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TAMPERE UNIVERSITY OF TECHNOLOGY

EUNICE NDUTA KAMAU

ENERGY EFFICIENCY COMPARISON BETWEEN 2.1 GHZ AND 28 GHZ BASED COMMUNICATION NETWORKS

Master of Science Thesis

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ABSTRACT

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Mobile communications have revolutionized the way we communicate around the globe, making communication easier, faster and cheaper. In the first three generations of mobile networks, the primary focus was on voice calls, and as such, the traffic on the networks was not as heavy as it currently is. Towards the fourth generation however, there was an explosive increase in mobile data traffic, driven in part by the heavy use of smart phones, tablets and cloud services, that is in turn increasing heavy energy consumption by the mobile networks to meet increased demand. Addition of power conditioning equipment adds on to the overall energy consumption of the base stations, necessitating deployment of energy efficient solutions to deal with the impacts and costs of heavy energy consumption.

This thesis investigates the energy efficiency performance of mobile networks in various scenarios in a dense urban environment. Consideration is given to the future deployment of 5G networks, and simulations are carried out at 2.1 GHz and 28 GHz frequencies with a channel bandwidth of 20 MHz in the 2.1 GHz simulation and 20 MHz in 28 GHz scenario. The channel bandwidth of the 28 GHz system is then increased ten-fold and another system performance evaluation is then done. Parameters used for evaluating the system performance include the received signal strength, signal-to-interference-plus-noise-ratio, spectral efficiency and power efficiency are also considered.

The results suggest that deployment of networks using mmWave frequencies with the same parameters as the 2.1 GHz does not improve the overall performance of the system but improves the throughput when a bandwidth of 200 MHz band is allocated. The use of antenna masking with down tilting improves the gains of the system in all three systems. The conclusion drawn is that if all factors are the same, mmWave systems can be installed in the same site locations as 2.1 GHz systems. However, to achieve better performance, some significant modifications would need to be considered, like the use of antenna arrays and beam steering techniques. This simulation has considered outdoor users only, with indoor users eliminated. The parameters in a real network deployment might differ and the results could change, which in turn could change the performance of the system.

PREFACE

This thesis was performed as a partial completion fulfilment requirement for the Master of Science (Technology) degree in Information Technology. The research was performed at the Radio Network Planning research group in the Laboratory of Electronics and Communications Engineering, Tampere University of Technology, Finland, under the supervision of Prof. Professor Jukka Lempiäinen and Dr. Joonas Säe.

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I would like to thank my family in Kenya for always being there for me, being my anchor when life got tough here in Finland. I appreciate each one of you. To my mother Leah Muthoni, thank you for being the best mother I could have. Thank you for always being by my side. To my siblings Florence, Gladys, Martin, Hellen and Joyce, thank you for the motivation.

I dedicate this thesis to my son Yngwe Linder. Your presence in my life has made me stronger, a better and more fulfilled person than I could have ever imagined.

Helsinki, 30.11.2018

Eunice Kamau

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LIST OF SYMBOLS AND ABBREVIATIONS

Abbreviations

1G	First generation
2G	Second generation
3D	Three dimensional
3G	Third generation
3GPP	Third generation partnership project
4G	Fourth-generation
5G	Fifth generation
AC/DC	Alternate current/direct current
ADAC	Automatically detected and automatically cleared
ADMC	Automatically detected and manually cleared
ANR	Automatic neighbour relation
AoD	Angle of departure
AoD	Angle of departure
BBU	Base band unit
BS	Base station
BTS	Base transceiver station
CAPEX	Capital expenditure
CCO	Coverage and capacity optimization
CDF	Cumulative distribution function
CDMA	Code division multiple access
CIR	Channel impulse response
CO2	Carbon dioxide
CRE	Cell range extension
CSI	Channel state information
DoD	Direction of Departure
DoD	Direction of departure
DRC	Dynamic radio configuration
DRX	Discontinuous reception
DSSS	Direct sequence spread spectrum
DTX	Discontinuous transmission
E_b/N_o	Energy per bit to spectral noise density
EDGE	Enhanced data rates for GSM evolution
eNB	Evolved node b
ETSI	European telecommunications standards institute
EU	European union
FDMA	Frequency division multiple access
FPGA	Field programmable gate arrays
GHG	Greenhouse gases
GO	Geometrical optics
GPRS	General packet radio service
GPS	Global positioning system
GSM	Global system for mobile
HD	High definition
HeNB	Home eNB
HetNets	Heterogeneous networks

HPBW	Half power beamwidth
HSDPA	High speed downlink packet access
HSPA	High speed packet download access
HSUPA	High speed uplink packet access
HTML	Hypertext markup language
HVAC	Heating, ventilation, and air conditioning
IBO	Input back-off
ICT	Information and communication technologies
ICT4EE	The ICT for energy efficiency
IMT	International Mobile Telecommunications
IoT	Internet of things
IP	Internet protocol
IRP	Integration reference point
ISI	Inter symbol interference
IT	Image theory
ITU	International telecommunication union
ITU-R	International telecommunications union-radio communications sector
LCD	Liquid crystal display
LOS	Line of sight
LTE	Long term evolution
MaMi	Massive MIMO
MIMO	Multiple-input and multiple-output
MMS	Multimedia messaging service
mmWaves	Millimetre Waves
MNO	Mobile network operators
MP3	MPEG layer-3
MPEG	Motion picture experts group
MRO	Mobility robustness optimization
NLOS	Non-line of sight
OBO	Output back-off
OFDMA	Orthogonal frequency division multiple access
OPEX	Operational expenditure
PA	Power amplifiers
PAPR	Peak to average power ratio
PC	Personal computer
PDU	Power distribution unit
QoE	Quality of experience
QoS	Quality of service
RACH	Random access channel
RAN	Radio access networks
RBS	Radio base station
RET	Remote electrical tilt
RF	Radio frequency
RN	Relay node
RRC	Radio resource control
RRH	Remote radio head
SBR	Shooting and bouncing ray
SINR	Signal-to-interference-plus-noise-ratio
SLL	Side lobe level
SM	Spatial multiplexing

SMS	Short message service
SNR	Signal to noise ratio
SON	Self-organizing networks
TDMA	Time division multiple access
UDN	Ultra-dense networks
UE	User equipment
UHD	Ultra-high definition
UMTS	Universal mobile telecommunications system
UPS	Uninterruptible power source
WAP	Wireless Application Protocol
WCDMA	Wideband code division multiple Access
Wi-Fi	Wireless fidelity
WLAN	Wireless local area network
VoLTE	Voice over LTE

Symbols

C	Shannon capacity
B	Noise bandwidth
d	Distance
G	Total antenna gain
$G_{\mathrm{h}}(\varphi)$	Horizontal plane polarization gain
G_{m}	Maximum antenna gain in horizontal plane
I	Interference
k	Boltzmann's constant
L	Free space path loss
N	Thermal noise power
N_{cell}	Cell density
NF	Noise factor
P_{Area}	Total area transmission power
P_{BS}	Base station transmission power consumption
P_{eff}	Transmission power efficiency
T	Temperature
W	Channel bandwidth
Γ	SINR (linear scale)
η	Spectral efficiency
$\overline{\eta}_{\mathrm{Area}}$	Area spectral efficiency
$\overline{\eta}_{\mathrm{cell}}$	Cell spectral efficiency
λ	Wavelength
θ	Angle of departure
φ	Direction of departure

1. INTRODUCTION

The internet has revolutionized the way we access and disseminate information, entertain, educate and conduct business. Subsequently, the development of cellular networks has made it easier to access the internet, anytime, anywhere, resulting in high and sustained traffic growth since the beginning of the 21^{st} century.

Globally, mobile data traffic per month in 2016 was reported to be 7.2 exabytes, representing a growth of 63 percent with fourth generation (4G) accounting for 69 percent of the mobile traffic, from the 4.4 exabytes per month in 2015. The highest growth was recorded in the Middle East and Africa region at 96 percent, with western Europe and North America showing tapering growth, that could be attributed to maturing of mobile markets, and steady mobile network penetration in these regions. There has been an exponential growth in mobile devices connections and it was reported that there were 8.0 billon mobile device connections in 2016, up from 7.6 billion in 2015. This growth represents an 18-fold growth of mobile data traffic in the last 5 years. Cisco forecasts monthly mobile data traffic increase to 49 exabytes by 2021. [1]

GSM/EDGE still constitutes the most number of connected mobile devices subscriptions, especially in developing markets, while smart phone subscriptions are mostly for third-generation (3G) and 4G. With device affordability driving smartphone adoption, there were 3.9 billion subscriptions in 2016 [2]. By 2021, when the fifth generation (5G) networks are expected to be rolled out, average mobile data download speeds are also expected to rise to 20.4 Mbps from the 6.8 Mbps in 2016[3].

The demand for high data rates and an increase in the use of sophisticated applications has driven extensive and heavy deployment of mobile broadband networks by mobile network operators and service providers, with heavy investments in large data centres, upgrades of access networks and expansion of the core network capacity. However, expansion and upgrades of existing networks cannot meet the increasing demand requirements, especially during peak periods, which in turn strains the mobile network, because there is no sufficient licensed electromagnetic spectrum for the operator. More spectrum- with other factors remaining constant-means that the operators have more bandwidth and can carry more traffic. In this regard, unlicensed spectrum allocation could be critical to future mobile network developments, considering how the currently licensed spectrum is crowded. However, there are inherent problems with unlicensed networks including interference that can be unpredictable. Mobile operators have been using the IEEE802.11 Wireless Local Area Network (WLAN) networks to offload data from the mobile networks, especially during peak-time. [3].

The 5G technology is predicted to bring a new era in mobile networks. The use of frequencies above 6 GHz that were considered unfavourable due to unpredictable interference and unfavourable propagation characteristics. However, advancement in coding and modulation schemes as well as new developments in semiconductor technologies now allow favourable propagation in these frequencies. This allows cellular communication at millimetre waves (mmWaves) using large antenna arrays. Among others, the 28 GHz frequency band has been suggested and is being studied as a likely candidate in mmWave system deployment, that provides a large amount of bandwidth compared to those available in lower frequencies. Deployment of mmWave technologies means that many base stations (BSs) will have to be deployed to provide sufficient network coverage, resulting in Ultra-dense networks (UDN), due to the small wavelengths of the mmWaves, which means that the propagation distance is shorter in comparison to the lower frequency transmission that have larger wavelengths. This means that densely populated urban centres would be the first candidates for deployment of 5G using mmWaves. [4]

The proposed formula for network energy efficiency is:

$$\text{Network Energy Efficiency} = \frac{\text{Total Traffic Delivered to User}}{\text{Total Power per User}} \quad (1)$$

However, in this thesis, the analysis is done per site and a different equation (18) is used.

This thesis analyses energy consumption and efficiency in mobile networks in various scenarios at the 28 GHz and at 2.1 GHz frequency bands. The simulations are done in dense urban environment scenarios to project the likely deployment areas of 5G networks. System performance is evaluated and then a comparison is done on the energy efficiency of the two propagation frequencies. In this thesis, power efficiency and energy efficiency have been used interchangeably.

2. ENERGY CONSUMPTION IN MOBILE COMMUNICATION NETWORKS

2.1 Evolution of Mobile Communications

Mobile networks standards are spoken of in terms of generations. From first generation, hereby referred to as 1G, second generation (2G), (3G), (4G), and (5G) , there has been marked changes to network architecture and configuration through the generations, in part due to the advancement in technology. Every new cellular technology has seen an increase in mobile subscribers, in both voice and data sectors, due to the rapid uptake by consumers. Today, 2G, 3G and 4G cellular networks exist simultaneously in many regions of the world.

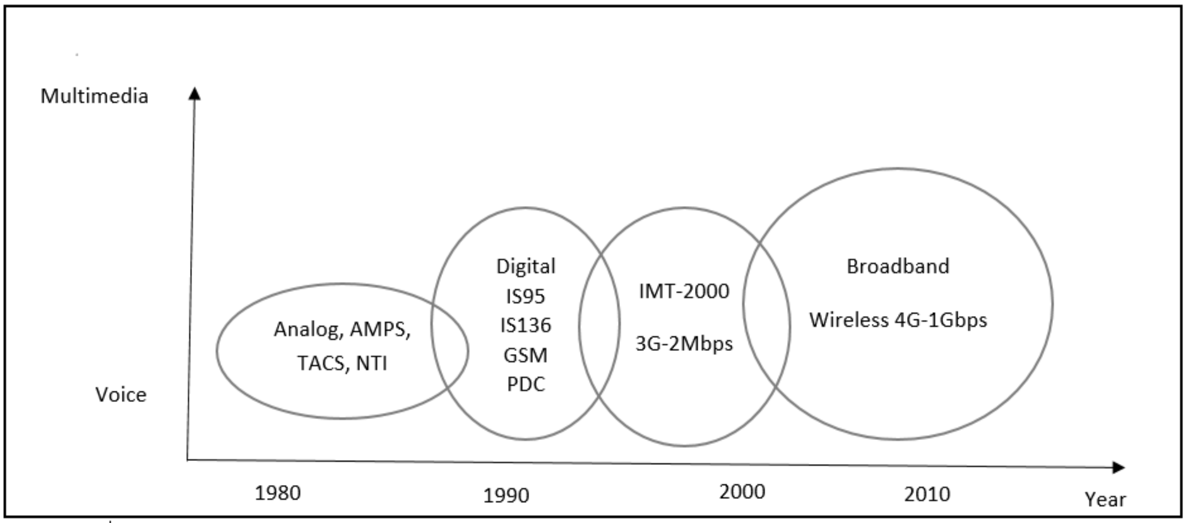


Figure 1. *The mobile network evolution [5].*

Figure 1 shows the general mobile evolution and the major changes that are involved in every generation. Subsequent generations of mobile networks were developed to meet a need that arose in the use of the previous generation. For example, 3G laid more emphasis on data in comparison to 2G.

The first generation mobile technology was developed in the 1970s by Bell Labs [6], and rolled out in the 1980s. It was majorly used to support the existing fixed telephone networks and introduced mobile voice services. The core idea with 1G was the introduction of mobility. A geographical coverage area was split into cells, and each cell was served by a base station. Licensed spectrum was sold to mobile network operators (MNOs), and they deployed BSs to provide access to subscribers, thereafter the frequency re-use concept was introduced to use the spectrum more efficiently. Uptake of mobile telephone services was weak, and voice services remained the most dominant in generating revenues. The cellular network was analogue, and faced several challenges, which included lax security that resulted in interception of phone calls and theft of airtime. Frequency division multiple access (FDMA) was utilized in 1G, and that resulted in poor spectral efficiency, requiring large spectrum gaps between users to reduce or avoid interference, and only one user was supported per channel. Scalability problems were a big issue in 1G, because the devices in use were very large and heavy. They also had heavy power and inefficient power consumption, and they were also. [5]

The global system for mobile communications (GSM), 2G, a standard based mobile telephony service is a digital wireless technology that utilizes digital signals for voice and data transmission, with speeds of up to 64 kbps. One of the biggest achievements of GSM was the development and introduction of the short message service (SMS). Initial 2G technologies were based on time division multiple access (TDMA) and voice encoding enabled compression of voice, enabling multiplexing of multiple users for each channel. However, to reduce interference, as in the case with 1G, large frequency gaps were required, and the users experienced hard handovers that increased the frequency of dropped calls reducing user experience. Later, in the initial stages of 3G development, code division multiple access (CDMA) was introduced. CDMA uses the same spectrum available to support much more users than TDMA, meaning more voice capacity, and encryption meaning better security compared to 1G. Another development in 2G was the introduction of the general packet radio service (GPRS), that was introduced to provide data services. This marked a huge evolution in mobile telephony and data services. There was a marked uptake of 2G services. Although most of the traffic was voice, demand for data services increased, especially as the uptake of the internet and email was also on the rise. However, the data rates were very limited, and enhanced data rates for GSM evolution (EDGE) was introduced with a maximum data rate of 384 kbps. [7]

While 2G overcame the previous issues with 1G and was widely adopted, there was in insatiable demand for higher throughput. The 2G data rates were very slow and the networks could not handle the high data demands. The International Mobile Telecommunications-2000 (IMT-2000) was introduced as a 3G network. The result was the widespread introduction of broadband internet which had introductory speeds of up to 2 Mbps, that were much faster than those offered by EDGE at the time. In Europe, the 3G standard adopted was Universal Mobile Telecommunications System (UMTS), a wideband code division multiple access (WCDMA) based 3G standard. There was a corresponding development in mobile phone technology, with the introduction of the era of the smart phone. The development in the proliferation of the use of smart phones led to a corresponding increase in the development of applications and compression algorithms that is still on the rise today. Users can stream videos or even access mobile television on their smartphones. Data transfer was by packet switching, and voice calls by circuit switching. WCDMA and direct sequence spread spectrum (DSSS) modulation are used in 3G for radio transmission, employing a channel bandwidth of 5 MHz, and can accommodate up to 100 simultaneous voice calls. The use of WCDMA took advantage of adaptive modulation to increase data rates for users who had better signal quality. This enabled introduction of the mobile broadband services by optimizing data channels where the channels were split into intervals of time, enabling a single user to utilize all the resources at once. The introduction of user scheduling increased the overall channel capacity. Global roaming was another feature that was introduced in 3G. [8]

The data rates offered by the initial 3G cellular system became insufficient as uptake of smartphones increased, necessitating a need to increase the offered data rates. high speed packet access (HSPA), which is the amalgamation of two protocols, high-speed downlink packet access (HSDPA) and high-speed uplink packet access (HSUPA) was introduced to increase the downlink and uplink speeds respectively [9]. Energy consumption became a focus in 3G because of the increased data transmission rates and use of legacy protocols as well as the mobile specific architectures. To alleviate this problem, many MNOs imposed limitations on data usage, which was not well received by their customers [5].

The past decade has seen a lot growth in internet users, with increased growth in both mobile broadband subscribers as well as increase in internet speeds, and it has become part and parcel of our daily life. Most of the connected wireless devices are smartphones, resulting in high demand for multimedia content. Whilst 3G could offer decent download speeds, it could not match up with demand of High Definition (HD) content, which required faster data throughputs. Some MNOs rolled out Wi-Fi networks to offload the 3G networks in areas with heavy demand, but as prices of data dropped, demand for mobile broadband rose. Mobile broadband is considered such a necessity that in July 2010, Finland became the first country in the world to make access to broadband internet access a legal human right. Service providers are mandated to provide a minimum of 100 Mbps [10] for all citizens, by 2015. Finland is one of the most connected countries in the world with an estimated 95 percent of the population having access to the internet [11]. Globally, better smartphones were developed with the ability to process information as personal computers did, but had the advantage of being smaller in size, and hence portable. Presently, a wide variety of applications have been developed for smartphones for services such as video streaming and sharing, and even global positioning system (GPS) navigation. Ultra-high definition (UHD) video content and television content are a recent entrant into this market, alongside live streaming, all requiring even faster data rates for steady streaming. Considering the increasing demand and connected devices, better mobile broadband networks were needed. Long Term Evolution (LTE) was developed by the Third Generation Partnership Project (3GPP) as a 4G wireless broadband technology. The International Telecommunications Union Radiocommunication sector (ITU-R) specified the 4G requirements. Peak service speeds were set at 100 Mbps, providing more data capacity with faster and better mobile broadband.

The 4G cellular network was deployed within the existing frequency spectrum, some of which were originally used to deploy 2G, which is advantageous to the MNOs because they reuse the same spectrum for both technologies. Orthogonal frequency division multiple access (OFDMA) is also used in the downlink in 4G, allowing for wider channels that supported bandwidths of up to 20 MHz. The use of OFDMA mandated the widespread use of advanced multi-antenna technique, multiple-input and multiple-output (MIMO) techniques providing spatial diversity, which increased connection stability, reduced latency to improve user experience. A high signal to Noise Ratio (SNR) improves the coverage and achieves high throughput. [4]

One major difference between the three commonly used cellular technologies is that 4G supports all-Internet Protocol (IP) services, including messaging and voice call services commonly known as Voice over LTE (VoLTE) much like the wired broadband does. Another difference is a simplified flat ip architecture core network. With an all ip network, 4G eliminates the circuit switched part of the core network. The result is a flattened architecture. It is important to note that 3G and 4G exist side by side, and improvements on 3G have continued being released for more data capacity. The third difference is in spectral efficiency. 3G is estimated to have eight times the spectral efficiency of 2G, and 4G is estimated to have 20 times the spectral efficiency of 2G.

The next frontier is 5G, and the future of connectivity is to have everything connected. Internet of Things (IoT) would be the biggest differentiator from 4G. There have been many discussions on the 5G technology requirements. So far, some of those that have been put forward include:

- end-to-end speeds from 1 to 10 Gbps
- end-to-end latency of less than 1 millisecond
- perception of 100% geographical network coverage and 99.999% network availability
- support for 10 to 100 times number of connections compared to those connected today
- longer battery life in low power devices
- up to 90% reduction in energy consumption by the network. [8]

To meet the large demand for mobile broadband services, MNOs have made use of network densification practices, that have given rise to heterogeneous networks (HetNets) especially in crowded areas. HetNets in modern mobile communications are implemented as hybrid networks using diverse types of cells, such as macro cells, micro cells, pico cells and femto cells as well as different access technologies. A HetNet could, for example, combine GSM, UMTS, LTE and possibly Wireless Fidelity (Wi-Fi), using different frequencies and configured in a way that they operate together seamlessly. Figure 2 shows an example of a HetNet.

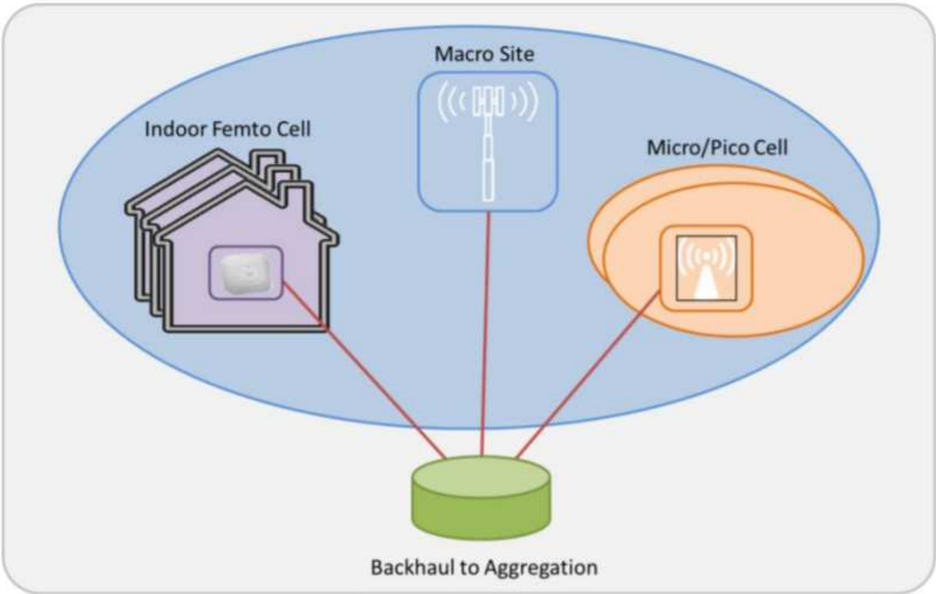


Figure 2. *General implementation of a heterogeneous network [12].*

The core idea behind HetNets is that the macro cells are used to provide the required geographical network coverage, while the micro and picocells are then used to enhance capacity in areas with high demand as shown in figure 2. Wi-Fi and femtocells are mostly deployed for indoor use. HetNets are a concept that is well established within LTE networks. [13]

2.2 Considerations in Energy consumption

One of the considerations for MNOs regarding energy consumption is the increase in global awareness on climate change that is driving the world towards green and renewable energy sources such as hydropower, geothermal, solar and wind energy, and doing away with fossil fuels, coal and nuclear energy sources. There are many aspects and causes of climate change that occur naturally, however, man-made activities are the greatest concern, because they are reported to accelerate the warming of the planet by greenhouse gases (GHG), whose primary source is in the production and use of energy. The International Telecommunication Union (ITU) estimated that the information and communication technologies (ICT) sector is responsible for generating about 2.5 percent of total global GHG emissions. One of the fastest growing contributors to GHG in ICT sector come from the increased use of user devices that need power and radiate heat, increase in the processing and transmission power of user devices, as well as continuous use of these devices. [14]

Considering that IoT is the next big thing in the evolution of communications and the internet itself, the concerns are justified, because it means that an increased number of devices will be interconnected and in use. In 2010 alone, the number of devices estimated to be connected to the internet was 12.5 billion, while the world's human population at the time was estimated at 6.8 billion, which shows that the number of devices connected was more than the human population, meaning the number of devices connected were 1.84 per person. Extrapolation of this data shows that the predicted number of devices connected to the internet by 2020 will be about 50 billion. [15]

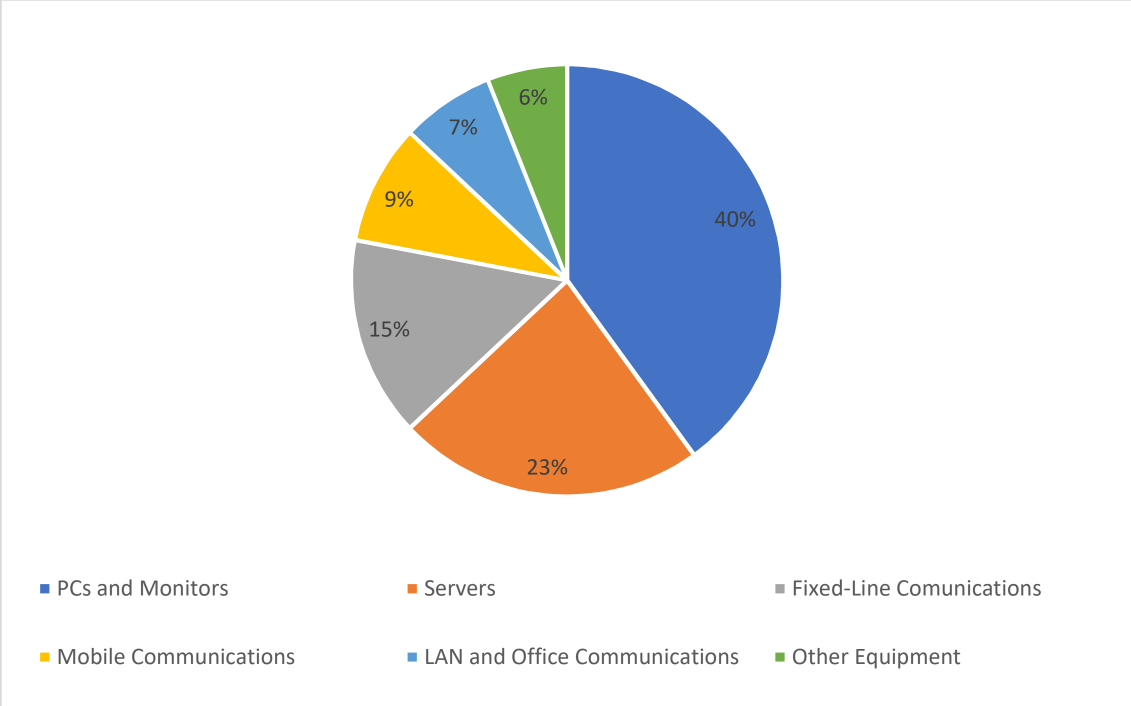


Figure 3. *Breakdown of energy consumption in the ICT industry [16].*

Broadband and telecommunication networks consume considerable amounts of energy as shown on Figure 3. If consumption of energy by servers is considered, the amount of energy consumed by telecommunication networks are almost 50% of the total energy consumption of the ICT industry.

Today's mobile networks are designed for continuous operations. They are supposed to offer a high level of reliability. Combining those two conditions with high traffic capacity resulting in high data rates without a lot of consideration for energy performance, although that is now changing. Aside from peak time traffic load increases, most access nodes and cells have most often very little traffic. With continuous operations of the current mobile networks, presence or absence of traffic makes very little difference to the overall network energy consumption, because it is not dependent on the load. The European Commission, jointly with other groups and research centres, commissioned studies to assess and address the environmental impact of the ICT industry. The ICT for Energy Efficiency (ICT4EE) forum was launched in February 2010, inviting the ICT industry to develop a framework with the aim of measuring the industry performance in energy and environmental issues, and set the industry's energy efficiency targets [4]. This forum represents the ICT industry players in Europe, Japan and America. The European Union (EU) targets a reduction of 20% in carbon dioxide (CO_2) emissions by the year 2020 [17].

Another consideration is in the cost of energy and other business considerations. MNOs, like any other business, have their priorities in turning a profit, reducing cost and providing value for their shareholders, even as they provide what is now considered a crucial service. On the one hand, the constantly changing technology in mobile broadband, coupled with the increase in demand have presented unique challenges to MNOs in terms of planning and implementing the networks, and require heavy investments in network upgrades. On the other hand, the unit cost price of consumed data has been on a steady decline over the years, and now consumers in some regions of the world enjoy unlimited mobile broadband data at a flat rate. Mobile network upgrades are often developed and implemented as an advanced plan, for example, a five to 10-year plan to upgrade to meet certain requirements and meet demand and coverage, and frequently, energy consumption is often secondary in this plan. Nokia Solutions and Networks [3] asserts that in mature markets, energy consumption for an operator is about 10 to 15 percent of the total operational expenditure (OPEX), and up to 50 percent in developing markets due to the high proportions of off-grid cells. The telecommunication sector in general constitutes about 4% of the electricity consumption globally. While Green radio is a topic that is gaining traction, the most crucial driver in the decision-making process is a business one: the increasing cost of energy. The price of energy is often increasing, and energy from non-renewable sources is finite, in contrast to the growing demand for energy from developing countries, it is safe to conclude that energy prices will keep increasing into the foreseeable future [12].

One way of cutting energy consumption is in network modernization by upgrading and replacing older equipment with more energy efficient ones. A reduction in energy consumption will automatically reduce energy costs. However, upgrading a network to minimize energy consumption and reduce carbon emissions increases a MNO’s capital expenditure (CAPEX), and ultimately, this cost could outweigh the benefits gained in the form of costs saved from energy consumption.

2.3 Energy Consumption of Cellular Networks

One of the major downsides of providing reliable mobile broadband services requires that MNOs must continuously increase the number of installed base station for overall geographical coverage. This means that globally, there is an increase in the number of BSs, which are the major power sink in cellular networks. We split the cellular network into its two major entities; radio access network (RAN), and core networks and later we consider the user equipment (UE).

Radio access network equipment and components account for 60% to 80% of the cellular network’s energy consumption as shown on figure 4, and therefore the main target of studies and methodology in reducing energy consumption [12].

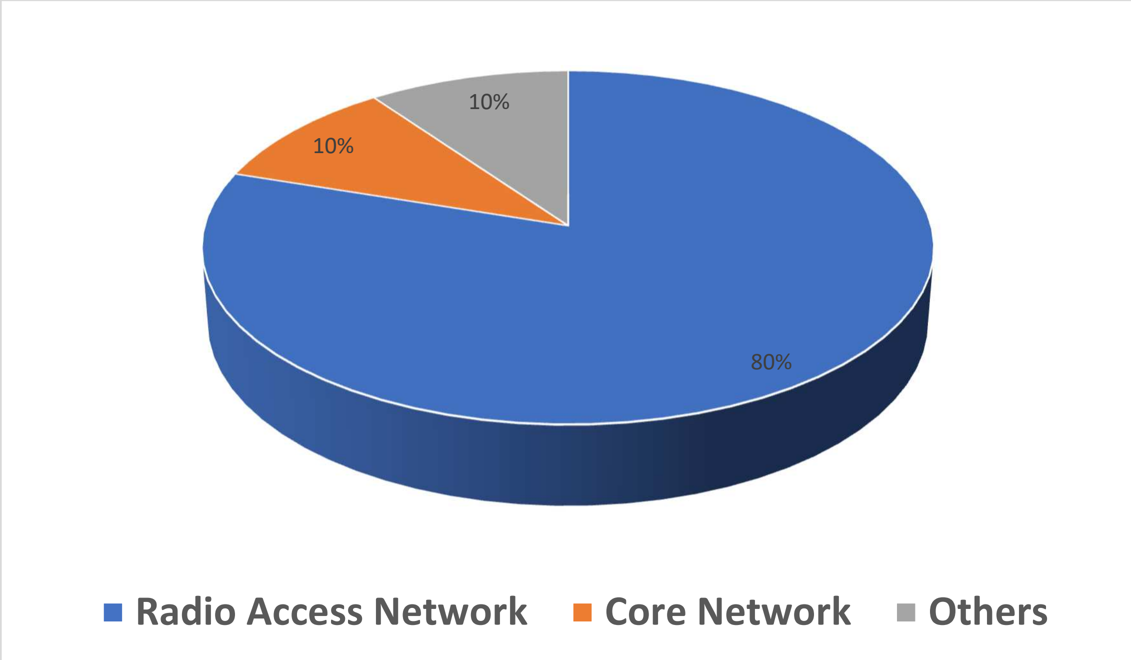


Figure 4. *Total energy consumption breakdown in cellular networks*

The core network is central in providing charging and billing, user authentication, data aggregation, invocation of services, call control and switching, hosting subscriber databases, and acting as gateways to access other network functionalities. RAN provides access servers to services offered on the network to subscribers, or user equipment via BSs. A base station is defined as the equipment used for the communication with mobile stations as well as the backhaul network.

2.4 Energy consumption of Base Stations

The basic components of cellular networks are base station sites, which are easily identifiable by the antennas on rooftops or tower masts, while supporting equipment is usually housed indoors, or in a cabinet. Base stations vary in size, shape and components depending on the vendor as well as the technology in use. Figure 5 shows the typical structure of a cellular BS.

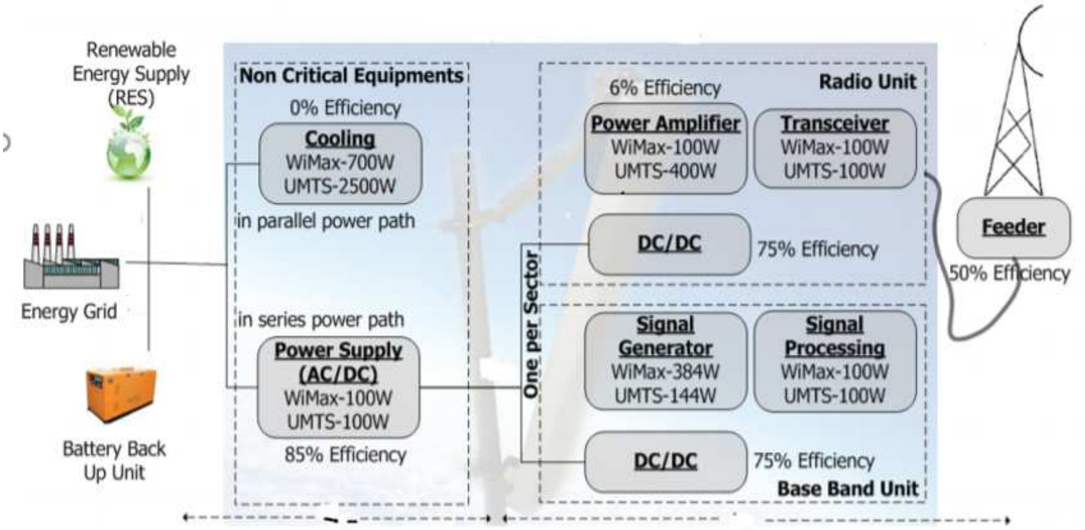


Figure 5. *Typical structure of a base station [16].*

The basic components across all vendors and technologies are similar, comprising of antennas for transmission and receiving of signals, the BS equipment otherwise referred to as base transceiver station (BTS) in GSM, node B in UMTS and evolved node B (eNB) in LTE. There are also power supply systems that include alternate current to direct current (AC/DC) power converter modules, and digital and analogue signal processors. There is also additional equipment that may be found within the BSs that provide auxiliary functionalities, including but not limited to air conditioning and climate control equipment, battery backup, power backup generators, security and monitoring.

It has been established that BSs take the lion's share of energy consumed in cellular networks, and therefore it is of significant importance to identify elements contributing to this. In GSM networks, BSs can be sectored and in theory, can cover an area with a diameter of up to 70 km, but 5 km in practice[18]. This coverage area is also known as a cell. However, the coverage radius is dependent on the number of users that are simultaneously served by the cell in 3G for example. In dense areas, cell area is significantly reduced to a few kilometres, and sometimes to a few hundred metres in areas such as airports, markets, malls, train stations and such heavily populated areas. Here, we shall break down the energy consumption of various components of a BS.

2.4.1 Radio frequency unit

Radio frequency (RF) equipment consumes the largest amount of power in a base station. The biggest culprits include the power amplifiers (PA) plus the transceivers and cables which consume around 65% of the total energy consumption of the BSs, with efficiency values ranging between 40% and 50% . Broad bandwidths and demand for higher data rates often mean that the PA operates in the non-linear regions, resulting in peak to average power ratio (PAPR) of around 6 dB to 10 dB. As a result, research is focusing on linearization and energy efficiency of the PA. Conventional power amplifiers utilize a high voltage, which is constant. This power is then applied to the transistors in the PA, that are high-power high-frequency. This is done to prevent output signal distortion especially when the amplitude is maximized. However, in current cellular communication network systems that utilize WCDMA and OFDMA, there are large amplitude variations over time, meaning that a lot of energy is lost when the modulated signal amplitude is small. [25]

2.4.2 Baseband unit

The baseband unit (BBU) normally consists of the base band transmitter, receiver as well as a cooling fan. This unit is responsible for digital data processing, which is then fed into the RF unit. In some designs, this unit also contains a system clock that is used for BS synchronization. It could also house the main power unit that is used to distribute power to itself, as well as to the RF unit. With later releases of UMTS and LTE, there has been an increase in the need for the BBU to support features such as coordination and site optimization. This increases the processing requirements and therefore, increasing the power consumption.

2.4.3 Feeder cables

The feeder cables, as shown in Figure 5, are used to connect the RF unit to the antenna ports. Attenuation happens as the RF signal travels from the RF unit to the antenna, which also depends on the length of the cable as well as the transmission frequency in use. This loss is defined as decibels per unit length, which obviously means that longer cables amount to greater losses. Since this loss also depends on the transmission frequency, higher frequencies mean higher losses. The losses in the cables are broadly categorised as resistive loss and dielectric loss [12]. Resistive loss is as a result of conductor resistance and current that flows in these conductors, which is limited due to the skin effect, resulting in heat dissipation. The skin effect is a phenomenon where the AC current travels near the surface of a solid conductor instead of traveling near the centre. This means that the cross-sectional area for the transmission of the current in the conductor is reduced, and its resistance is increased in comparison with a conductor that is transmitting DC current.

Resistive losses increase as the square root of transmission frequency, but dielectric losses are linearly dependent on frequency, and are not dependent on the cable size. Therefore, resistive losses are dominant in lower frequencies, and dielectric losses are dominant in high frequencies. These losses in the feeder cables are all dissipated as heat, which means that the cables pick up interference. A loss of 3 dB is often assumed, meaning that only about a half of the RF module power is transmitted to the antenna. Normally, other connections are made between RF modules and the antennas which could play a small part in losses. These include splitters and combiners.

2.4.4 Air conditioning and cooling

From the RF unit to the cables, a big proportion of energy consumption loss at the base stations is therefore dissipated as heat. All the equipment that carry electronics have a specified range of operating temperatures. In absence of any cooling equipment, and depending on BS site locations and weather season, temperatures in the cabinet could rise beyond this range and effectively damage the equipment or, if safety measures are inbuilt, cause the equipment to shut down. This is the reason why BS sites are equipped with cooling equipment, and sometimes air conditioning equipment in cases where the BS site is a hub, or where there exist very harsh weather conditions. This equipment maintains the temperature of the cabinet at a specific range. Still, it is estimated that cooling accounts for 25-30% of the overall energy consumption of a BS [12], [16].

2.4.5 Backhaul

Many studies done on the energy consumption of mobile networks have been done on the aggregated consumption in the BSs and largely omit or ignore the contribution of the backhaul network [19]. While the backhaul network layout is greatly affected by the BSs site deployment, the energy consumption impact on the overall network cannot be ignored.

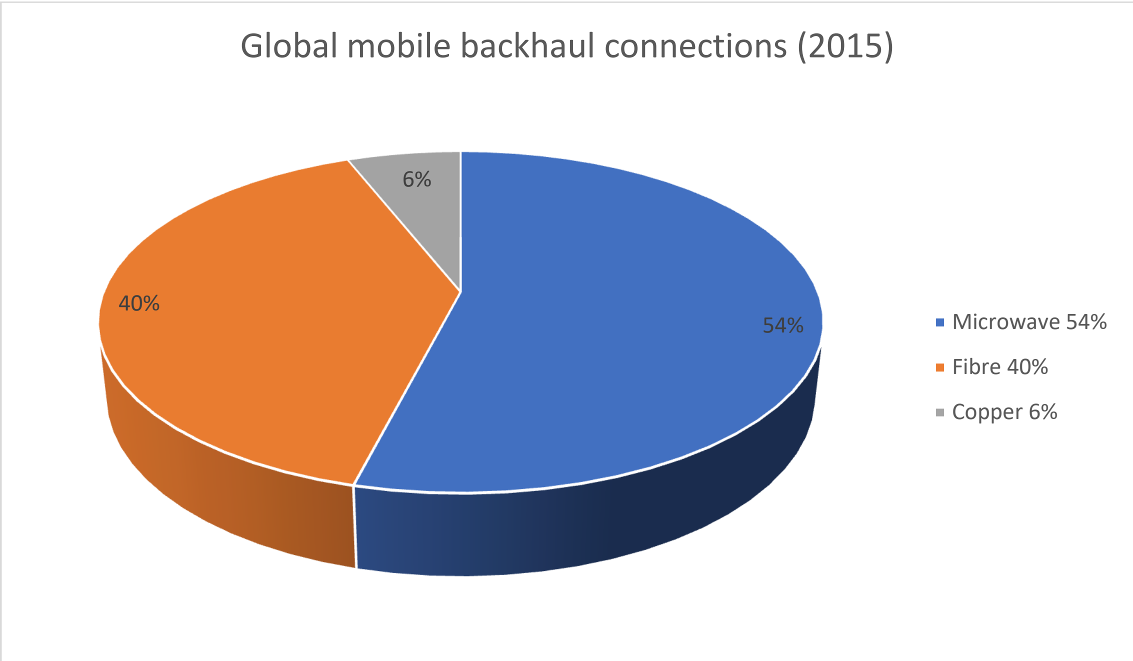


Figure 6. *Installed Global mobile backhaul connections (2015).*

Currently, as shown in Figure 6, conventional methods used for backhauling macro BSs are microwaves, copper cables and optic fibre. In some remote regions of the world, a satellite connection is used for the mobile backhaul when previous methods are not viable because of lack of communication infrastructure and power between base station equipment and core network equipment. These methods have their own different advantages and disadvantages. Microwave links offer simple deployment, low cost and short time to market advantages to MNOs, while optic fibre is relatively expensive and is costly to deploy, it has long term advantages in terms of increased capacity offerings. Backhauling mobile traffic through satellite also has its own challenges. One of which is the dealing with traffic that is sensitive to delays, low synchronization and low data throughput, as well as cost performance. It is quite expensive to transmit data via satellite on a large scale. Tombaz et al. [20] concluded that power consumption in the backhaul increases with the use of low power base stations, and is significant in heterogeneous network deployment. However, they concluded that the effect of energy consumption in the backhaul in macro BS network deployment, and therefore, a trade-off is considered between use of macro sites and low power base stations. They also concluded that the latter gives a better overall network reduction in energy consumption.

2.5 Energy consumption of the core network

The core network is the backbone of a mobile network. This is the most efficient part of the mobile network today with gains in making it energy efficient occurring in the last decade. There have been achievements in power supply efficiency and monitoring, with improved core network architectures. However, because the core network equipment is housed indoors, there is a limited capacity for heat extraction in confined spaces, and therefore, the use of mechanical fans, heating, ventilation, and air conditioning (HVAC) systems for this heat extraction means that large amounts of energy are consumed in data centres housing the core equipment. The other factor that is contributing to low energy efficiency is the low efficiency in the use of the network elements. The routers in current core networks are designed and implemented in ways such that a typical packet could transit through multiple hops before reaching its destination instead of using direct routes. This could result in unnecessary packet switching and processing.

Another issue is the over-provisioning of the core network. Due to increased demand and usage of networks, some MNOs over-provision services to meet these demands especially at peak times to enable the network to handle huge traffic loads. These core network elements and designed to maximise their performance. As demand for data grows, so does the number of the equipment required to meet this demand. Resources such as memory, bandwidth and processing power are over-provisioned, which means that in low peak times, these resources are underutilized, or laying entirely idle, and wasting energy.

Core network equipment is also concentrated in data centres which also house servers, large scale data storage facilities, networking equipment all connected to the power distribution unit (PDU) and various uninterruptible power sources (UPSs). These two power systems have very high-power losses in the form of heat as a result of AC/DC/AC power conversions. Power consumption of the telecommunications equipment is also affected by the environment, as well as data traffic.

2.6 Energy Consumption of User Equipment

The mobile phone and other peripheral devices, hereby referred to as the UE has become such an integral part of our lives that it is difficult to imagine life without one, even though they have not been in existence for long. Users need them for work and keeping in touch with friends and loved ones. Nowadays, smart phones play the role of the clock or watch, calculator, calendar, diary among others. They have replaced almost all personal electronics, including the personal computers (PC). Phones today support more than one cellular technology: 2G, 3G, 4G and Wi-Fi, Bluetooth and other technologies for transfer of data. User devices should not be ignored when studying the overall energy consumption of cellular networks.

2.6.1 The Evolution of the mobile phone

The present view of the mobile phone is that of the smart phone. However, the smartphone is a relatively new device technologically, and the mobile phone itself, as we know it today, has been in existence for less than 50 years. The first handheld mobile phone was developed and tested in April 1973 by Motorola. It was another decade before mobile phones were manufactured and released for the mass market in 1983, again, by Motorola. This phone weighed nearly 1.1 kg, and for 30 minutes of talk time, a charging period of 10 hours was needed. This mobile came at a pricey sum of 4000 US dollars, and therefore was only affordable to the rich. It was large, bulky and had huge external aerials, making it impractical to carry in one's pockets. In 1989, Motorola released a phone with a foldable keyboard cover, setting the standard for the famous flip phones that gained popularity in late nighties and early 2000s. Unlike today, these phones were only used for voice calls.

With the launch of GSM in 1992 [21], phones were mass produced with cost-effectiveness in mind. Nokia joined the fray and released mobile phones with digital displays. The SMS was invented as well as mobile gaming. By now, the aesthetics had started improving and the design was sleeker compared to the early mobile phone designs.

The last half of the 1990s were defined by the introduction of coloured phone screens by Siemens [22], the phone vibrate feature by Motorola and on the widespread use of GPRS and the World Wide Web, the email was carried on the phones as well. Customization of front panels and reduction or elimination of the external antenna gained ground in 1997. This marked the start of fashion conscious and aesthetically pleasing mobile phones.

In 1999, Nokia released the first phone to feature wireless application protocol (WAP) for browsing the internet. Although this standard had some popularity in the early 2000s, it was later replaced by other standards, such as hypertext markup language (HTML). Phones with cameras were released in the year 2000, and by the year 2002, the consumers had started to pay keen attention to mobile phone photography that has now become a mandatory requirement on mobile phones. By 2002, some of the additional features included browsing the web, video calling, GPS navigation, predictive text, inbuilt mobile phone cameras, availability of polyphonic ringtones, motion picture experts group (MPEG) layer -3 popularly known as MP3, Bluetooth connections were introduced, removable memory cards and multimedia messaging service (MMS).

The mobile data revolution started in 2003 when 3G implementation offered download speeds of up to 2 Mbps. The front facing camera was also introduced, although its usage did not become immediately popular. Waterproof phones were also introduced at this time. Near-field communication (NFC) was also introduced in 2006 by Nokia.

The year 2007 revolutionized the mobile phone as we know it today. This is the year that the first smartphone was introduced into the mass market. Although Apple's iPhone is credited for introducing the smart phone, LG was the first to introduce the touchscreen to the market 6 months before Apple released their own [23]. However, Apple was a more superior brand and the iPhone had a superior capacitive touchscreen. Apple introduced a myriad of mobile apps through the Apple Store and started their dominance on the smartphone market. Wireless charging was also introduced to the market in 2009 [24]. It is important to note that from the introduction into the mass market, mobile phone manufacturers had also concentrated on the aesthetics, and reducing the size of the phone as much as possible, in tandem with introducing new and distinguishing features.

In the 2010's, the smart phone became a constant companion in life. Voice recognition was introduced to the market by Google's Voice and Apple's Siri. In contrast to the early 2000's where the manufacturers were reducing the size of the phones for portability, in the current era, the opposite is true, screen sizes are ever increasing due to increased demand in video calling and streaming services, and also increase in mobile apps to do everything from reading to payments. Fingerprint readers and Iris recognition are now major security features in the current smartphones.

2.6.2 Energy Consumption in Mobile Phones

Daily energy consumption of mobile phones in the early 90's was 32 Wh, and now it is approximated at 0.83 Wh per day, including consumption by terminals and battery chargers [25]. With the increased demand and use of mobile broadband, battery life is becoming a very critical factor. Smartphones run on batteries that are limited in both size and energy storage capacity, due to limitations on size and weight of the mobile device [26] . Smart phones in general have limitations in battery life due to applications that run and that require intensive computations, this limitation will become even more pronounced in the coming years due to the increased usage of smartphones in daily life. Energy efficiency is therefore paramount to understand and improve the efficiency of the limited battery power.

In order to understand and manage energy efficiency, it is important to know how power is consumed in a smart phone. Niranjan et al. [27] found that, energy consumption of smartphones was tied to the transfer of the information load characteristics, not just the total size of the load. In addition, they found that when utilizing 3G connections, nearly 60 percent of the energy was wasted when the phone remained in a high-power state even after a data transfer was complete. The phone stayed in this state for 12 seconds. In comparison, when using 2G, the phone remained in the high-power state for half the time, 6 seconds, although more energy was spent in the transfer of data due to the low data rates. Their third observation on Wi-Fi was that the data transfer was more efficient compared to the data transfer in 3G, even though the overheads were comparable to the high-power state energy consumption of 3G. [27]

A radio resource control (RRC) mechanism known as discontinuous reception (DRX) is often used in mobile phones to conserve the device's battery in LTE networks. This is especially important because of the numerous applications that are often running in smart phones. These applications are often connected to the network even when the user is not actively using the mobile phone or the applications themselves, meaning that the UE is often transitioning between the connected state RRC_CONNECTED and idle state RRC_IDLE which will often drain the battery. By default, LTE required that the mobile always monitor the physical downlink control channel (PDCCH) which sends out control signals to the mobile device. This forces the mobile phone to monitor PDCCH continuously and therefore the device must be in the connected state continuously. For the DRX feature to work on the mobile devices, it must be activated on the network. The DRX mechanism allows the mobile phone to only monitor the PDCCH channel when data related to the specific devices transmitted in both the uplink and downlink transmissions. The UE will then only wake up during the DRX ON period, monitor the PDCCH channel and then sleep during the DRX OFF period. However, the attainable UE energy savings are dependent on the DRX cycle, with a longer DRX cycle resulting in higher energy savings but with a trade off on degradation on data packets delays. Figure 8 shows a typical DRX mechanism in the RRC_CONNECTED state in an LTE network. Timers configured by RRC in this mechanism are: on duration timer (T_{ON}), DRX inactivity timer (T_I), Long DRX cycle (T_{LDC}), drxstartoffset and short DRX cycle (T_{SDC}). [28]

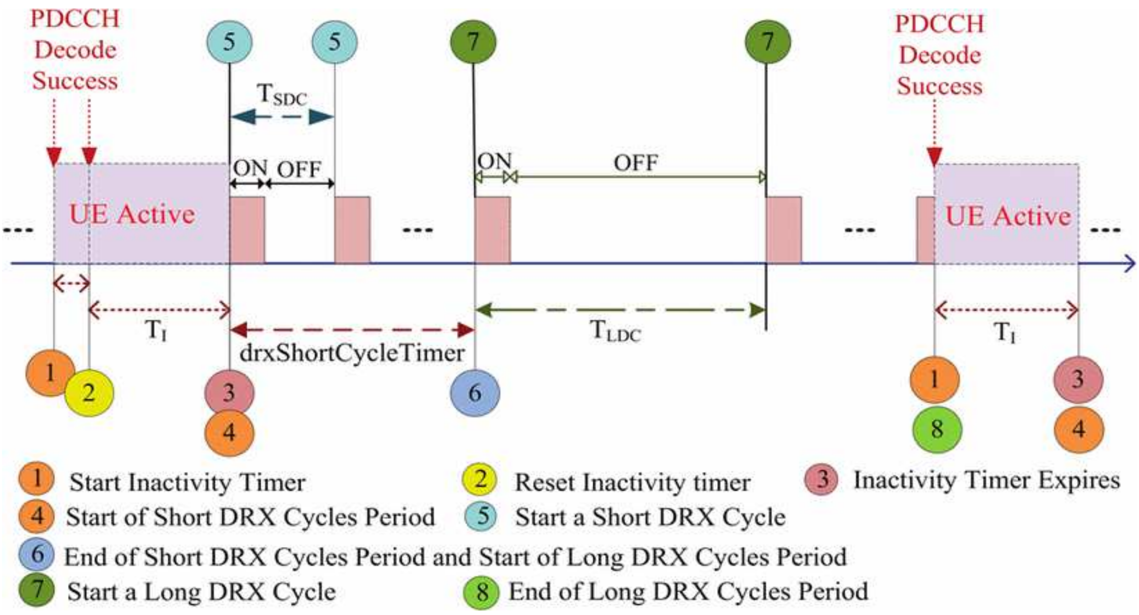


Figure 7. *A typical DRX mechanism in LTE [28]*

The UE runs continuously and monitors PDCCH when T1 is active, after which the T1 tier is reset and the UE then triggers TSDC to enter the DRX short cycle. which repeats the short cycle till the long DRX cycle TLDC is triggered. In the absence of the short cycle, TLDC is usually triggered immediately timer T1 ends.

Carroll and Heiser [26] run an analysis on an android phone while it was on the suspended state and in the idle state with the backlight on and the results of their experiment are presented below.

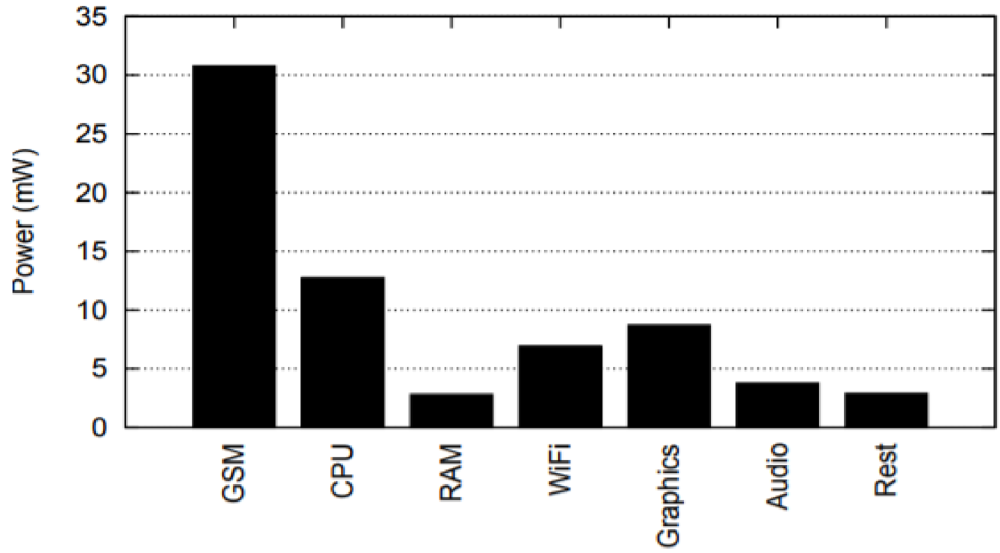


Figure 8. *Average power consumption in suspended state [26].*

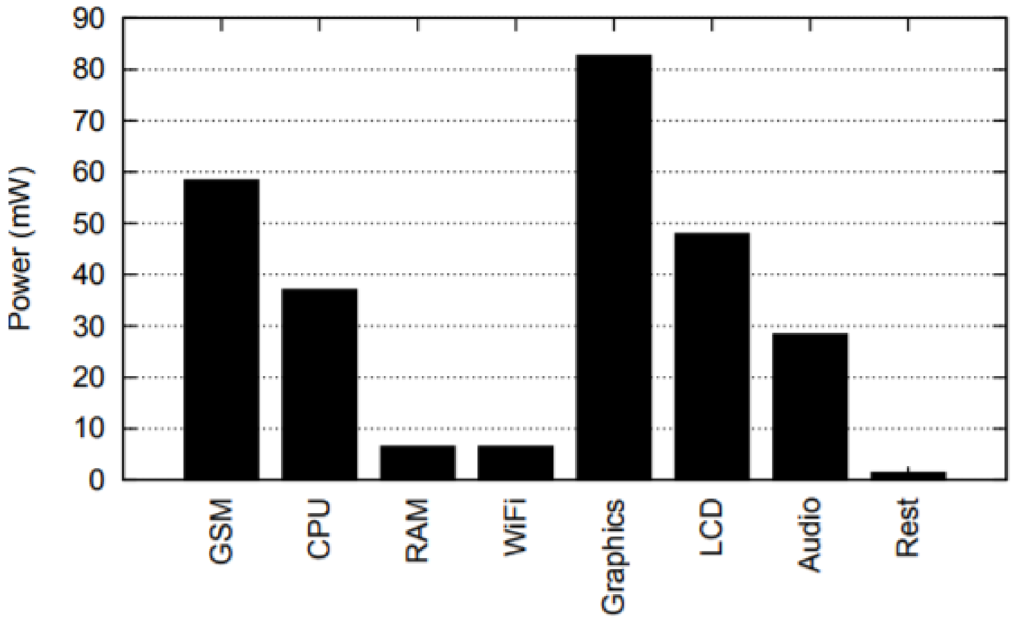


Figure 9. *Average power consumption in idle mode and backlight off [26].*

The android device was forced into the suspended state for 120 seconds and the power was measured. This procedure was repeated 10 times. The observed results are given in figure 8. The average aggregate power was given as 68.6 mW. The GSM subsystem consumed approximately 45% of the overall power consumed by the device in suspended state, while the random-access memory (RAM) consumed less than 3 mW of power despite being in full state. The results of the test when the device was in idle state are presented in figure 9. The experiment was run 10 times as in previous state. The results showed that subsystems that were display-related consumed the largest proportion of the overall power consumed by the device. These include the liquid-crystal display (LCD), backlight and the graphics chip. In this case, GSM also consumed a large amount of power. It was concluded that brightness of the backlight is the most critical factor when considering energy consumption in user devices, and that aggressive backlight dimming could potentially save a lot of energy. The authors also recommended shutting down idle applications in smartphones, as much as possible to save on battery life. [26]

2.7 Energy Consumption due to propagation losses

Radio network plan and optimization is a fundamental requirement of every radio network implementation as well as successful operation of any cellular network. Network planning and optimization saves MNOs both time and money, as well improving radio spectrum efficiency. Network planning and optimization (NPO) involves using the least number of BSs to provide required service is the most common approach. Issues to be considered include analysing the traffic present and coverage requirement of the geographical area, to ensure that a proper analysis of the expected capacity is carried out, which includes traffic distribution and coverage demands. After this analysis, capacity dimensioning is carried out, and a nominal coverage plan is produced. Usually, this is a cell pattern on a map.

The next step in network planning involves surveying of BS location. Whilst a rough location estimation is produced in the first step, suitability is assessed by a site visit. Various countries have laws governing installation of BS antennas and masts. Other issues that are considered are for example, accessibility to electricity connection, terrain and presence of backhauling network, for example, fibre optic cables.

Actual system design follows the BS location surveying. In this step, the type of equipment to be used is determined. This includes the sight structure or enclosure, antenna heights, down tilt, feeder cables among other, after which, the installation and commissioning of the equipment is done. For optimization purposes, drive tests are done and changes to coverage are effected and system tuning is done during the life cycle of the network.

At the planning stages, a calculation of a link budget is done. A link budget is used to calculate and account for power gains and losses in a cellular system from the transmitter, through the transmission medium to the receiver, thus enabling calculation of received power. Armed with the information on the level of the gains and losses, corrective measures can then be used to ensure the system operates within the desired levels, while at the same time minding the overall cost of the system. The most basic form of expressing a link budget is the formula below:

Received Power (dBm) = Transmitted Power (dBm) + Gains (dB) – Losses (dB). (2)

Using the basic formula above, the link budget is deemed sufficient under perfect conditions if the received power estimated at the receiver is sufficiently larger relative to the sensitivity of the receiver in question. If the received power is more than the receiver sensitivity, this excess power is referred to as the link margin. [29]

A radio link budget is however not as simple as the equation (1) above. The propagation environment and resulting gains and losses are considered. Path loss plays a significant role in signal attenuation. The most significant aspect of path loss is due to distance. This loss is due to propagation of the radiating signal over a given distance, which is proportional to the inverse square of the distance, referred to as geometric spreading, as well as the square of the signal frequency. In simple terms, this means that path loss will increase as distance and frequency increases. This is best explained using Friis' transmission equation:

$$P_r = P_\mathrm{t} + D_\mathrm{t} + D_\mathrm{r} + 20\log_{10}\left(\frac{\lambda}{4\pi d}\right)^2 . \quad (3)$$

Where P_r is the receiving antenna's power, P_t is the transmission power of the transmit antenna, D_t denotes the directivity of the isotropic transmitting antenna, D_r denotes the directivity of the isotropic receiving antenna, d is the separation distance between the transmitting and receiving antennas, λ denotes the wavelength of the receiving antenna's effective aperture area. This form applies in cases where $d >> \lambda$.

Methods used to calculate path loss are often very complicated. However, some deterministic models are common, such as ray tracing, ground reflection models and free space propagation model. The free space modelling is used in determining losses due to line of sight transmission from a transmitter to a receiver. Friis free space equation is used, disregarding reflected signals. [29]

$$L_\mathrm{dB} = 32 + 20\log_{10} f_{MHZ} + 20\log_{10} d_{km}. \quad (4)$$

where f represents the transmission frequency in MHz, and d represents the separation distance between the transmitting and the receiving antenna in kilometres. For typical radio applications however, the formula is simplified with the frequency expressed in GHz. Therefore, formula number 4 is then illustrated as [4]:

$$L_\mathrm{dB} = 92.4 + 20\log(f) + 20\log(d). \quad (5)$$

Taking these specific losses into account, a typical link budget expressed as:

$$P_\mathrm{RX} = P_\mathrm{TX} + G_\mathrm{TX} - L_\mathrm{TX} - L_\mathrm{P} - L_\mathrm{RX} + G_\mathrm{RX}. \quad (6)$$

Where P_{RX} is the received power, P_{TX} is the transmitted power, L_{TX} is the transmission path loss, L_{RX} is the receive path loss and L_P is the propagation path loss that includes fading margins, antenna mismatch losses and other losses. G_{TX} is the transmitter antenna gain and G_{RX} is the receiver antenna gain. Propagation loss L_{p} is then broken down to three main components as shown below:

$$L_P = L_O + L_S + L_L. \quad (7)$$

Where L_O represents the average path loss which could be for example free-space path loss. L_L represents shadowing losses and L_S represents multipath fading.

Calculating the anticipated losses in the transmission environment aids in coverage predictions by considering the signal levels, signal-to-interference-plus-noise ratio (SINR), channel throughput and downlink throughput. However, since propagation in an actual environment does not follow the free-space path loss propagation model, other models, such as the Hata model are used in calculation of transmission losses.

After calculation of probable losses, the next step is undertaking a simulation of the network design in a network simulation tool. This gives the planner a chance to change parameters and optimise the network before it is physically rolled out, which saves time and costs. This simulation helps to optimize the location of BSs or how many BSs are required to cover the area under consideration.

After fine-tuning propagation models and calculating the details of the needed equipment, the next step is network implementation or optimisation. After the physical network is implemented, periodical optimisation exercises must be undertaken to ensure that the original conditions hold and that the QoS as perceived by the customer is as expected.

3. ENERGY EFFICIENCY TOWARDS FUTURE COMMUNICATION NETWORKS

One of the biggest undesired consequences of rapid cellular network expansion due to heavy mobile broadband use is the rapid increase in energy consumption and in turn, increase in the CO_2 emissions, and an increase in operating costs to the MNOs. The 5G mobile network is expected to revolutionize how we make calls, from moving networks to redefining the fundamental meaning of a cell coverage area. Another major expectation of 5G network is the perception of 99.99% coverage, which in essence means that many base stations are going to be deployed, to form UDNs, especially in urban areas. To achieve significant energy efficiency, network planning and system dimensioning are critical factors. As pointed out earlier, the current working methodology for most network elements is an always-on mode. Network planning has always been done to guarantee performance, and not achieve any energy efficiency. Therefore, any interventions have to either reduce the total energy consumption of the network elements, or reduce the required operating time of the elements, by, for example, putting BSs that have less loads to sleep.

There are classical and widely used metrics to define energy efficiency in telecommunications networks. The most widely used is the bit-per-joule metric [30]. It is simple and still used today in some studies. This metric is used to represent or compare the system throughput and energy consumption per unit. Energy per bit to spectral noise density (E_n/N_o) is another metric that is used to measure signal strength in terms of the signal to noise ratio (SNR). It is used as a way to predict the performance of a transmission link. Most of these methods can be used in parallel to achieve better energy efficiency levels.

3.1 Green communications

Green communication aims at using energy-efficient technologies in the implementation of communication networks and reducing consumption of energy when possible. Some of the methods used include:

- efficient base stations
- mimo
- self-organizing networks
- turning off components selectively
- hetnets
- use of alternative energy solutions

These methods are explored in detail below.

3.2 Methods used to improve energy efficiency in Radio Access

The conclusion that the BSs are the largest energy hogs in a mobile network brings us to the next challenge; how to fix it. Several of the current interventions aim at reducing energy consumption in the base stations. Energy efficiency of base stations can be achieved at both hardware and software interventions. Since the PA is the largest power consumer in the base station, there are several ways in which this can be reduced.

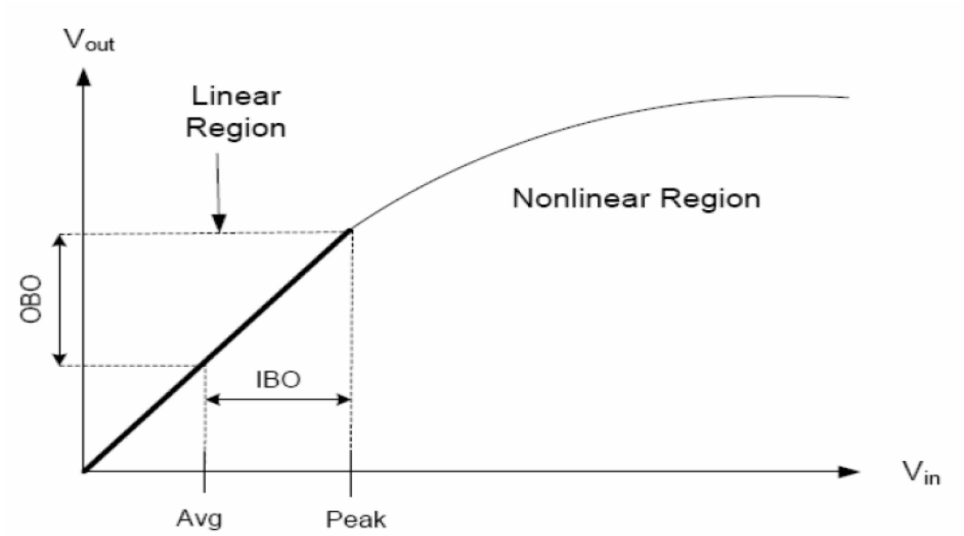


Figure 10. *Typical response of a power amplifier [31].*

Figure 10 shows the amplitude to amplitude modulation response of a typical PA. Increasing the input power does not increase the output power beyond the saturation point. This phenomenon is known as amplitude to amplitude modulation distortion. To obtain linearity, the back-off method is applied with associated input back-off (IBO) and output back-off regions (OBO). The PA increases the power level of a transmitted signal such that the corresponding signal on the receiver side can be demodulated within a predetermined error probability. Therefore, the efficiency and the linearity of the PA are of very high importance.

PA linearization methods can be used to help improve their performance. Some of the linearization methods include; Cartesian feedback, feed-forward, and digital pre-distortion methods [12], as well as envelope elimination and restoration methods [32]. Significant increase in the PA energy efficiency also means that the power consumption of the cooling system will be significantly reduced in return. The 5G network will make use of the MIMO system, and this case, each antenna has its own PA, therefore, significantly impacting on plans to reduce overall network consumption. One of the suggested mitigating practices is activating sleep mode in idle or lightly loaded transmit antennas.

Software level interventions include energy-aware cell zooming, which many MNOs have deployed on 3G and 4G networks. Cell zooming means that a congested cell reduces its coverage area, and the surrounding cells, if not congested, will expand their coverage area to cover mobile users whose coverage falls in the region of that of the congested cell. Cognitive radio and the use of cooperative BSs is another technique that can used to reduce the overall energy consumption. It works by switching underutilised BSs to low power modes.

Another method used to reduce energy consumption is the use of fixed relays. The relays store and forward data and are also used in scheduling as well as routing procedures. Relaying can also be used to convert single hop long links to shorter multihop communication links, which results in less destruction in communication or data packets, which could save power by reducing the need for retransmission of information. However, it increases the cost of the installation of network nodes. While user cooperation relays are more cost effective, they increase the complexity of the network. Cognitive radio is used to manage the power efficiency at spectrum level. Dynamic management of the spectrum can reduce energy consumption, by undertaking efficient spectrum allocation and frequency re-use mechanisms, and efficient channel allocation. [32]

Energy efficiency of the baseband unit can be increased with the introduction of clocks that could be switched on and off on the basis of the BSs loads and use of field programmable gate arrays (FPGAs). [31]

Another method used to save on power consumption in base stations is the use of downlink discontinuous transmission (DTX). This feature has been used for a long time in UEs but is also used on BSs. On the BSs it is known as downlink DTX or cell DTX. This is deployed as a way of allowing the switching off of radio transmitters when there is no information to send. For example, during speech pauses, and enables adaptations on power consumption on the node level. In LTE, the radio transmitters that carry no data or reference symbols can be routinely shut off [33]. The purpose for DTX according to the European telecommunications standards institute (ETSI) is to reduce power consumption in the UE and to reduce the air interface interference levels. An investigation done by [34] to evaluate reduction of power consumption in HetNet macro BSs revealed that there was a marked decrease in macro cell power consumption when the user density is high, which means that the cell did not have any time to go to sleep. In the first scenario, the macro cell had cell DTX activated but the femto cells did not. The results showed that with lower user density, power consumption increased with the increase in the number of femto cells. The indication was that offloading from macro cells to femto cells is only effective in terms of reducing power consumption when the macro cells have high loads. The results of this are presented in the figure below.

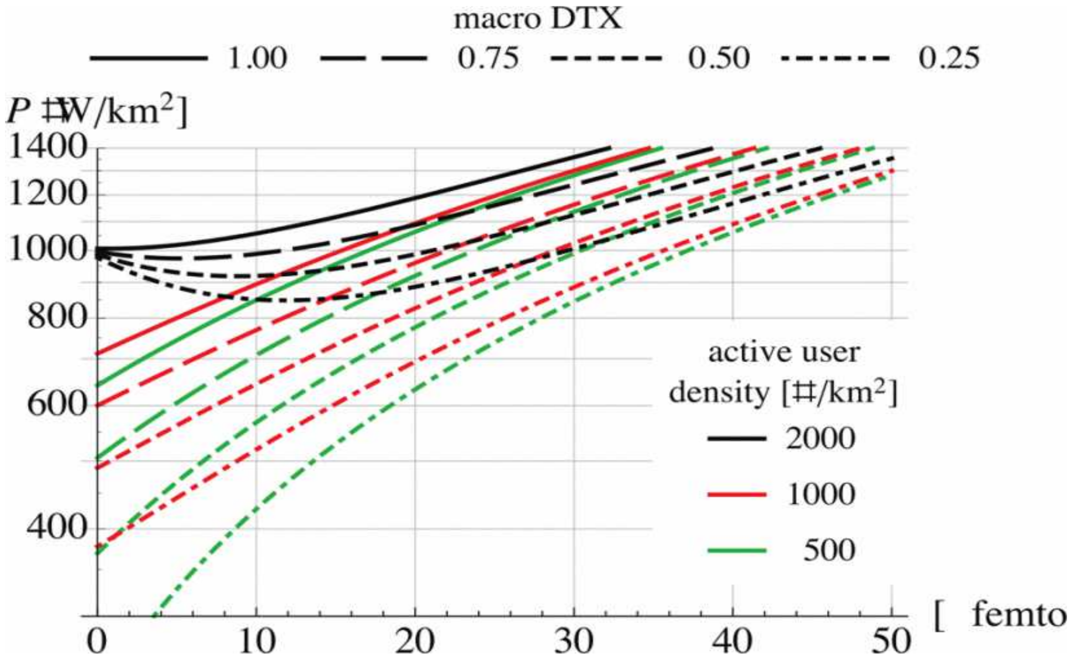


Figure 11. *Power consumption: user density vs. number of femto cells (inactive cell DTX) per macro [34]*

The black curve in figure 11 shows the power consumption for the macro DTX. The experiment was repeated with the cell DTX activated on both the macro and femto cells. The results are shown in figure 13 below.

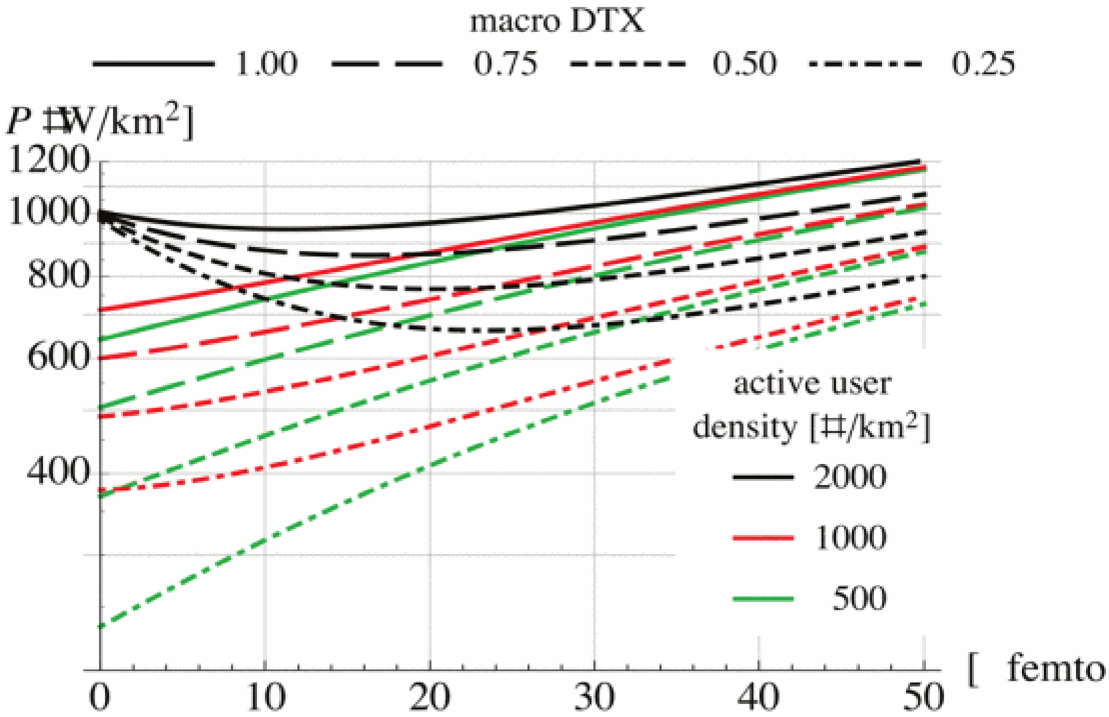


Figure 12. *Power consumption: user density vs. number of femto cells (0.5 cell DTX) per macro [34]*

From figure 12, the simulation results showed that a 29% reduction in power consumption was achievable with the femto DTX set to 0.5 compared to a macro only environment.

The overall results of the simulation concluded that the best way for MNOs to decrease energy consumption was to densify the macro cells and using DTX on the top of that layer. However, the cost of dense macro layer would be too high and therefore, adding small cells with DTX was the best option to save energy and costs.

3.3 MIMO

When data is transmitted over a radio channel with high data rates, the channel impulse response (CIR) can distort the transmitted data and spread it over more symbol periods as a result of multipath propagation signals. This means the transmitted signal travels through several different paths and these copies of the signal arrive at the receiver at different times and are often attenuated. The result is inter-symbol interference (ISI). Multipath signals can be harmful and waste a lot of the transmitted energy. As a result, various techniques were put in place to mitigate this. In legacy networks, the weaker multipath signals were ignored, wasting the energy contained in them. Other techniques used included using several antennas to capture each arriving strong signal at a given moment of time, while other techniques used meant adding delays to re-align the signals.[35]

MIMO is considered as one of the most significant modern digital communication breakthroughs and has been largely used in 3G and 4G cellular networks and a large-scale version, massive MIMO, is a viable candidate under consideration for use in 5G networks.

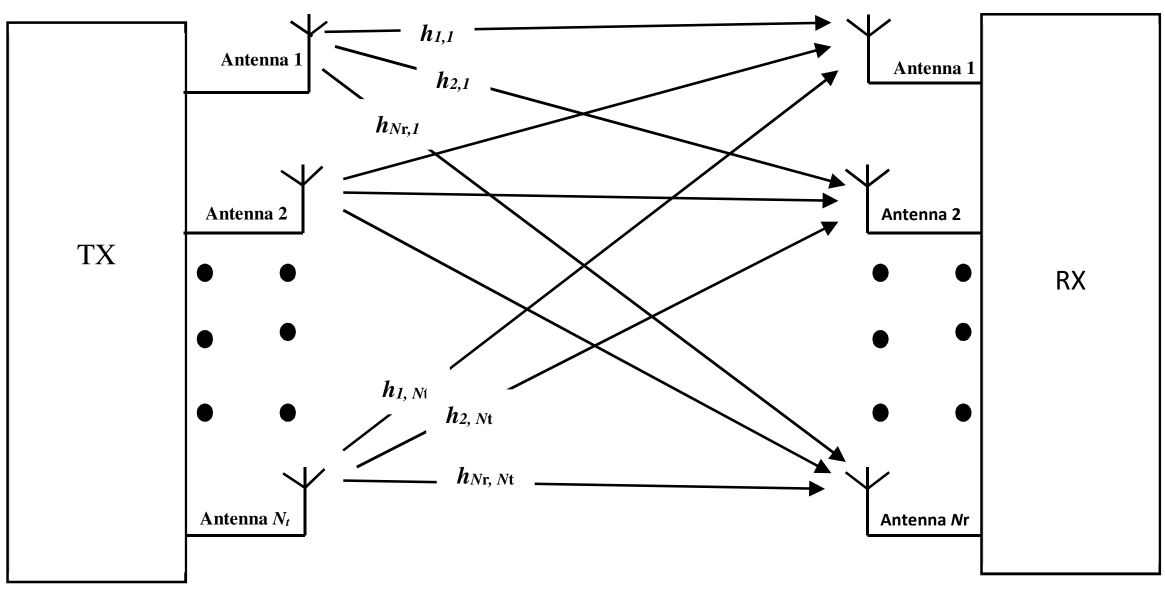


Figure 13. *A MIMO channel block diagram [35].*

The MIMO system has three elements as presented on figure 13. The transmitter, the channel and the receiver. The symbol N_t is used to represent multiple antenna on the transmitter side, N_r the multiple antennas on the receiver side.

MIMO systems contain multiple transmit and receive antennas that capture and manage multipath signals. It is used in conjunction with OFDM to provide high capacity and provide reliability by exploiting as much bandwidth as possible and alleviate multipath fading and offer good quality of service (QoS). It provides both diversity gain by reducing probability of error when signals carrying the same information are sent using different paths from transmit to receive antennas. Multiplexing gain to maximize the transmission rate can be achieved by transmissions of independent streams of information in parallel through the channel, but a trade-off has to be made between the two gains, and systems are designed to achieve both goals or a little of both.

The greatest interest in MIMO systems have been on increasing network capacity and spectral efficiency, with little consideration for energy efficiency. On the other hand, using multiple transmit and receive antennas allows use of full diversity that allows for reduction in transmit power. Mahmood et al. [36] found that with the assumption of a perfect channel state information (CSI), an in-depth study of diversity and spatial multiplexing (SM) concluded that diversity orders of two and three showed the biggest impact on energy consumption.

One MIMO technology that is slated to be key to providing high capacity and coverage to users is Massive MIMO (MaMi), developed as a solution to mobile terminals affected by shadow fading and cell-edge effects. MaMi uses hundreds of antennas that are installed at the base stations by means of antenna arrays. While 5G using higher frequency bands and therefore utilizing mmWaves could use MaMi to provide high-gain antennas, the MaMi technology currently has the most to offer in frequencies between 1 GHz and 6 GHz. This is because propagation and path loss are more understood and predictable, providing higher system throughput in a given spectrum. [37]

3.4 Self-Organizing Networks

Self-organizing networks (SON) is a term used to describe cellular network automation. This is done to speed up the planning, configuration and optimization of mobile networks with minimal human intervention. This has mostly been done on LTE and LTE-Advanced networks.

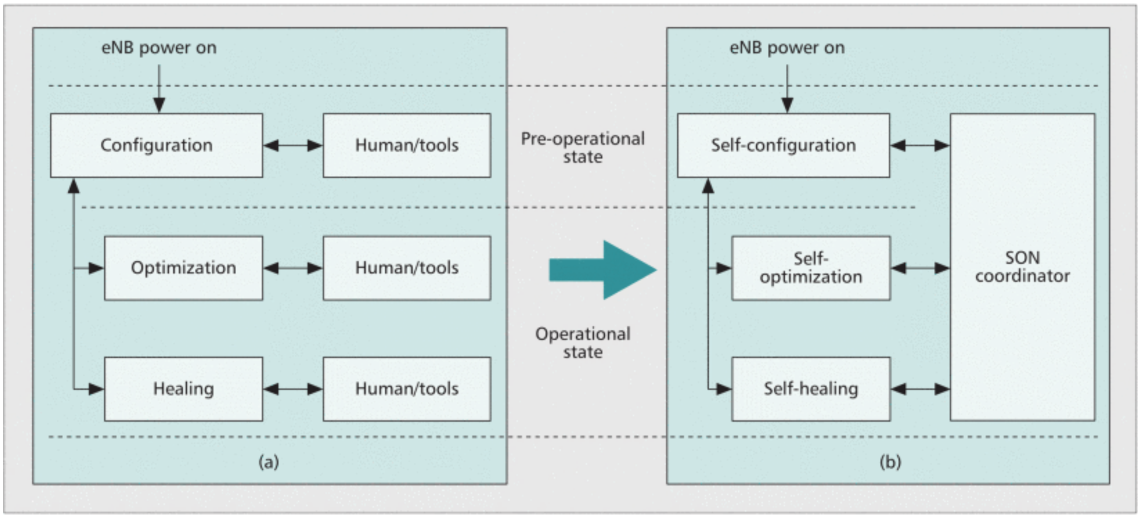


Figure 14. *Cellular network operations modes a) manual b) SON [38].*

Figure 14 shows the operations of a network where humans or humans using tools do everything manually on the network. The most used functions in SON is self-configuration and optimization. Self-healing SON is now gaining traction amongst well established MNOs. Network configuration can be time consuming if done manually. This is because neighbour relations of a BSs take quite some time to set up. With the self-configuration function of SON, automatic neighbour relationships are done automatically, reducing on the BS set-up time. With the dense deployment of micro, pico and femto cells, thus creating UDNs, manual configuration of neighbour relations manually becomes increasingly difficult and time consuming, increasing the probability of having errors. [39]

3.4.1 Self-configuration

This feature of SON enables plug-and-play configuration of new eNBs. With large network parameters to handle, this feature comes in handy because most of the features in individual BSs are shared by most BSs across the network, thereby saving time, costs and ensuring accuracy. Elements included in this aspect of SON include: automatic configuration of the initial parameters in transmission. After the initial planning stage, some parameters within the base station might be incorrect and need changing or upgrading to enhance system performance. Doing this manually could be very time consuming. Dynamic radio configuration (DRC) technique is utilized. This technique allows the base stations to adapt to the existing parameters already in the network, such as cell ID, antenna tilting and down tilt among others. [39]

The second aspect of self-configuration is automatic neighbour relation (ANR). Neighbour relationships in cellular networks are needed to facilitate handovers between different BSs. Proper handovers are a critical factor in the overall performance of the network key performance indicators (KPIs). If neighbour relations are not properly defined, then handovers cannot be properly completed, and the result is dropped calls. Neighbour relations are even more complicated when handovers need to be done between two different technologies for example, between 4G and 3G. This aspect of self-configuration can be automated so that automatic neighbour confirmation is performed. The ANR function means that the network can optimize itself automatically and keep an up to date list of neighbours and reduce loads on needed manual network configurations, hence greatly reducing OPEX, improve overall network performance in improve efficiency. Self-configuration was standardised by 3GPP release 8. [40]

3.4.2 Self-optimisation

The self-optimization techniques are used to analyse cell and network performance and then make the necessary changes to meet the best level of efficiency needs from the operator and the customer. Some network parameters are also changes regularly and it may not be optimal to do the changes manually. Some of the changes include:

- change in the propagation characteristics of the network, for example, a new building being built in the propagation path. SON optimization can help mitigate the effects of this to the network.
- changes in network deployment. This could be because of addition of new BSs or addition of new sectors or even because of the change of parameters of other cells.
- traffic pattern changes. Consumer usage patterns could change over the lifetime of a cellular network. This could be because of increase in the concentration of users, for example, when an office building is built in a new location, people moving during long vacations or holidays like in the countryside during the summer among other reasons. Optimisation is required in this case to provide good QoS. Self-optimisation is ideal specially where traffic changes are seasonal because the coverage requirements would be automatically reassessed when the need changes.

The self-optimizing SON functionality is undertaken in several areas in a network with several features:

- random access channel (RACH) optimization deals with the sent RACH preambles distribution and their associated access delay. This function utilizes information that the handsets and the base stations feed back to the network [41].
- load balancing optimization function ensures that network elements have fairly shared traffic by moving traffic from heavily loaded nodes to less loaded nodes within their coverage neighbourhoods with consideration to minimize interference. Within HetNets, the function offloads traffic to smaller cells like Wi-Fi from the macro cells to better use the macro cells. At the same time, the self-optimization is used to detect UE movement, because handing over a mobile UE to smaller cells means it is constantly moving out of cell range and would experience frequent handovers.
- mobility robustness optimization (MRO) function is used to optimize active and idle mode handover parameters within the network. This ensures good user

experience by minimizing dropped calls which is one of the major reasons for customer dissatisfaction. Reducing dropped calls improves the user's perceived quality of the network, and one way to achieve this is by reducing the number of unnecessary handovers, especially when a UE is mobile. Another way to ensure good user experience is to reduce idle mode problems by enabling a quick set up of the handset from its idle state. The MRO function also helps improve network performance while also considering other parameters such as ANR and load balancing by minimizing waste of network resources due to unnecessary handovers and radio link failures caused by these handovers.

- coverage and capacity optimization (CCO) is one of the most frequent operational tasks in cellular networks. Optimization is based on measurements from the network as well as the desired performance that is based on theoretical models. The concept behind CCO is to adjust BS parameters like antenna tilt and the transmitter power levels to adjust to the desired optimization levels. To carry out adjustments of antenna parameters such as the angle of tilt, the process requires a remote electrical tilt (RET) antenna and the adjustment can be mechanical or electrical.
- energy saving capabilities in SON is an increasingly important functionality that is motivated by the need to reduce emissions of carbon dioxide for MNOs and also have the added benefit of reduced costs due to reduced power consumption of the network equipment. The energy savings are targeted at the UE and the network, particularly within the eNBs. Some options that can be employed to reduce energy consumption include:
    - reduction of active carriers during the off-peak periods while guaranteeing minimum acceptable service levels to the active users.
    - Activation of sleep mode when traffic demand is low in some regions, while increasing the coverage of others at the same time. This method could be useful in areas where there is a significant difference in user movement within short periods of time. For example, city centres require high capacity during the day because of the many people there during the day, but the requirements drop significantly at night as users leave for their homes. Similarly, capacity demands at night are very low in residential areas, resulting in the same effect. However, it would be important to be careful not to reduce coverage so much that there are holes and service is not sufficient for any users that still need it. It would also be necessary to design the algorithm such that the base station can be awoken quickly when demand rises.
    - use of renewable energy sources is now gaining ground especially in the developing countries due to poor coverage of the mains power grid system. To reduce their carbon footprint, many MNOs are using locally generated power, solar or wind to power their BSs. This reduces power costs as with an added benefit of reducing the impact of the operator's network on the environment. More concrete methodologies for energy savings are being developed by 3GPP. [41]

3.4.3 Self-healing networks

The self-healing functionalities of SON were extensively covered in 3GPP release 14 [42]. Self-healing enables detection of faults and their effect to users while taking remedial action. It is the most complex of the SON functionalities as a network is not able to recover from physical damage but is useful in identifying a faulty network element [43]. The expectation is that an alarm is generated once a fault is detected in the network, whether the fault is an automatically detected and automatically cleared (ADAC) or an automatically detected and manually cleared (ADMC) fault. The self-healing functionality can activate a recovery action after making an analysis of the fault from measurement data and other factors and is also expected to supervise and monitor the recovery action execution. After the recovery action is completed, the self-healing functionality is then expected to generate and a notification about the fault and forward it to the integration reference point (IRP) manager with the information on the fault and the recovery action performed. Some examples of recovery actions that can be done include: reloading backup software in case of software faults, system reboot, reconfiguration of the network element, isolation of a faulty node and it's all dependencies from service to reduce disturbances in the network, among others. An activation to a redundant system could be done if it is available and configured [42].

3.5 Selectively turning off components

Mobile networks have been designed with the main objective of providing optimum coverage and capacity and maximizing spectral efficiency and achieve higher throughput. Hence, the networks are designed to handle maximum traffic at peak times and other extreme conditions. However, very often, this capacity is underutilized if the conditions for maximum use are not realized and targeting this area could result in a significant improvement in energy consumption of the overall network[30].

One of the methods used is sleep mode. This method is proposed to dynamically turn off some BSs when the traffic load on the network in a coverage region are low. Care must be taken while running an algorithm to put the BSs to sleep or to wake them up to avoid outages. Some things to consider when running an algorithm to put some BSs to sleep include: QoS, quality of experience (QoE), which is a measure of how a user perceives the service, channel outage probability, which gauges the probability of guaranteed service to users on the cell-edge. The number of BS transitions from off to on should be considered as well, among other parameters. The use of BS sleeping modes requires accurate and fast decision making as well as good traffic predictions, because neighbouring cells have to serve the users that are associated with the sleeping BSs. One way to deal with coverage gaps when BSs go to sleep is to use cell zooming techniques. This is commonly known as cell breathing, where the coverage area of a cell is expanded or shrunk depending on mobile traffic conditions. This method has an advantage in load balancing. The heavily loaded cells can offload some of their traffic to lightly loaded ones, which results in overall energy saving. The sleeping base stations could then be put off for as long as possible, provided that the users are delay tolerant. [44],[45]

With the expected deployment of 5G networks soon, [46] noted that switching off BSs doesn't always result in the desired energy savings as expected. There must be a trade-off between energy consumption and QoS and that transitioning BSs from sleeping to active modes requires more energy to switch on the equipment, and therefore concluded that there needs to be design improvements inbuilt into the BSs hardware to efficiently deploy the witch off strategy.

3.6 HetNets

The typical response to the increase in demand for mobile broadband from most MNOs is densifying the network by either rolling out more macro BSs or adding more sectors to the existing macro eNBs, or a combination of both. However, the result of this is the increase in energy consumption, which in turn increases the OPEX for the operators by increasing the electricity bill costs. The costs are even higher for off-grid BSs, deployed far beyond the electricity grid coverage. In this scenario, fossil fuels in electricity generators add to the cost, and damage the environment. One of the major drivers of the need for HetNets is the need to operate a combination of various cellular access technologies seamlessly and increase capacity. Margot et al.[47] looked at designing energy efficient wireless access networks for LTE and LTE-Advanced networks through the implementation of HetNets.

Typically, LTE-based HetNets are usually networks with two layers that include a macro cell that is an eNB and forming the layer below that are small cells that could be remote radio heads (RRH), low power eNBs, relay nodes (RNs) or home eNBs (HeNBs). These are added to the macro-eNBs for increasing capacity in areas where user demand is high, where they improve the service quality by offloading the macro cell, and to provide coverage in areas not covered by the macro network both indoors and outdoors. To determine the most energy-efficient base stations to utilize, consideration is on parameters such as the number of users, required coverage as well as bandwidth among others. The smaller base stations deployed can use renewable energy sources like wind or solar since their energy consumption is lower than that of the macro BSs. According to Khirallah and Thompson [48], cellular networks that deploy network topologies in the form of HetNets have the best topologies. They concluded that HetNet topologies are more energy efficient than Macro-only topologies. Heterogenous networks use different cells. Here they are listed in the order of decreasing BS power; macro cells, micro cells, pico cells and femto cells.

Although HetNets are considered as the paradigm for enhancing capacity, but as HetNets become even denser, there are challenges that have become associated with HetNets such as interference, resource allocation as well as user association problems. To ensure that these small cells are serving as many users as possible, one of the optimisation methods have been to increase service area of the cells, called cell range extension (CRE). This is necessary because UEs tend to connect to macro cells instead of smaller cells because they have a higher transmit power, hence the small cells are underutilized in this scenario. The figure below explains the concept of CRE.

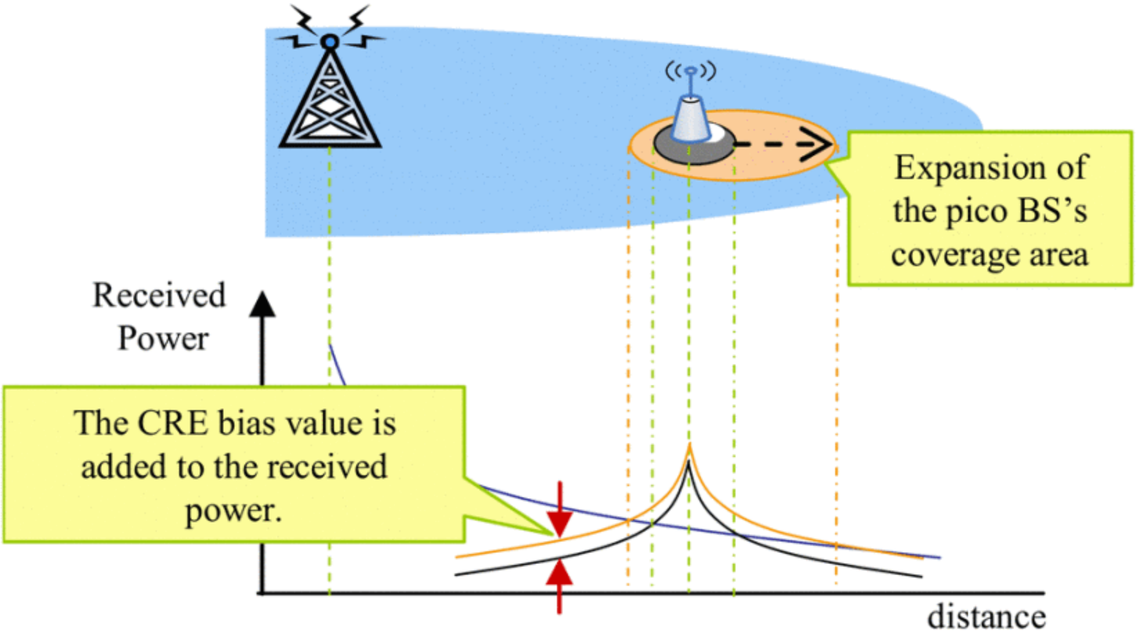


Figure 15. *Base station coverage extension using CRE [49]*

With the addition of CRE, a bias value which is already predetermined is added by the UE to the local BS received power. This expands the local BS coverage and the UE will then connect to the BS with the highest received power. This however does not reduce the severe interference from the macro BSs whose power is usually much greater than that of the local BS on which the UE is connected. [49]

A study by Ericsson [50], showed that increasing small cells in a network increases the energy consumption up to 3 times more than the equivalent macro cellular network, but a combination of Hetnets and sleep modes in LTE networks have were shown to save on energy consumption as shown in the figure below.

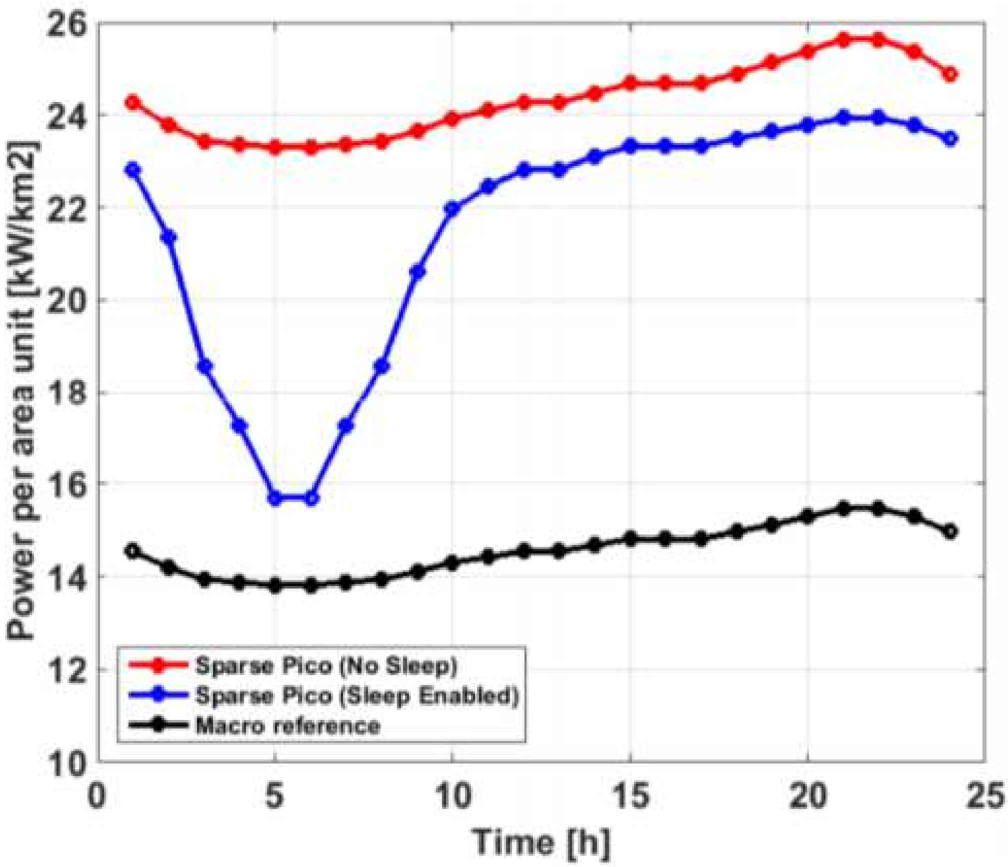


Figure 16. *Energy savings in a HetNet with sleep mode [50]*

Figure 16 shows the energy savings that are achieved by using pico cells in a HetNet. With sleep mode enabled, the power consumption per unit area is almost comparable to that of the macro cells.

3.7 Use of alternative energy solutions

Use of alternative energy solutions entails moving away from the usual connections to the electric grid and into energy harvesting from the environment. In emerging markets and remote areas such as in Africa, Latin America and some parts of Asia as well as other remote regions in the developed countries such as Canada, electrical grids are not available and where available, are not reliable. This forces MNOs in these regions to connect their BSs and other backhauling equipment in these regions to diesel powered generators. The use of fossil fuels can be very expensive if the generators are the only source of power for their equipment and raises their CAPEX significantly. Frequent site visits to check on the status of the generators and to add fuel also add to the cost of operations. In addition, these generators emit elevated levels of CO_2 which is then released into the environment. Energy harvesting from renewable energy sources is the way to go for these MNOs and other environmentally conscious operators. Such environmental sources include wind, solar and in some instances, bio fuels. [51]

The major advantages of using energy harvesting for MNOs is obviously in cost savings. But with such a mechanism in place, an operator can offer converge in remote and far off places, giving them a competitive advantage. Excess electricity generated could also be sold on to the grid operators where such an agreement is possible. Another advantage is that these systems are not affected by grid issues and will continue to work even if a disaster hits the grid or there is unstable power supply, as is often a case in most regions of the developing countries.

Some considerations for the disadvantages are put into place too. Currently, battery technology is still not too advanced, and the operator would need many batteries to maintain power for 24 hours to a BS harvesting energy from solar for example if the sun is not shining throughout that period. In the northern and southern hemispheres, the lack of sun during winter means the network operations could grind to a halt unless the MNOs have backup diesel generators.

4. HIGH FREQUENCY TRANSMISSION AND ENERGY EFFICIENCY

The current mobile technologies have relied heavily on lower frequencies below 3 GHz. The biggest advantage of transmission at these frequencies is that they have large transmission distances, and can easily pass through objects with low attenuation occurring [52]. However, the lower frequency spectrum is very crowded, meaning that there is less bandwidth for all the users. Table 1 shows the spectrum allocation for mobile communication networks in the united states as of 2013.

Table 1. *Current mobile communication spectrum allocation in the US. [53]*

Band	Uplink (MHz)	Downlink (MHz)
700 MHz	746 - 763	776 - 793
AWS	1710 -1755	2110 - 215
IMT Extension	2500 - 2570	2620 - 2690
GSM 900	880-915	925 - 960
UMTS Core	1920-1980	2110 -2170
GSM 1800	1710-1785	1805 - 1880
PCS 1900	1850-1910	1930 - 1990
Cellular 850	824-849	869 - 894
Digital dividend	470 -854	

It is estimated that each MNO in the United States has about 200 MHz bandwidth across all mobile network technologies available to them as shown in table 1. The result of this is slowed down or simply dropped connections. To overcome this problem, one of the solutions is to increase the bandwidth, and there is not a whole lot of it on the lower frequencies, hence the need to move to higher frequencies. These high frequencies promise higher bandwidth for users as well as low latency, especially for mission critical communications and gaming. [53]

4.1 Millimetre Waves

Deployment of mobile networks lays a lot of effort on efficient deployments. However, the rapid and continuous advancement in mobile computing and communications as well as high-end consumer devices always overwhelm the networks with capacity requirements and increased congestion. As shown earlier, the natural cycle of mobile network technology is about 10 years or less. Most of the current communication systems that include radio, television, satellite, Wi-Fi and others have been constrained in the 300 MHz to 3 GHz band in the spectrum, which is often referred as the *sweet spot* because it possesses favourable propagation properties for commercial transmission systems, leaving the bands above 3 GHz largely unused for commercial applications.

With the 5G technical specifications being in development, one of the enabling technologies for this generation of mobile networks is millimetre waves. The millimetre wave band is the spectrum lying between 30 and 300 GHz. It is estimated that frequencies of up to 251 GHz have the potential to be used in mobile broadband [54]. These radio waves are called so because the wavelengths vary from 1 millimetre to 10 millimetres. These waves give the operator expanded channel bandwidths, therefore, giving high data rates. Operators can also explore techniques such spatial processing and polarization as well as adaptive beam forming and steering. However, millimetre waves have huge draw backs. Their transmission distance is very short, they cannot penetrate buildings or other big obstacles and also suffer from molecular absorption that make non-line of sight (NLOS) very difficult to model for. These frequencies are however readily available for use. [55]

4.2 Millimetre Wave Propagation

Spectral efficiency as close as possible to the Shannon limit has been possible because of the improvement in the design of the air-interface. However, one of the advantages of mmWave frequency bands is that it is possible to have 1 GHz or more of contiguous blocks of spectrum. This provides better capacity and throughput. Another advantage has to do with the size of antennas. At these high frequencies, the antennas required are very smaller than those in use in other technologies. This enables the implementation of large antenna arrays. Clever implementation of these arrays in turn enhances adaptive beamforming that support increased performance of the network by enabling propagation loss compensation. The downside of implementation of large antenna arrays is the RF chain complexity for both mobile network and mobile phone implementations, resulting in increased costs. However, availability of these spectrum blocks could also mean that good data rates are possible without complex modulating schemes, hence lowering energy consumption, complexity and cost while trading bandwidth for spectral efficiency making mmWaves a great candidate for transmission in 5G. [56]

With the 5G frequency allocations done for countries around the world, countries in Europe have been allocated both low and high frequency bands for 5G trials. The table below shows the frequency allocations for Europe.

Table 2. *5G frequency allocations Europe [57].*

Country	Low Frequency Band	High Frequency Band
Finland	3.4 - 3.8 GHz	26.5 - 27.5 GHz
France	3.46 - 3.8 GHz	26 GHz
Germany	3.4 - 3.8 GHz	26 - 27.5 GHz
Ireland	3.4 - 3.8 GHz	26 GHz
Italy	3.6 - 3.8 GHz	26.5 - 27.5 GHz
Russia	3.4 - 3.8 GHz	26 GHz
Spain	3.4 - 3.8 GHz	26.5 - 27.5 GHz
United Kingdom	3.4 - 3.6 GHz, 3.6 to 3.8 GHz (in 2019)	26.5 - 27.5 GHz

The award or auction of the mid-band allocation of 3.4 GHz to 3.8 GHz is expected to be done in 2018, although Ireland already had an auction and award in 2017. The higher frequency awards to mobile operators are also expected to be done between the year 2018 to 2019. [4, 57]

One of the major advantages of the lower frequencies utilized in 2G, 3G and 4G is that these radio signals can provide a larger geographical coverage in the range of tens of kilometres in 1800 MHz GSM because of their long wavelengths. Therefore, building penetration is quite high and interference from naturally occurring molecules in the air or other scattering agents is low. Higher frequencies have shorter wavelength and therefore propagation distance is shorter. Poor foliage and building penetration is also a factor against mmWaves, but the biggest concerns are the free-space path loss combined with molecular absorption that is experienced at higher frequencies. Free space path loss has been observed to be significant for mmWaves and atmospheric absorption result in signal attenuation, especially at 60 GHz. [58]

Other disadvantages and issues of concern include mechanical resonance, that is pronounced at 24 GHz and 64 GHz, scattering by rain drops or other particles in the air that are a similar size as the radio wavelengths. Atmospheric absorption has been found to be negligible at 28 GHz and 38 GHz.

4.3 Antenna modelling

The antennas in the simulation are modelled as closely as possible to the real operating environment and modelling is done to generate the patterns for the vertical plane polarization (elevation) as well as the horizontal plane polarization (Down tilt). The 3GPP antenna model specifications provide the horizontal and vertical plane radiation patterns and the antenna boresight. The antenna model used for this evaluation mirrors the traits of the Kathrein 742215 [4]. This section explains the parameters of the antenna in greater detail.

The maximum antenna gain given for the horizontal plane is G_m = 18.26 dBi. The horizontal polarization gain $G_h(\varphi)$ is given by the formula below:

$$G_h(\varphi) = -\min\left(12 \cdot \left(\frac{\varphi-\varphi_{ref}}{HPBW_h}\right)^2, FBR_h\right) + G_m, -180° \leq \varphi \leq 180°. \quad (8)$$

where φ indicates the down tilt angle in the main beam in degrees. The value range is given as $-180 \geq \varphi \leq 180$, and the main beam reference down tilt is given by φ_{ref}. In this simulation, φ is given as the value of the direction of departure (DoD) for the BSs under investigation. DoD gives the angle between the receiver and the transmitter from the receiver's perspective. The parameter $HPBW_h$ (in degrees) represents the half power beamwidth in the horizontal plane, which is given as 65° for the purposes of this simulation. The front-to-back ratio (FBR_h) gives the signal strength transmission ratio in the forward direction to the transmission in the backward direction in a directional antenna. The value is given as 30 dB in this simulation. The down tilt values considered for this thesis are given in the table below. Table 3 below shows the down tilt angle assignment for the sites in the simulation.

Table 3. *Down tilt Values for the simulation.*

Site Name	Antenna Name	Down tilt	Site Name	Antenna Name	Down tilt
Site_1	1	140	Site_6	1	60
Site_1	2	260	Site_6	2	200
Site_1	3	0	Site_6	3	300
Site_2	1	130	Site_7	1	320
Site_2	2	250	Site_7	2	90
Site_2	3	10	Site_7	3	200
Site_3	1	350	Site_8	1	130
Site_3	2	110	Site_8	2	250
Site_3	3	230	Site_8	3	10
Site_4	1	120	Site_9	1	120
Site_4	2	260	Site_9	2	260
Site_4	3	20	Site_9	3	20
Site_5	1	110	Site_10	1	130
Site_5	2	240	Site_10	2	260
Site_5	3	0	Site_10	3	30

The down tilt values given in table 3 are used for both the 2.1 GHz system and the 28 GHz system. The simulation scenario with the down tilt angle means that 3 cells are counted for every BS. Therefore, considering that there are 10 BSs, then the total number of cells is 30 as shown in table 3.

The vertical polarization of the antenna gives a gain, $G_v(\varphi)$ in the elevation plane, which is calculated using the formula:

$$G_v(\theta) = \max\left(-12 \cdot \left(\frac{\theta-\theta_{tilt}}{HPBW_v}\right)^2, SLL_v\right), -90° \leq \theta \leq 90°. \quad (9)$$

$HPBW_v$ represents the half power beamwidth in vertical direction in degrees. The value used in this simulation for the vertical antenna pattern is 6.2°. In a macro cellular environment, one way to improve the coverage of the cell is by using electrical tilt, which is given by θ_{tilt} in this simulation. The value assigned in this simulation is 9°. The angle of departure (AoD) is represented by θ in equation 3 and represents the BS perspective of angle between the transmitter and the receiver in the vertical plane. The values of θ range between $-90 \geq \theta \leq 90°$, and $\theta = 0°$ is the value along the horizontal plane. The upward direction corresponds to the negative values of θ and the downward direction corresponds to the negative values of θ. The side lobe level (SLL_v) is the value of the side lobe level, given in dB, in comparison to the main beam's maximum gain. For this simulation, the value used was -18dB.

The next step is to calculate the total antenna gain, given by equation (10)

$$G_T(\varphi, \theta) = G_h(\varphi) + G_v(\theta). \quad (10)$$

The vertical and horizontal plane radiation patterns are showed in figure 17 below.

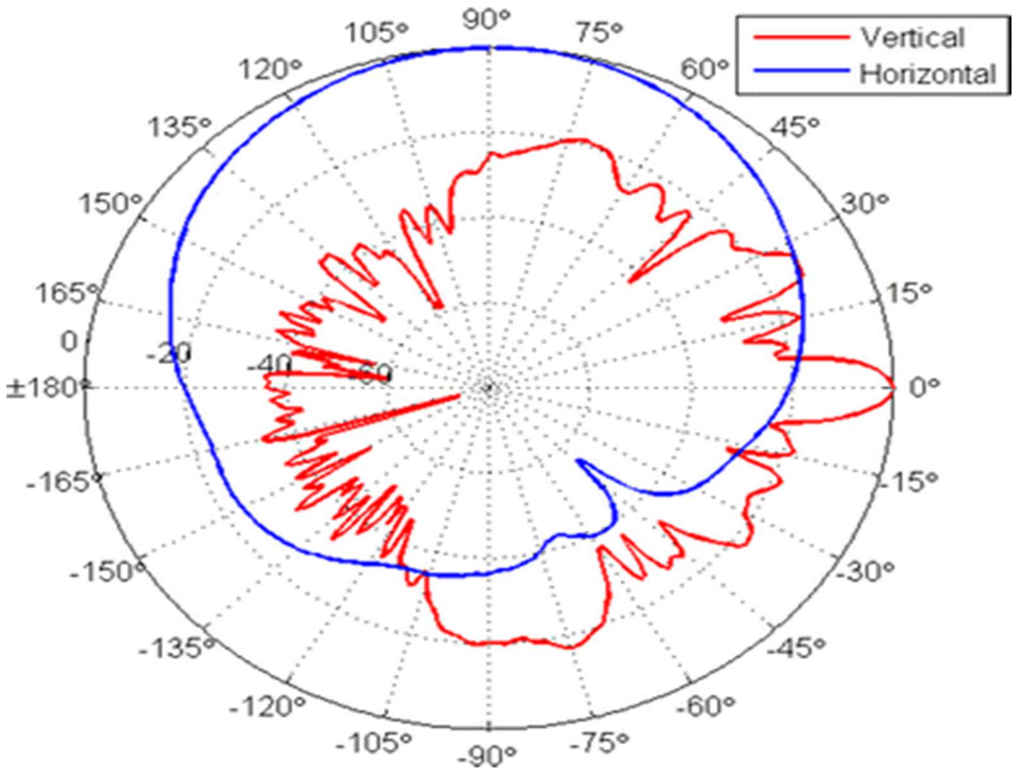


Figure 17. *Radiation pattern in vertical and horizontal plane[59].*

Table 4 gives an overview summary of the modelling parameters

Table 4. *Modelling parameters.*

$HPBW_h$	FBR_h	G_m	$HPBW_v$	SLL_v	θ_{tilt}
65°	30 dB	18.26 dBi	6.2°	-18 dB	9°

4.4 Performance Metrics

This section describes the metrics that were used in this thesis to determine the performance of the system. In this thesis, the received signal strength of the UE was used to make the analysis on the performance of the network. In calculating the received signal strength, attenuation due to multipath propagation and fading was a big consideration. Multipath fading occurs because of transmitted signals reaching the receiving antenna by two or more paths, which could be because of reflection from obstacles such as buildings. In comparison of the received signal strength, the reference signal strength of a user is calculated by first finding a user's serving cell in the isotropic antenna scenario. For every base station, the outdoor users were filtered, the 10 strongest multipath components for the UE were added together and all the other components treated as interference. The process was repeated over the 10 sites in the 2.1 GHz simulation and the 10 in the 28 GHz scenario. The resulting received signal strength was then filtered and the serving cell selected, i.e. the highest received signal strength per UE was used to select the serving cell. Antenna masking with sectorization was then applied on the vertical and horizontal plane with no down tilt. The process for the received signal strength was repeated, in this case, with individual sectors considered to find the serving sector. In the down tilt scenario, the calculation for the received signal strength was done with the calculation of the down tilt combined with masking considered, and the serving sector was determined for the analysis.

After calculation of the signal strength, the next metric that was used was the SINR. The SINR is used to give a channel capacity's theoretical upper bound. The higher the value of SINR, the better the system performance. To calculate the SINR of this system, the following formula was used.

$$SINR = \frac{S}{I+N} . \tag{11}$$

The unit of expression of the SINR is decibels. The received signal strength is denoted by *S,* that is calculated per user from the received multipath components that are received by the UEs. The interference is represented by *I* and was calculated from the sum of all the remaining signals that were received by the UE after the 10 strongest signals from the serving cell or sector were considered to calculate the received signal strength. The noise *(N)* is calculated is calculated using the following (13):

$$N_{\mathrm{dBm}} = 10 \cdot \log_{10} (\mathrm{k} \cdot T \cdot B) + NF. \tag{12}$$

From equation (13), T is the temperature in which the noise of the system is evaluated, at 290 Kelvin (K). The bandwidth *(B)* of the system used in this simulation was 20 MHz for the 2.1 GHz and 28 GHz, and a second calculation with a bandwidth of 200 MHz for the 28 GHz. The Boltzmann's constant (k) is a constant with the given value of 1.38064852 $\times 10^{-23}$ m^2 kg s^{-2} K^{-1} and the noise figure (*NF*) value used in the simulation is a constant 8 dB.

The Shannon capacity formula determines the maximum capacity that is achievable for a given channel and bandwidth.

$$C = W \cdot \log_2(1 + \overline{\Gamma}). \quad (13)$$

The capacity, C, is expressed in bits/second/hertz, and W is the bandwidth of a given channel. For the simulations in this thesis, the bandwidth was taken as 20 MHz for 2.1 GHz and 200 MHz for the 28 GHz simulations. The symbol Γ is the linear scale representation of the *SINR*, whose average $\overline{\Gamma}$ is calculated from the simulation data to evaluate system capacity.

The other value that was used to evaluate the system performance is the spectral efficiency. Spectral efficiency is a measure of the rate of the transmission or transfer of information in a radio system [4]. Spectral efficiency (η) of the system is directly proportional to the system *SINR* [59]. To calculate the average spectral efficiency, the following formula is used:

$$\overline{\eta} = \frac{C}{W} \quad (14)$$

An additional metric to determine the efficiency of the network in this simulation is the system throughput(R). Throughput refers to the amount of data that can be moved from the transmitter to the receiver in a given time period. The formula is given below.

$$R = W.\overline{\eta} \quad (15)$$

When all radio resources are in use in a fully loaded network, the BSs transmit the maximum allowed power. The system's average spectral efficiency is given in terms of bits/second/hertz, and the mean spectral efficiency per cell ($\overline{\eta}_{cell}$) is given by equation (15)

$$\overline{\eta}_{cell} = \log_2 (1+\overline{\Gamma}). \quad (16)$$

The mean spectral efficiency of a cell is expressed in [bps/Hz].

The mean spectral efficiency of an area ($\overline{\eta}_{Area}$) is calculated by the multiplication of the number of cells in a square kilometre with the mean spectral efficiency. However, in this simulation, the site constellation used is irregular and therefore the formula for the area spectral efficiency is modified to reflect this, and the area spectral efficiency is then expressed as bps/Hz/Area [4] using equation (16).

$$\overline{\eta}_{\text{Area}} = \overline{\eta}_{\text{Cell}} * N_{\text{cell}}. \tag{17}$$

In equation (16), N_{cell} is used to indicate the number of cells in the coverage area under consideration.

The other system performance metric that was considered is the transmission power efficiency (P_{eff}). Transmission power efficiency is defined as the ratio of the power received over the power transmitted in a transmission path [60]. The power efficiency is expressed in bps/Hz/W and is expressed using formula (17).

$$P_{eff} = \left(\frac{\eta_{\text{Area}}}{P_{Area}}\right). \tag{18}$$

The symbol P_{Area} gives the total area transmission power, expressed in watts. The total area transmission power is expressed as:

$$P_{Area} = P_{BS} * N_{Cell}. \tag{19}$$

Where P_{BS} is the transmission power consumption of a single base station, expressed in watts.

5. SIMULATION PROCEDURE

Radio waves experience attenuation as they propagate from the transmitter, with their strength decreasing the farther they travel, because they are affected by various environmental variables. Signal propagation and path loss models are used in mobile network design to predict coverage. Propagation models that are used can be classified as empirical or deterministic. Transmission of radio waves from an ideal transmitter are said to be unobstructed and follow the LOS propagation. However, practical transmitters are not ideal, and neither is the propagation environment.

Empirical models are based on actual field measurements and statistical analysis and are used on specific frequencies in specific environments, meaning they can be used to account for most propagation mechanisms influencing the propagation environment. They are simple and easy to compute. However, these methods may not consider different variabilities in the environment, for example, if there is a mix of open spaces with suburban or urban areas in the coverage regions, they are not very reliable. One of the most used empirical models is the Okumura-Hata model. Deterministic models generally use wave theory to estimate path loss, while considering all individual propagation path obstructions, and can be simulated in three dimensions. This makes these models complex to implement. Examples of deterministic models include Ray tracing and Ikegami. The third category of path loss models is the semi-empirical models. These models use both aspects of the empirical modelling and some of the deterministic modelling. A good example of a widely used semi-empirical model is the Cost 231 Walfisch-Ikegami model. The Cost 231 Hata is often used as an extension of the Okumura–Hata model for different propagation environments like urban, rural and suburban environments. [61]

5.1 Simulation tool

Ray tracing is one of the most accurate and widely used deterministic model to estimate propagation conditions and model the simulations scenarios as close to the real environment as possible. It requires a lot of computing power and is based on geometrical optics (GO) and is very useful when used to model the refraction as well as reflection of the optical rays. Ray tracing is used to identify all possible multipath components between the transmitter and receiver. After identifying all possible ray paths, the model then utilizes electromagnetic techniques to compute ray parameters that could include phase, polarization and delay of every ray. To be used effectively, ray tracing techniques require very clear details on the geometry of the environment, which could increase the computational time significantly. [62]

The basic ray tracing algorithms used for simulations include:

- Fermat’s principle of least time, which states that a ray traveling from one point to another will take the route that consumes the least time.
- Image theory (IT) algorithm. This algorithm assumes the presence of geometric and electromagnetic modelling of the propagation environment and it utilizes geometric modelling by flat patches such as buildings.
- Shooting and bouncing ray (SBR) whose basic idea is to trace every ray that is launched from the transmitter to see if it arrives at the receiver.

The most commonly used algorithms are IT and SBR. For the simulation data used in this thesis, the simulation is done using a MATLAB based 3D ray tracing tool known as sAGA, which uses a ray tracing technique that is based on the IT algorithm. Ray tracing based on IT is more efficient in this case than SBR because of the use of geometric modelling. However, the downside of the IT algorithm is the high requirement of computing power and a lot of time taken to do the computations. The disadvantages of using SBR include the fact that many rays are launched at the transmitter, which will not contribute to the received signals at the receiver. The spread of the diffracted rays makes it difficult to include diffraction in the final computation, and the number of the rays launched also determine the accuracy, with fewer rays resulting in higher errors. [63]

The diagram below gives a schematic view of how the sAGA ray tracing tool works.

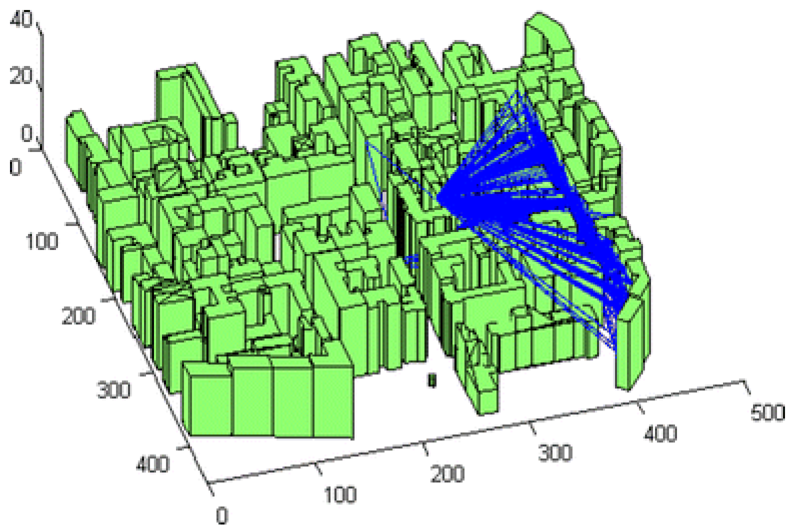


Figure 18. *Ray tracing using sAGA 3D illustration [60].*

Using the sAGA ray tracing tool, transmitters are placed on the rooftops and diffracted signal paths are tracked. All multipath components with pre-defined number of reflections and diffractions are traced. The tool also traces the multipath components occurring because of the reflection from the ground. The tool also supports both horizontal and vertical polarization of antennas.

From the simulation, the parameters of interest from the propagation paths include:

- Serial number of Multipath component
- AoD
- DoD
- Received Power

The serial number of the multipath components identify each multipath component that is arriving at the receiver from each transmitting antenna. The angle of departure is the elevation angle of the transmitter in respect to the receiver, in the vertical domain. Direction of departure is the down tilt angle of the transmitter in relation to the receiver on the horizontal plane. Both DoD and AoD are measured in degrees. The received power is taken as the power in watts of each multipath component as measured at the receiver.

5.2 Simulation Environment

A dense urban environment was considered for this simulation as a consideration of the kind of environment where 5G will most likely be deployed. An area of Helsinki city was selected. This environment is different from a hypothetical one where building height and spacing would be uniform. In this case, the research area had mixed type of buildings ranging from one floor to 10 floors, and some open spaces as well, representing a true microcellular environment for future and current networks. A three-dimensional model is made of this area as shown below.

Figure 19. *Helsinki City study area with details in 3D.*

In the simulation region, there are 10 macro sites with transmitting antennas placed at 30 metres in height, above the average levels of the rooftops in the buildings in the targeted area. The allocation and distribution of these sites was not done in the regular hexagonal or cloverleaf network layout, but their location was carefully considered. Figure 20 shows the general layout of the transmitting antennas.

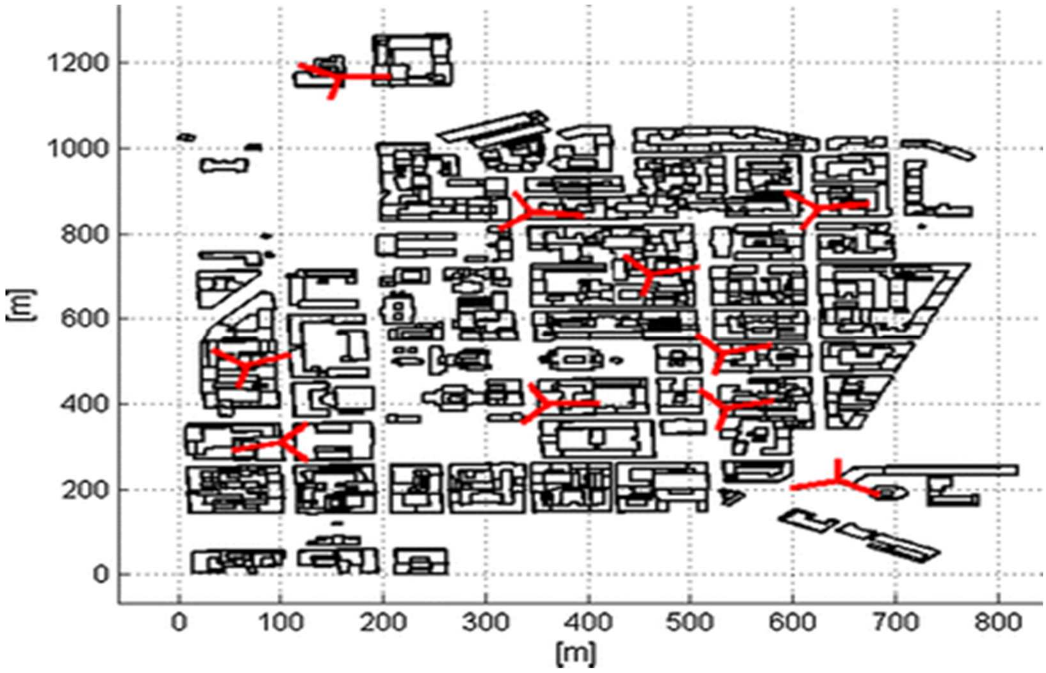


Figure 20. *Layout of the 10 3-sectored macro sites in the target area.*

For the purposes of this simulation, 884 receiver locations were randomly selected and distributed in the target area. However, it is important to note that in most commercial areas, most of the uses are indoors in comparison with those outdoors. For purposes of this research however, only outdoor users were considered. The general distribution of receiver locations is given in figure 21.

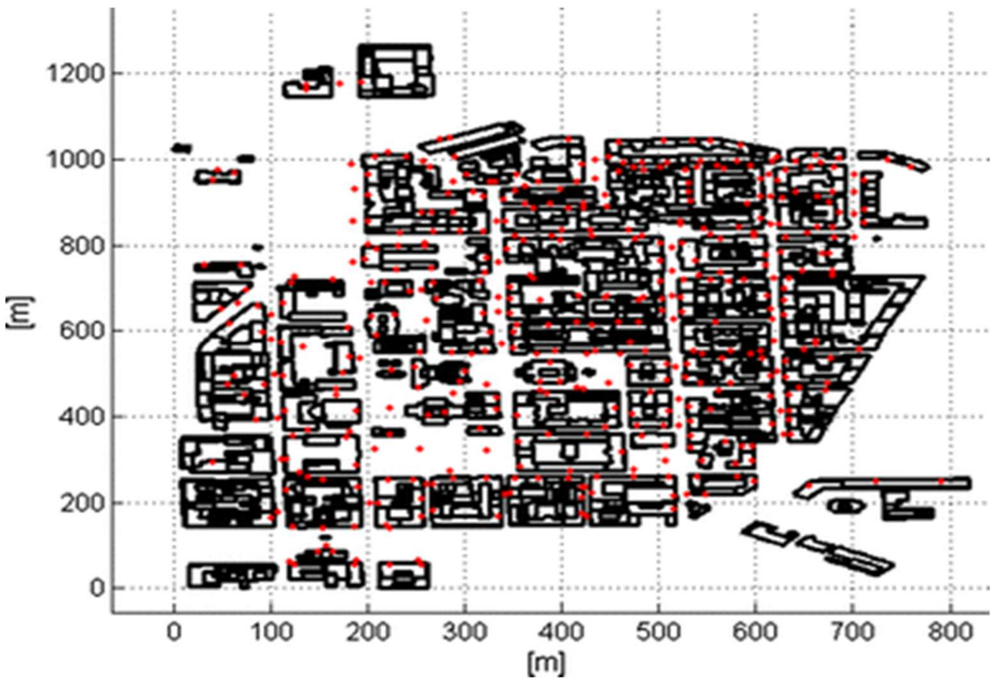


Figure 21. *General location of selected receivers in the target area.*

The receiver height was chosen as 1.5 metres and can be LOS or NLOS with respect to the transmitter.

5.3 Simulation parameters

There are two main cases considered for this simulation. One is simulation in the 2.1 GHz frequency and the other is the simulation in the 28 GHz scenario. The antenna transmission power for each antenna is given as 40 watts for both frequency bands. In this environment, there were 10 eNBs. In the simulation cases that involved 3-sectored sites, there were a total of 30 cells, each counted as having its own antenna. The antenna modelling presented in chapter 4 contains the modelling details that are used in the simulation for both frequency bands. In the 28 GHz simulation, a gain of 16.5 dB was additionally considered because there is the possibility of placing large antenna arrays on a single antenna in this frequency band.

While LOS is the desired propagation path, radio signals are often reflected from obstacles in the propagation path like buildings. These different signals arrive at the UE by different paths and at different times. These multipath signals can cause interference, fading and loss of data depending on the strength of the arriving signal and its corresponding time delay. In this simulation, the received signal level was considered as a summation of the LOS components and the multipath components. To determine the serving cell of a UE, the 10 strongest signals from all the signal components arriving at the UE were added, and the site that had the strongest signal was chosen as the serving cell of the UE. All the other signal components from the serving cell, sectors and BSs were treated as interference.

The processing of the simulation data is used to calculate the power of the received signal by using the different multipath components, spectral efficiency and throughput, and the results are then discussed in the next chapter.

5.4 Simulation cases

The purpose of this thesis is to study the power or energy consumption scenarios in 2.1 GHz and 28 GHz frequency bands used in cellular communication transmission and determine if it is possible to collocate or the 28 GHz in 5G with the 2.1 GHz based site locations. While 2.1 GHz is already in use by cellular networks, 28 GHz is being considered for 5G because of its proximity to the millimetre wave frequency bands and possesses some of the properties of mmWaves. For both frequency bands, the strongest signal is considered as the carrier wave and other remaining received signals as counted as interference.

Case i: omnidirectional antenna (Reference)

The first simulation scenario considered omnidirectional antennas, where power radiation is symmetrical. All the arriving multipath components from each site at each receiver are examined and the components with the 10 strongest received power are selected. These are then added up to determine the total received power of each UE. This process is repeated for all 10 antennas in 2.1 GHz frequency band as well as the additional 10 transmitting antennas from the 28 GHz frequency band.

Case ii: 3-sectored antenna masking with no tilt

The second simulation scenario considered a 3-sectored antenna at the same location as the omnidirectional antenna. The sectors were all mounted with a HPBW angle of 65˚ in the horizontal plane and a 0˚ HPBW in the vertical plane, which means no down-tilting was done. Just as in the omnidirectional case, the 10 strongest components were selected, 10 from each sector of the transmitting antenna after antenna masking was applied. All the gains were then added up to calculate the received signal for each receiver. And then all the gains were added together. The process was repeated for all components from all the sites in both 2.1 GHz and 28 GHz frequency bands.

Case iii: 3-sectored antenna with down tilt

The third scenario was similar to the second one except the inclusion of the down tilt. In this case, the angle of tilt in the vertical plane was set to 9˚ for all sectors in the base stations.

6. SIMULATION DATA ANALYSIS

This section discusses the performance of the different scenarios that are presented in chapter 5. The outputs in terms of the received signal strength, SINR, spectral efficiency and power efficiency have been used to determine the system performance. The scenarios considered is the transmission in 2.1 GHz, the frequency that is used in UMTS and LTE networks. Future networks are moving towards higher frequencies utilizing millimetre waves. This thesis analyses the performance of the network in 28 GHz frequency band. A bandwidth of 20 MHz is considered in the analysis of the 2.1 GHz transmission and 20 MHz and 200 MHz are used in the analysis of the 28 GHz.

Chapter 6 discusses all the system performance metrics discussed in chapter 4 with output graphs and tables after analysis of the simulation. The cumulative distribution function (CDF) plots are presented in the analysis of the received signal strength and the SINR, the means of the values are presented in a tables 5, 6, 7, 8 and 9.

6.1 Received signal strength

The received signal strength indicates the signal power measured in dBm that a UE receives from a BS in a cellular network. In NPO, engineers aim at providing the best possible signal level to ensure good user experience, which in turn gives a measure of the system performance.

Since only outdoor users are considered, some BSs did not have enough traffic at all serving the outdoor users and were therefore eliminated from the analysis. After filtering of outdoor users was done, the resulting outdoor users were 115 for the 2.1 GHz and 104 users for the 28 GHz scenario. Due to the limited number of users, the smoothness of the curves is not as expected. The system performance is also affected by the position of the user relative to the position of the serving cell. The mean and median values of the received signal strength are given below.

Table 5. *Mean and median of received signal strength at 2.1 GHz.*

Scenarios	**Reference**	**Masking**	**Masking with d**own tilt
Mean(dBm)	-60.70	-41.11	-37.41
Median(dBm)	-59.03	-40.17	-36.59

From Table 5, the mean of the reference received signal strength between the 3 scenarios have highly varying values, with the reference values lower than those of the masking and masking with down tilt scenarios.

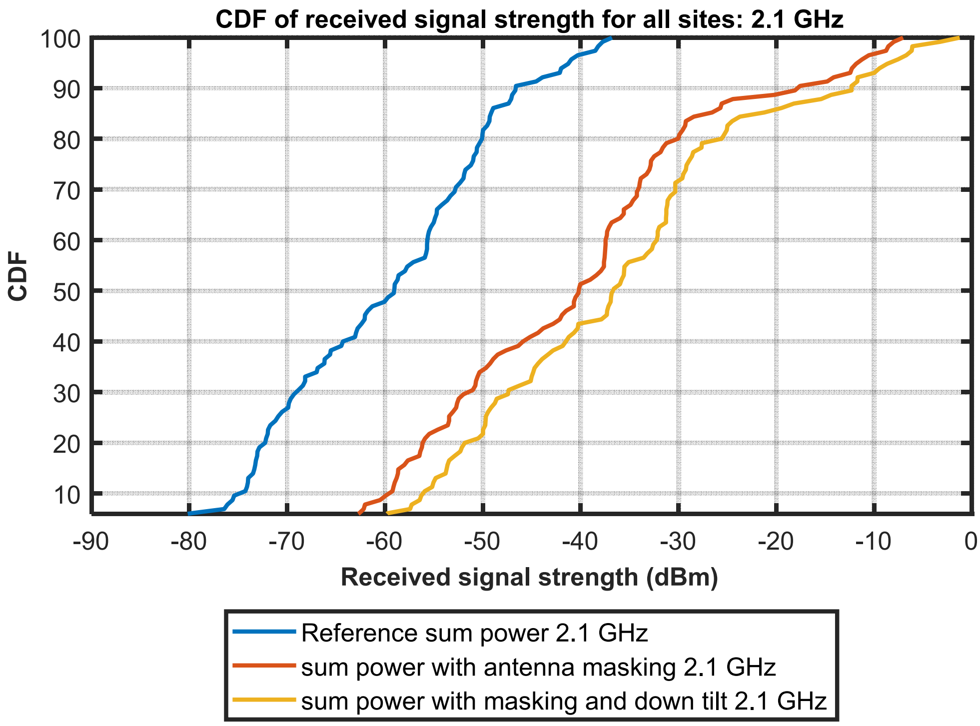


Figure 22. *CDF of received signal strength of all simulation scenarios in 2.1 GHz.*

Figure 22 illustrates the power received by the users in all scenarios in the 2.1 GHz frequency transmission simulation. There is a stark difference in the average values of the received signal strength between the reference scenario with the average received signal strength being 59.8 dBm. The average received signal strength with the masked antenna is -40 dBm and -36.8 dBm for the antenna masking with the down tilt angle scenario. Therefore, the conclusion is that antenna masking improves the signal strength to users, avoiding wastage of signal power because of radiating equally in all directions as it is the case with the isotropic antenna. There is a difference of about 4 dB between the sectorized antenna with masking but no tilting and the scenario with both masking and down tilt. The received signal strength with the latter scenario is stronger, with the conclusion that it is the best implementation in a cellular network.

The received signal strength was also evaluated in the 28 GHz frequency scenario, and the results show a similar pattern to those of the 2.1 GHz frequency band. Table 6 gives the mean and median values of the received signal strength in all scenarios.

Table 6. *Mean and median of received signal strength at 28 GHz.*

Scenarios	**Reference**	**Masking**	**Masking with down tilt**
Mean(dBm)	-87.58	-66.33	-49.26
Median(dBm)	-83.52	-66.68	-42.74

From Table 6, the mean of the reference received signal strength between the 3 scenarios have significant differences compared to the 2.1 GHz frequency band. The reference values are once again lower than those of the masking and masking with down tilt scenarios. The masking with down tilt scenario gives better performance than earlier two scenarios.

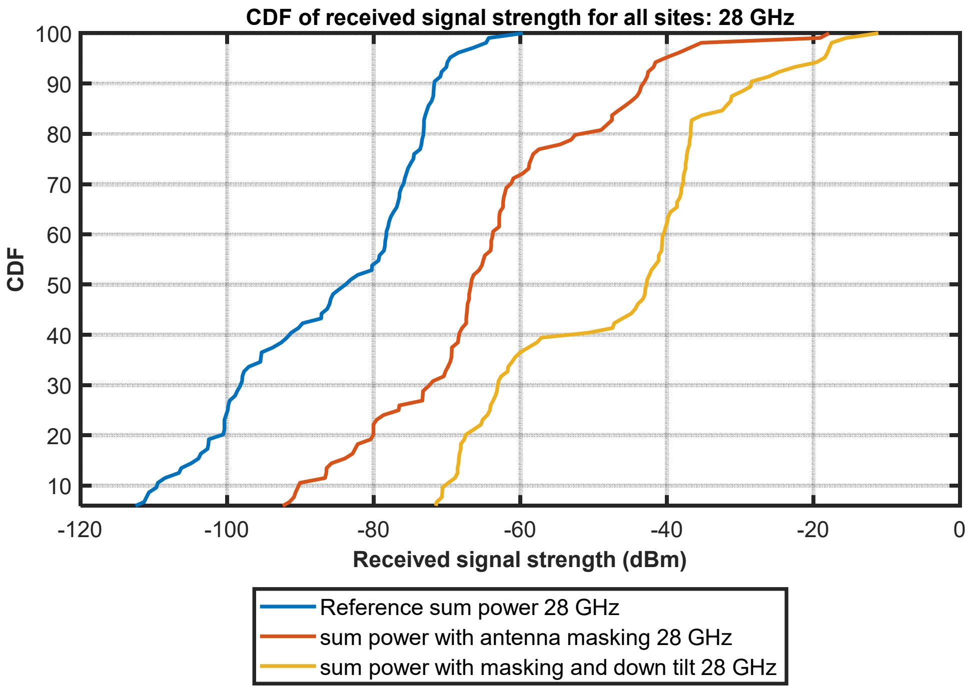
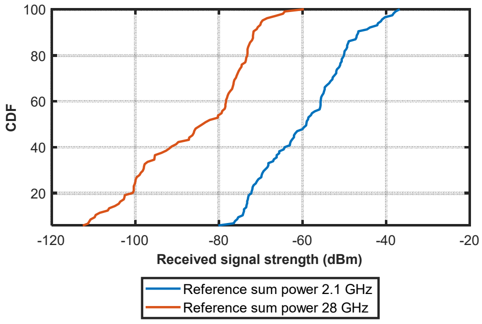


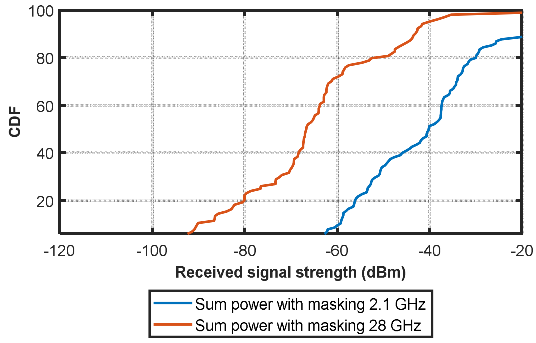
Figure 23. *CDF of received signal strength of all simulation scenarios in 28 GHz.*

Figure 23 shows the received signal strength for all users being served by all the sites in the 28 GHz frequency band. There are significant differences between all the scenarios than in the 2.1 GHz frequency band. The difference between the reference and the masked antenna scenario is about 21 dB, while the difference between the reference and the masking with down tilt scenario is 38 dB. Therefore, signal losses when using an isotropic antenna are significant in millimetre waves, and sectorization, masking and tilting have a big effect in high frequency band transmission.

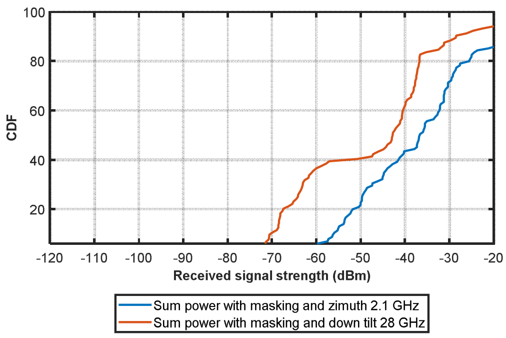
Figure 24 (a) – (d) illustrates the comparison between the 2.1 GHz frequency and the 28 GHz frequency in each simulation scenario. For the reference scenario has the largest difference between the 2.1 GHz and the 28 GHz. Since the isotropic antennas radiate equally in all directions, it is expected that the 28 GHz scenario experiences more losses as discussed in earlier chapters due to shorter wavelengths and higher diffraction and reflection losses.



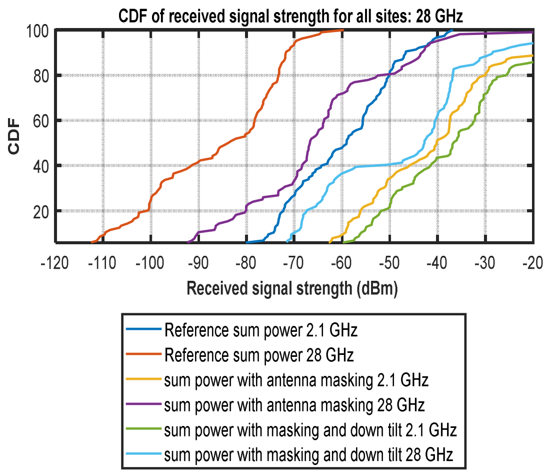
(a)



(b)



(c)



(d)

Figure 24. *CDF of received signal strength comparison between each simulation scenario for 2.1 GHz and 28 GHz. (a) Reference, (b) Antenna masking, (c) Antenna masking with down tilt, (d) All scenarios in 2.1 GHz and 28 GHz comparison.*

Figure 24 (b) also shows that the system performance of the 2.1 GHz system is better in comparison to that of the 28 GHz system. This is expected because of the losses experienced by mmWaves. The performance of the masking and down tilt scenario as shown in figure 24 (c) follows the expected trajectory as the reference and masking scenarios, but without the markedly large margins in the performance. It is therefore observed that the 28 GHz systems experience larger losses during transmission than those at 2.1 GHz. Figure 24 (d) gives a better view of the comparison of all scenarios in 2.1 GHz and 28 GHz for better analysis. The figure shows that the 2.1 GHz system has a better performance overall.

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

The SINR was calculated by adding up the ten most useful signals received by a user, which were then divided by all the other signals arriving at UE and the calculated noise of the system. The unit of measurement is dB. To calculate the noise, a bandwidth of 20 MHz is considered for the 2.1 GHz system and both 20 MHz and 200 MHz for the 28 GHz scenario. The expectation is that a large value of SINR indicates that the system performance is better. Table 7 shows the mean and median values of the SINR in the 2.1 GHz frequency band simulation scenarios.

Table 7. *Mean and median of SINR at 2.1 GHz.*

Scenarios	Reference	Masking	Masking with down tilt
Mean(dB)	11.49	53.62	58.62
Median(dB)	3.29	30.53	35.71

The mean and median values at 2.1 GHz are significantly larger for the reference scenario and the antenna masking with down tilt scenario, with a mean difference of 47.13 dB and a median difference of 32.42 dB

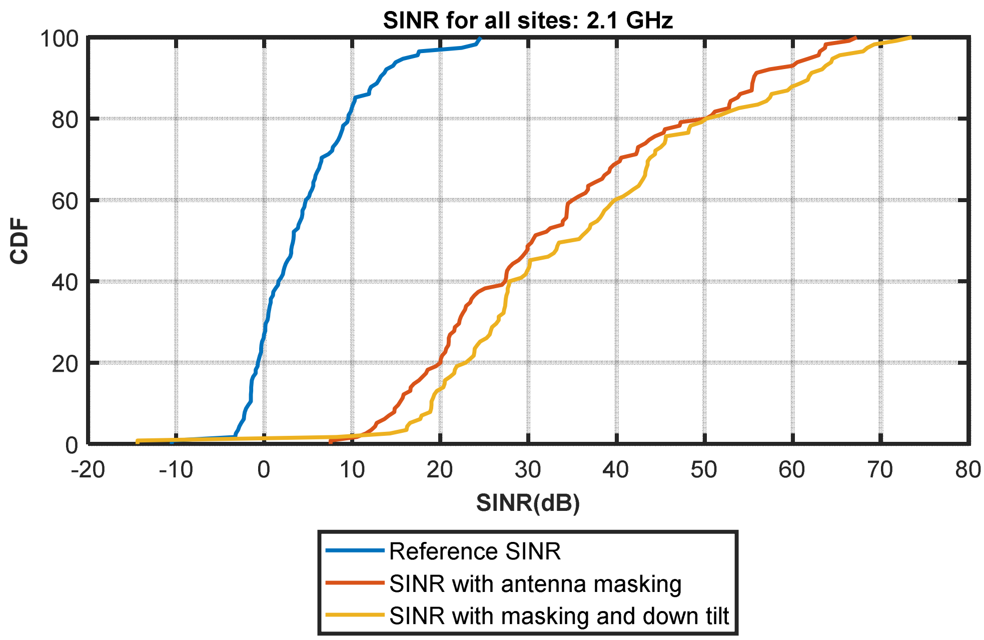


Figure 25. *CDF of SINR of all simulation scenarios in 2.1 GHz.*

Figure 25 shows the CDF of all three scenarios in the 2.1 GHz frequency band. There is a substantial difference between the reference scenario and the antenna masking as well as masking with down tilt and a difference of 5dB in the mean between the SINR of the antenna masking and antenna masking with down tilt scenario. The SINR values are quite high because only the strongest 10 signals are considered for the signal power. The rest of the poor signals are treated as interference. Overall, the masking scenario and masking with down tilt angles scenario are comparable and therefor provide better SINR values.

Table 8. *Mean and median of SINR at 28 GHz (20 MHz bandwidth).*

Scenarios	Reference	Masking	Masking with down tilt
Mean(dB)	9.75	44.07	56.13
Median(dB)	1.65	24.34	44.06

Table 8 shows the mean and median of the 28 GHz simulation scenarios with an allocated bandwidth of 20 MHz. Figure 26 shows the SNIR values of all the scenarios in 28 GHz frequency band.

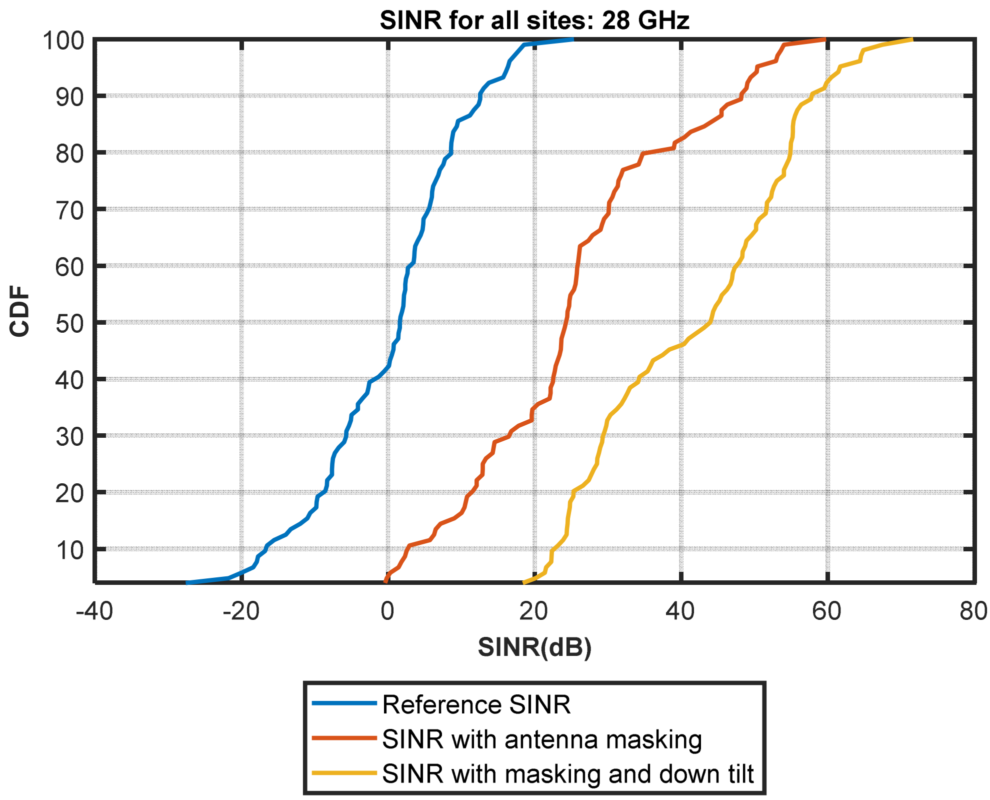
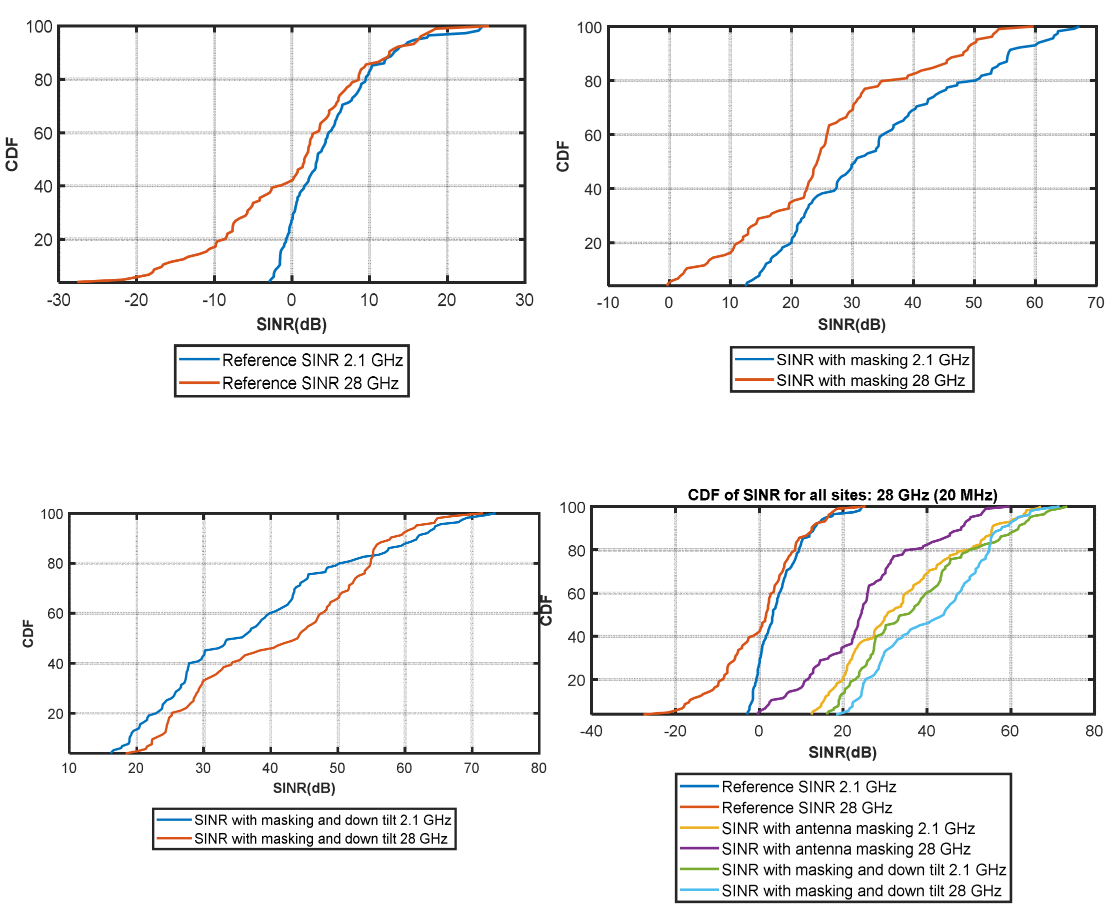


Figure 26. *CDF of SINR of all simulation scenarios in 28 GHz (20 MHz).*

It can be seen that the mean of the reference scenario that the SINR is lower than that of the antenna masking scenario, with a difference of 34.32 dB, and a difference of about 46.38 dB in the mean between the reference scenario and the masking with down tilt scenario, meaning that masking antennas and tilting the antennas improves the system SINR in mmWaves frequency band significantly. The median values of the reference signals are 22.69 dB lower than that of the masking scenario, and 42.41 dB lower than the antenna masking with down tilt scenario.

Figure 26 illustrates the SINR values of all scenarios and as previously discussed, the differences between the three simulation scenarios are marginal, but the antenna masking with down tilt scenario gives slightly better SINR values.



(a) (b)

(c) (d)

Figure 27. *CDF of received signal strength comparison between each simulation scenario for 2.1 GHz and 28 GHz. (a) Reference, (b) Antenna masking, (c) Antenna masking with down tilt, (d) All scenarios in 2.1 GHz and 28 GHz comparison.*

Figure 27 (a) – (d) shows the comparison in SINR values between the 2.1 GHz frequency band simulation scenarios and the 28 GHz frequency band scenarios. From the figures, the 2.1 GHz SINR values are higher than those of the 28 GHz in all scenarios except in the antenna masking with down tilt scenario where the performance of the 28 GHz system is slightly better than that of 2.1 GHz An additional gain of 16.5 dB has been added for the 28 GHz system by assuming the presence of antenna arrays that are used in mmWaves cellular transmission antennas.

The simulation at the 28 GHz is also repeated with an allocated bandwidth of 200 MHz and the comparison was repeated.

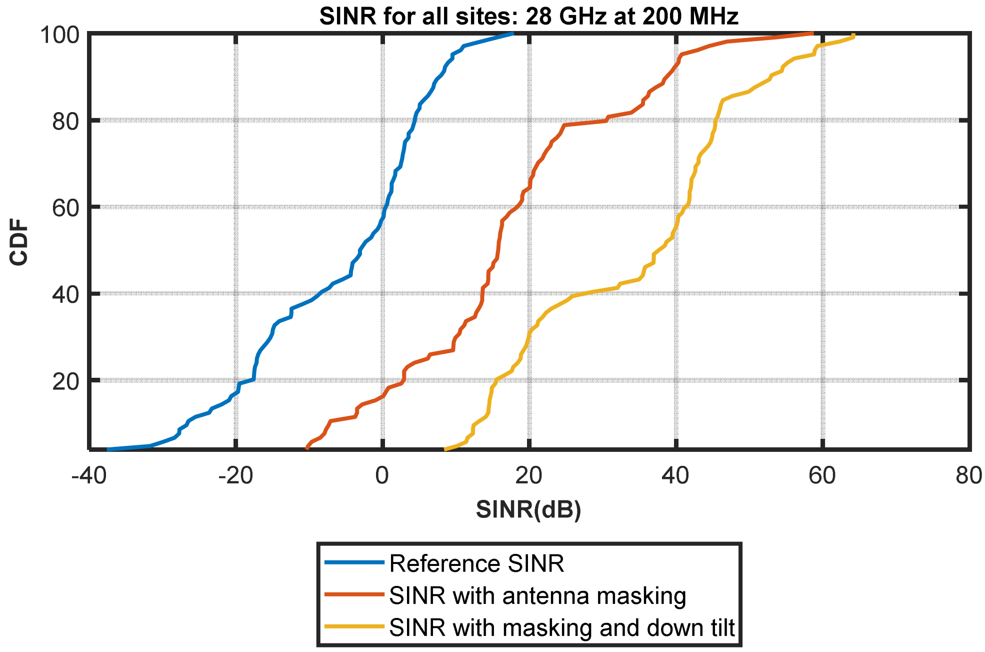


Figure 28. *CDF of SINR of all simulation scenarios in 28 GHz (200 MHz).*

Figure 28 shows the result of the simulation when the bandwidth is changed from 20 MHz to 200 MHz. The reference scenarios have the lowest SINR values as was the case with the 20 MHz bandwidth simulation. A mean of 4.29 dB is observed for the reference scenario. There is a difference of 36.29 dB between the reference and the antenna masking scenario, and a difference of 46.38 dB between the reference scenario and the antenna masking with down tilt.

Table 9. *Mean and median of SINR at 28 GHz (200 MHz bandwidth).*

Scenarios	**Reference**	**Masking**	**Masking with down tilt**
Mean(dB)	4.29	40.54	50.67
Median(dB)	-2.90	15.75	38.03

From table 9, the median SINR value of the 28 GHz scenario with 200 MHz bandwidth system in the reference scenario case is a negative value. This means that interference plus noise is higher in this scenario. follow the same trajectory as those of the 20 MHz bandwidth. The differences between the 20 MHz and the 200 MHz systems are higher than those between the 20 MHz system and the 2.1 GHz system. The SINR values in the 28 GHZ system with 200 MHz band have decreased slightly. The biggest decrease is a 5.46 dB drop in the antenna masking with down tilt scenario, which means that there is increased noise and interference with an increase in bandwidth in the system, but it is more pronounced in an isotropic antenna. The conclusion observed here is that increasing bandwidth reduces the SINR of the system.

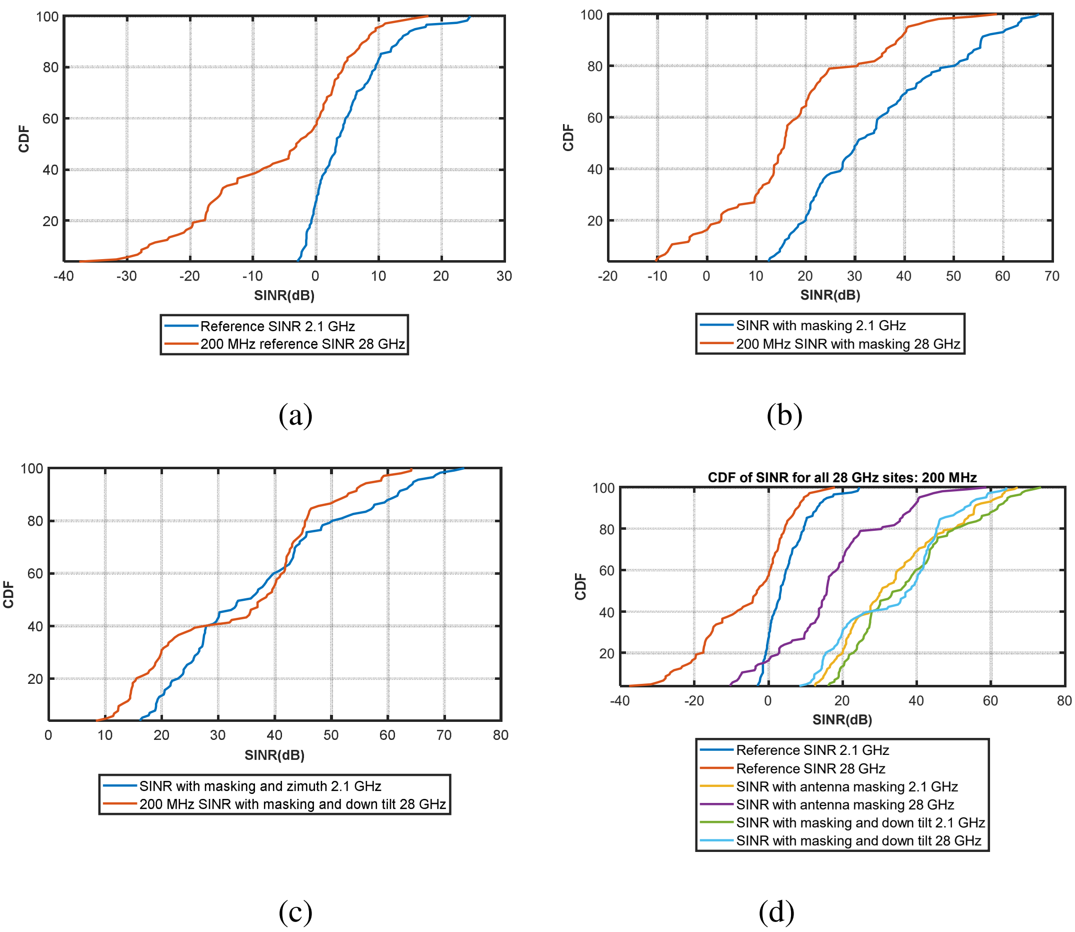


Figure 29. *CDF of received signal strength comparison between each simulation scenario for 2.1 GHz and 28 GHz with 200 MHz (a) Reference, (b) Antenna masking, (c) Antenna masking with down tilt, (d) All scenarios in 2.1 GHz and 28 GHz comparison.*

Figure 29 (a) – (d) compares all the scenarios between the 2.1 GHz frequency band with 20 MHz bandwidth and 28 GHz frequency band with 200 MHz bandwidth. The 2.1 GHz system has higher SINR values compared to the 28 GHz. The biggest difference is in the mean of antenna masking scenarios that has a difference of 13.08 dB. An additional gain of 16.5 dB was added to the antenna gains in the 28 GHz simulation just like the previous case, with the assumption of the presence of antenna arrays.

6.3 Spectral efficiency

The spectral efficiency of a radio transmission system is a measure of the rate of the transmission or transfer of information in the system. It is used to determine the number of concurrent users that a system can serve when we have set requirements for each user. The formula used (14) is described in detail in chapter 4. A higher spectral efficiency indicates that the allocated bandwidth in use is efficiently utilized. Since the spectral efficiency is related to the SINR level, a better spectral efficiency is therefore achieved with higher SINR values.

A comparison between the different simulation scenarios is presented in table 10 and figure 30 below.

Table 10. *Spectral efficiency for all the scenarios at 2.1 GHz 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	2.20	1.70	1.05
Masking	11.17	8.32	5.95
Masking with down tilt	12.31	13.51	11.07

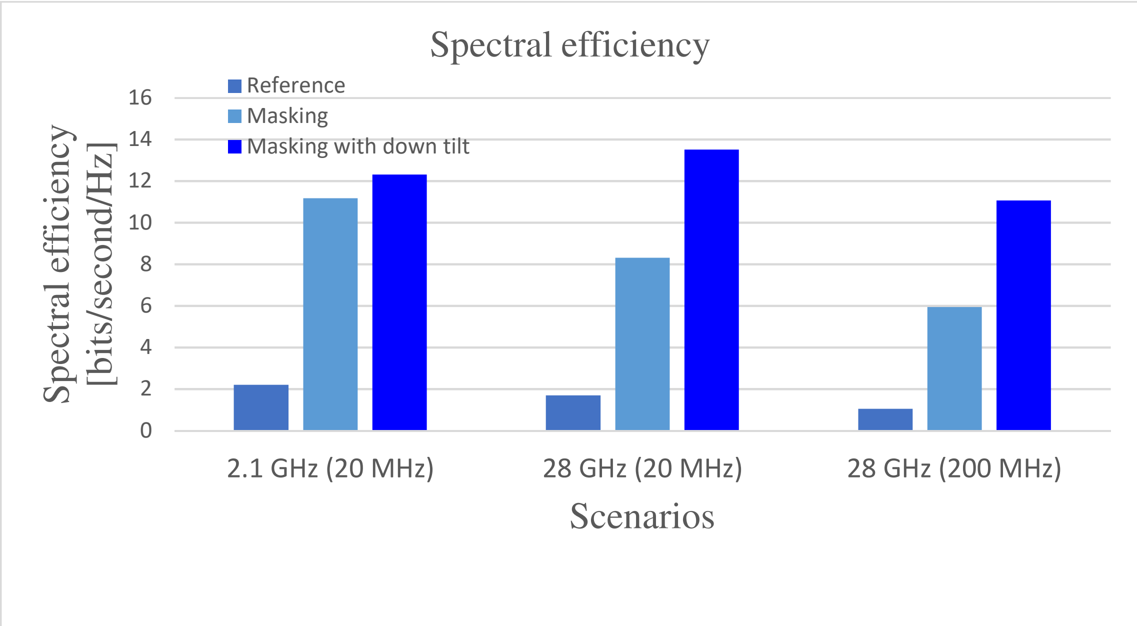


Figure 30. *Spectral efficiency comparison summary of all scenarios in 2.1 GHz and 28 GHz.*

The evaluation is done over 2.1 GHz with a bandwidth of 20 MHz, as well as over 28 GHz with bandwidth values of both 20 MHz and 200 MHz. The unit of measurement is bits/second/hertz. From table 10, the observation is that the spectral efficiency of the masking with down tilt scenario in the 28 GHz has the highest value of all other scenarios. But it is not significantly higher than the same scenario in the 2.1 GHz system. The same down tilt angles have been used for the 2.1 GHz frequency band and the 28 GHz frequency band.

In the 28 GHz frequency scenarios, there is a slight drop in the spectral efficiency from the 20 MHz and 200 MHz cases. It is therefore observed that increasing the bandwidth of the 28 GHz scenario from 20 MHz to 200 MHz reduces the spectral efficiency marginally.

6.4 Area spectral efficiency

The area spectral efficiency is defined as the total of the maximum average data rates for a unit bandwidth for a BS or cell unit area. This parameter can be used to calculate the best and worst-case scenarios in interference configurations. The area spectral efficiency can be expressed as a function of the re-use distance in this calculation. In this simulation however, it is calculated as the product of the cell density and spectral efficiency because of the irregular site constellation used in this simulation. The expression used to calculate it is shown in equation (17). The unit of measurement is bits/second/hertz per area.

Table 11 gives the summary of the area spectral efficiency in all scenarios in the 2.1 GHz and 28 GHz frequency band systems. The two scenarios with antenna masking and antenna masking without down tilt meant that there is a total of 30 sites, instead of 10 as is the case in the reference scenario with only one isotropic antenna.

Table 11. *Area spectral efficiency for all the scenarios in 2.1 GHz and 28 GHz frequency.*

Frequency bands	**2.1 GHz (20 MHz) [bits/second/Hz/Area]**	**28 GHz (20 MHz) [bits/second/Hz/Area]**	**28 GHz (200 MHz) [bits/second/Hz/Area]**
Reference	22.02	17.07	10.55
Masking	335.1	249.79	178.69
Masking with down tilt	369.41	405.40	332.26

From table 11, it is observed that in the reference scenarios in 2.1 GHz, 28 GHz with 20 MHz bandwidth and 28 GHz with 200 MHz bandwidth have the lowest area spectral efficiency. The antenna masking with down tilt scenarios in both the 28 GHz simulation and the 2.1 GHz scenario with a bandwidth of 20 MHz have the best area spectral efficiency values, with the 28 GHz scenario with 200 MHz bandwidth has the best area spectral efficiency values. However, there is a significant decrease in area spectral efficiency with the allocated bandwidth increased from 20 MHz to 200 MHz in the 28 GHz system. Since 30 sites were considered in the antenna masking and antenna masking without down tilt scenarios, it is expected that the area spectral efficiency is much higher than in the reference case. In this simulation, an increase in bandwidth increased the area spectral efficiency.

6.5 Throughput

Throughput is a performance metric that is used to measure the amount of data that is moved from a transmitter to a receiver over a given link in a given time period. The system throughput is determined by summing up the data rates from all the users in the system under consideration.

The throughput is determined by first calculating the system capacity according to Shannon's capacity formula, used to determine the information transfer upper bound theoretically. The results are expressed in Mbps. Equation (15) is used to calculate the system throughput, and the results are summarised in table 12.

Table 12. *Summary of throughput for all scenarios in 2.1 GHz and 28 GHz frequency.*

Frequency bands	**2.1 GHz (20 MHz) [Mbps]**	**28 GHz (20 MHz) [Mbps]**	**28 GHz (200 MHz) [Mbps]**
Reference	44.04	34.15	211.04
Masking	223.46	166.53	1191.30
Masking with down tilt	246.28	270.27	2215.1

Table 12 illustrates the summary of the throughput values for all scenarios in 2.1 GHz with a bandwidth of 20 MHz and 28 GHz with both 20 MHz and 200 MHz bandwidth values. The reference scenarios for all three cases have lower throughput values than the other two scenarios. The highest throughput is the antenna masking with down tilt scenario in the 28 GHz frequency with 200 MHz bandwidth. The increase in bandwidth in the 28 GHz frequency case increases the system throughput by over 8 times. On the other hand, with a bandwidth of 20 MHz for both 2.1 GHz and 28 GHz systems, the throughput of the 28 GHz system drops slightly compared to that of 2.1 GHz in the reference and the antenna masking scenarios but improves slightly in the antenna masking with down tilting scenarios. The overall system throughput in all three cases are significantly high because the BSs are assumed to be serving only outdoor users, and serving very few users.

6.6 Transmission power efficiency

Transmission power of BSs has a direct relationship with power efficiency in the network. Power efficiency is the ratio of the total output power to the total input power. In this thesis, the equation (19) for transmission power efficiency is given in chapter 4. The unit of measurement of power efficiency is bps/Hz/W/Area.

The summary of the power efficiency for all scenarios is given in table 13 below.

Table 13. *Power efficiency for all scenarios in 2.1 GHz and 28 GHz frequency.*

Frequency bands	**2.1 GHz (20 MHz) [bps/Hz/W/Area]**	**28 GHz (20 MHz) [bps/Hz/W/Area]**	**28 GHz (200 MHz) [bps/Hz/W/Area]**
Reference	0.0551	0.0427	0.0264
Masking	0.2793	0.2082	0.1489
Masking with down tilt	0.3078	0.3378	0.2769

From table 13 above, the conclusion is that the power efficiency is slightly higher in the masking with down tilt scenario of the 28 GHz frequency system with 20 MHz. The difference in power efficiency between 2.1 GHz and 28 GHz masking with 20 MHz bandwidth scenarios is 0.071 bps/Hz/W/Area, which would give a reduction in power efficiency of 34.14% in the 28 GHz system. In the antenna masking with down tilt scenario, the difference between the 2.1 GHz and 28 GHz with 20 MHz bandwidth is 0.003 bps/Hz/W/Area which is an improvement of 9.74% in the 28 GHz system. Therefore, there is no significant improvement when using the mmWaves as compared to the 2.1 GHz transmission frequency, all other factors being constant. An increase in bandwidth however slightly lowers the power efficiency. This could be due to increased noise when using a larger frequency bandwidth. The 28 GHz frequency with 200 MHz bandwidth performed the worst amongst all 3 systems. It is important to note that the assumption made when calculating the power efficiency is that the BSs are transmitting at full power and only serving the outdoor users. This could alter the analysis compared to instances where the indoor users are considered.

7. CONCLUSIONS

The global shipment of smartphones and other mobile devices such as tablets has continued to rise year-on-year, as users prefer to use more technologically advanced devices for personal and professional use. At the same time, there is a major shift to mobile broadband usage. With numerous devices connected to their networks, MNOs need to meet the demand for bandwidth hungry and low latency applications. The conventional networks as currently designed and deployed are not able to meet this demand sufficiently, partly due to limited spectrum that constraints the amount of bandwidth that is available for use, and the amount of transmission power from the BSs. Mobile network technologies are not evolving fast enough to meet the demand for support of numerous devices and high data consumption. Shortage of adequate spectrum below 6 GHz has spurred research into high frequency bands, where large unlicensed bandwidth is available in the mmWave bands, which in turn can provide higher data rates and low latency. The next generation of mobile networks, 5G has been allocated spectrum in these higher frequency bands.

The expectation on 5G is that it will solve some of these issues. However, the issue of having more base stations and more antennas leads to the conclusion that power consumption will be higher than that of 4G. Energy is a limited resource and therefore, research on 5G has brought the issue to the fore and there are suggested ways of increasing energy efficiency of the entire network. There are already suggested solutions such as more efficient modulation schemes and use of massive antenna arrays. It remains to be seen how effective these methods are in a real-life deployment of 5G networks.

The aim of this thesis was to study the energy efficiency performance of mobile networks based on the more common frequency of 2.1 GHz and those operating at higher frequencies, with 28 GHz being used in this case. The two systems were then compared. For the 2.1 GHz system, 20 MHz was the allocated bandwidth for the simulations, and for the 28 GHz case, an initial bandwidth of 20 MHz was allocated, and then it was increased 10 times to 200 MHz and the simulation evaluated again. The first scenario involved the use of an isotropic antenna. This is an antenna that radiates power in all directions uniformly and was used as the reference antenna. The second and third scenarios involved sectorization of the antenna into three different sectors. To obtain gains in the elevation and down tilt plane, antenna modelling was then done. Performance metrics under consideration were the received signal strength, SINR, spectral efficiency, area spectral efficiency, throughput and transmission power efficiency. These were evaluated and analysed, and then a comparison between the two different systems done.

The first performance metric to be evaluated was the received signal strength. The CDF plots showed that the received signal strength values of the 2.1 GHz system were higher than those of the 28 GHz frequency system in all scenarios. It can also be seen that the reference scenario performed the worst in both systems. The best received signal strength values were obtained in the 2.1 GHz system where both antenna masking and down tilt was done. The simulation network was only assumed to be only serving outdoor users in both systems and therefore indoor users were eliminated. The 10 strongest signals of the serving cell were the only ones considered and therefore, it is possible the results are not completely replicable in a real network. One way to improve the received signal levels in the 28 GHz system could be the use of antenna arrays or HetNets to cover users located away from the macro sites.

The next parameter considered was the SINR. This is the ratio of the signal power to the total power of the interference plus noise. When both the 2.1 GHz and 28 GHz systems have the same allocated bandwidth of 20 MHz, the 2.1 GHz has better SINR values in all scenarios, with the isotropic scenario having lower values than the antenna masking and the antenna masking with down tilt scenario. The allocated bandwidth for the 28 GHz system was then increased to 200 MHz and it was observed that there was a slight decrease in the system SINR as compared to the 20 MHz case, and the SINR of the 2.1 GHz system was still higher than that of the 28 GHz frequency system. In both systems, the antenna masking with down tilt scenario had better SINR values than the values in antenna masking only scenario and reference scenarios. The same down tilt angles were used for both systems. One way of improving the SINR would be to optimize the down tilt angles to prevent overshooting and inter-site interference.

The spectral efficiency and the area spectral efficiency were studied next. Spectral efficiency of a radio transmission system is a measure of the rate of the transmission or transfer of information in the system. The area spectral efficiency is defined as the total of the maximum average data rates for a unit bandwidth for a BS or cell unit area. It was observed that the spectral efficiency and area spectral efficiency of the 2.1 GHz frequency system was higher compared to the 28 GHz system when the allocated bandwidth for both systems was 20 MHz, except in the antenna masking with down tilting scenario, where the 28 GHz system with 20 MHz bandwidth performed slightly better. In this case, the improvement was due to the down tilting. Increasing the bandwidth of the 28 GHz system to 200 MHz reduced spectral efficiency of the 28 GHz system in all scenarios.

System throughput is used to measure the amount of data transmitted from a transmitter to a receiver over a given link in a given amount of time. It was observed that the 2.1 GHz frequency system produced the best throughput compared to the 28 GHz system when they both have the same allocated bandwidth of 20 MHz. Increasing the bandwidth of the 28 GHz frequency system from 20 MHz to 200 MHz increased the throughput significantly by 8 times in the masking plus azimuth scenario. System throughput is dependent in part on the number of users that are connected to the system and the system capacity, therefore, few users result in higher throughput because there is a big amount of free bandwidth.

The final parameter that was evaluated in this thesis was the transmission power efficiency. Power efficiency is the ratio of the total output power to the total input power of a system. It was observed that the power efficiency of the system reduced slightly in the reference scenario from the 2.1 GHz system to the 28 GHz system with the 20 MHz bandwidth. There was a further drop in power efficiency in the 28 GHz system once the bandwidth was increased to 200 MHz in the same scenario. However, in the antenna masking and the antenna masking with down tilt scenario, the 28 GHz system with 20 MHz bandwidth had higher transmission power efficiency. It was assumed that the BSs were transmitting at full power of 40 W as is often the case in mobile networks. The conclusion is that with all things constant, a mmWave frequency transmission with higher bandwidth has slightly worse power efficiency in comparison to the lower frequency transmission systems but a similar bandwidth results in a slightly poorer outcome for the mmWave system.

The simulation environment was modelled as closely as possible to a real network deployment scenario, and the accuracy of the results were dependent on the modelled environment, simulation parameters and the simulation tools. Therefore, values may vary from those obtained from a real network deployment. The results suggest that the 28 GHz transmission systems perform slightly worse in a macro environment than the 2.1 GHz systems if all the parameters are similar. However, this may not be the case in a practical network deployment. The results suggest that it is theoretically possible to deploy the 28 GHz frequency 5G macro cells in the same site locations as the 2.1 GHz cells in a dense urban environment as was in the simulation scenario.

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