 2.1 GHz and 28 GHz were used for the simulations. For 28 GHz, the bandwidth was increased ten times from 20 GHz to 200 GHz in order to study the performance of the system with the increase in bandwidth. Antenna modelling was done in order to obtain gains in the azimuth and elevation plane. System performance defining parameters such as the received signal strength, SINR, spectral efficiency, area spectral efficiency and throughput were calculated and analyzed in order to evaluate the system performance.

The first parameter that was studied in order to evaluate the system performance was the received signal strength. The CDF plots for the received signal strength for the various CoMP scenarios showed that the utilization of CoMP did not affect the received signal strength. Every scenario had similar received signal strength values. At 28 GHz, it was observed that due to high penetration losses incurred by mmWave systems, the mean received signal strength was lower in comparison with 2.1 GHz. A way by which this can be alleviated is by utilizing antenna arrays and HetNets which provide coverage for users located indoors.

The parameter studied next for the evaluation of the system performance was the SINR. The SINR describes the ratio between the signal power and the sum of the power of the interference and noise. It was observed that the use of CoMP increased the SINR of the system. The more the number of coordinating cells the better was the SINR. It was observed that at 28 GHz the SINR increased in comparison with 2.1 GHz when the bandwidth was 20 MHz. With the increase in bandwidth (to 200 MHz) at 28 GHz, the SINR values decreased in comparison with the SINR values at 2.1 GHz and 28 GHz when the bandwidth was 20 MHz. The utilization of antenna arrays can help in improving the SINR when the bandwidth used is 200 MHz.

The spectral efficiency and the area spectral efficiency of the system was studied next. The spectral efficiency represents the rate of information transfer. The area spectral efficiency generally describes the rate of information transfer per unit area. It was observed that the values of both these parameters increase with the number of coordinating cells. CoMP in general improved the value of both these parameters compared with the reference scenario. When the bandwidth was 200 MHz, at 28 GHz it was noted that the spectral efficiency and the area spectral efficiency decreased in comparison with the results obtained at 2.1 GHz and 28 GHz with 20 MHz bandwidth.

The throughput of the system was studied next which represents the amount of information transferred per unit time. It was observed that the use of CoMP increased the system throughput. The increase in the throughput was related to the number of coordinating cells. Better throughput was achieved with more number of coordinating cells. It was observed that the values of the throughput increased slightly when the bandwidth was 20 MHz and the frequency band changed from 2.1 GHz to 28 GHz. Nevertheless, the use of 200 MHz bandwidth increased the system throughput by a great deal. However, ten times increase in bandwidth did not result in the increase in throughput by ten times. There was about seven times increase in the throughput because the noise bandwidth increased when 200 MHz bandwidth was used. The transmit power was kept constant for both the bandwidths therefore the received signal strengths for both the bandwidths remained the same.

The simulation environment was chosen to reflect the dense urban environment where 5G systems are the most likely to be deployed. However, the transmitting antennas can be located differently in practical deployments. The obtained results were based on the preciseness of the simulator and the modeled simulation environment. Therefore, the values may vary in real world deployments. The results suggest that CoMP techniques improve the system performance. However, they only serve as a figurative indication of how the system performance metrics varies, for different scenarios that were considered in the simulations. Hence, these values may change for practical deployment scenarios. Systems operating in the mmWave frequency band, suffer penetration losses for users located indoors. This can be mitigated in practical deployments by using HetNets.

7.1 Future work

The use of CoMP helps in improving the system performance by providing better SINR, spectral efficiency, area spectral efficiency and throughput. The use of 28 GHz enables the utilization of large continuous bandwidth. The system performance can be studied by using cognitive radio in coherence with the CoMP and mmWave systems. By using a procedure called dynamic spectrum management, cognitive radio dynamically utilizes network resources simultaneously [53]. This provides the scope of improving the network performance though there a trade-off that needs to be reached with the amount of network resources utilized. Massive MIMO can also be used in coherence with these systems to study the effect that massive MIMO has on the performance of the system.

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