Tampere University

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# MMWAVE COMMUNICATION FOR 5G MOBILE NETWORKS

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# ABSTRACT

Triet Nguyen Le Minh: mmWave communication for 5G mobile networks
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Fifth generation (5G) mobile networks are one of the huge developments in recent years. This thesis presents a study on the use of millimeter-wave (mmWave) communication in 5G mobile networks. It begins with an overview of 5G technology, including the various frequency bands utilized. The enabling technologies for mmWave, such as radio access network (RAN) architecture, antennas, and beamforming techniques, are examined, including beam acquisition and tracking. The characteristics and performance of mmWave communication, including signal transmission, system design implications, and physical limitations like blockage and multipath fading, are discussed. The potential applications and future prospects of mmWave technology, including commercial applications and the possibilities for hybrid sub 3GHz/mmWave networks with enhanced spectral, energy, and cost efficiency, are also examined.

Overall, mmWave communication emerges as a promising technology for 5G mobile networks, offering faster data rates, improved capacity, and reduced latency. However, it also presents unique challenges, necessitating careful system design and the mitigation of physical limitations. As we move into the future, it is crucial to continue exploring the possibilities of mmWave technology and finding innovative solutions to overcome its challenges. This thesis contributes to our understanding of mmWave communication for 5G mobile networks, offering an overview of this important and rapidly evolving field.

Keywords: 5G networks, mmWave technology, beamforming, antennas

The originality of this thesis has been checked using the Turnitin Originality Check service.

# PREFACE

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Tampere, 16 May 2023

Triet Nguyen Le Minh

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| 3G | Third generation |
| 4G | Fourth generation |
| 5G | Fifth generation |
| AM | Acknowledged Mode |
| APA | Analog Phase Array |
| ARQ | Automatic Repeat Request |
| BSs | Base stations |
| CoMP | Coordinated Multipoint |
| CP | Control Plane |
| CU | Central Unit |
| DL | Downlink |
| DU | Distributed Unit |
| FRs | Frequency Ranges |
| GHz | Gigahertz |
| HPA | Hybrid Phase Array |
| IoT | Internet of Things |
| IP | Internet Protocol |
| LOS | Line-of-sight |
| MAC | Medium Access Control |
| MIMO | Multiple Input Multiple Output |
| mmWave | Millimeter wave |
| MSC | Mobile Switching Center |
| NLOS | Non-line-of-sight |
| NR | New Radio |
| PDCP | Packet Data Convergence Protocol |
| PHY | Physical Layer |
| RAN | Radio Access Network |
| RF | Radio Frequency |
| RLC | Radio Link Control |
| RRC | Radio Resource Control |
| RX | Receiving |
| SNR | Signal-to-Noise Ratio |
| TM | Transparent Mode |
| TX | Transmitting |
| UE | User Equipment |
| UL | Uplink |
| UM | Unacknowledged Mode |
| UP | User Plane |

# 1. INTRODUCTION

The introduction of the fifth generation mobile networks (5G) has been a significant milestone in telecommunications. With the world rapidly moving towards digitalization, the demand for high-speed and reliable communication has never been higher. 5G technology offers a faster and more efficient communication experience compared to its predecessors, such as the fourth generation mobile networks (4G). It has the potential to bring about a new era of connected devices and the Internet of Things (IoT), changing the way we live and work.

This thesis aims to investigate the potential of millimeter wave (mmWave) technology as one of the main enabling technologies of 5G networks. Specifically, the thesis seeks to address how mmWave can be utilized to provide higher data rates and lower latency for 5G networks. As licensed frequency bands are getting congested for commercial mobile network operators, it is important for the telecom industries and academia to utilize the radio spectrum using mmWave frequency bands. These higher frequency bands provide a large amount of unused spectrum, enabling the 5G network to offer a wider bandwidth and lower latency than 4G. The use of mmWave in 5G technology is crucial in addressing the increasing demand for high-speed and reliable communication in the era of digitalization. By investigating the potential of mmWave technology, this thesis provides an overview of its advantages and limitations in the context of 5G mobile networks.

The work of this thesis was assisted by chatGPT for wording and checking grammar.

# 2. AN OVERVIEW OF 5G TECHNOLOGY

This chapter provides an overview of 5G technology, specifically focusing on its frequency bands. It begins by introducing the fundamental concepts of 5G technology and then explores the various frequency bands used in 5G communication networks.

## 2.1 5G technology

Currently, 5G technology is being utilized in various industries such as commercial mobile networks, healthcare, transportation, and more, showing its wide-ranging potential and impact. For instance, in healthcare, 5G technology can be used to facilitate remote surgeries and improve the overall quality of care. In the entertainment industry, 5G technology provides users with a high-quality and low-latency experience, making it possible to stream high-definition videos and play online games with less latency. In the transportation industry, 5G technology can be used to improve the safety of autonomous vehicles and reduce the risk of accidents. In short, 5G will bring revolutionary improvement to many industries and to user experience. To understand its potential, it is essential to learn its key technologies and what differentiates it from the previous generation of mobile network generation.

## 2.2 5G frequency ranges and sub-bands

5G technology works on two primary frequency ranges (FRs): the frequency range below 6 GHz (the sub-6GHz), and the millimeter wave frequencies (mmWave). Figure 1 [19] demonstrates various sub-bands in the two primary ranges. For example, sub-6GHz ranges include 600 MHz, 700 MHz, 800 MHz, 900 MHz, 2.3 GHz, 2.6 GHz, and 3.5 GHz bands, and mmWave ranges include the 24 GHz, 28 GHz, 37 GHz, 39 GHz, and 47 GHz bands.

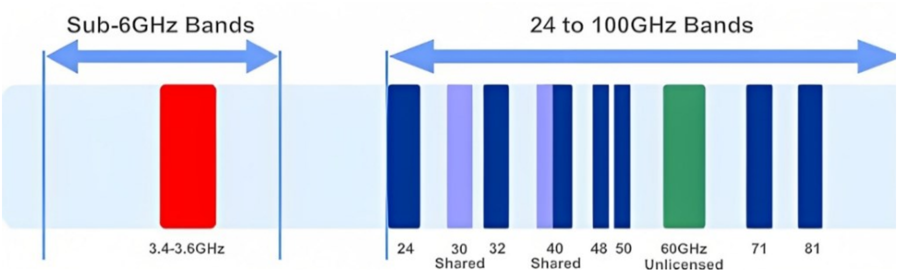


***Figure 1.*** *Usage of different frequency bands in 5G technology.* [19]

The sub-6GHz frequency range is the lower frequency range used by 5G technology. It offers improved coverage and penetration through walls and other obstacles, surpassing those of higher frequency ranges. This range has a wider coverage area and can reach up to several kilometres from a single cell tower. However, it is important to note that the data rate of the sub-6GHz range is not significantly high compared to mmWave range. The benefits of the sub-6GHz range are mainly in its increased capacity compared to 4G technology, which allows for more devices to connect to the network simultaneously.

The sub-6GHz range operates at a frequency below 6 GHz. This is similar to the frequency range used by 4G technology. In fact, many carriers are using this range for their initial 5G deployments. However, this range has a limited spectrum, which means that it can become congested quickly as more devices connect to the network.

The mmWave frequency range is the higher frequency range used by 5G technology. It offers data rates are notable higher than in the other frequency range, but its coverage area is limited. The mmWave frequency range operates at frequencies above 24 GHz, which allows for much faster data transfer rates compared to sub-6GHz frequency range and older mobile network technology. However, this frequency range has a much shorter range and cannot penetrate through walls and other obstacles. This means that a much larger number of small cell towers will be required to provide coverage in an area, compared to having the area covered by a lower frequency range.

The mmWave frequency range can provide download speeds up to 10 Gbps [16], which is significantly faster than what is currently available through 4G technology. However, it is important to note that the actual speeds that users will experience on the mmWave range will be highly dependent on the density of the network, signal strength, device capabilities, network congestion, and environmental conditions, in a given area.

5G technology offers significant improvements over 4G technology in terms of speed, capacity, and reliability. However, the technology has its limitations. The sub-6GHz range offers improved coverage and capacity, while the mmWave range offers incredibly fast download speeds but a limited coverage area. As 5G technology continues to be deployed, service providers will need to balance these two frequency ranges to provide the best overall experience to their users.

# 3. ENABLING TECHNOLOGY FOR MMWAVE

This chapter presents an overview of the key technologies that are involved in the utilization of 5G mmWave frequencies. This includes Radio Access Network, antennas and beamforming technology.

## 3.1 RAN architecture

Radio Access Network (RAN) has been a crucial part of commercial wireless networks since the first generation of mobile networks and is still evolving today. It connects the end-user devices to the core network through a wireless interface, and comprises a set of base stations, antennas, and other network equipment that provides wireless coverage to end-user devices.

In the early days of cellular networks, the RAN architecture was simple, and consisted of a set of cell sites, each of which provided wireless coverage to a particular geographic area [1]. These cell sites were connected to a mobile switching center (MSC) which was responsible for routing calls and managing the network. This architecture was suitable for voice-centric services but was not capable of supporting advanced data services. Throughout the third generation (3G) and 4G networks era, technologies like packet switching, Internet Protocol (IP) based networks, or multiple-input multiple-output (MIMO) techniques and carrier aggregation were introduced. These technologies contributed to higher data rates and improved spectral efficiency.

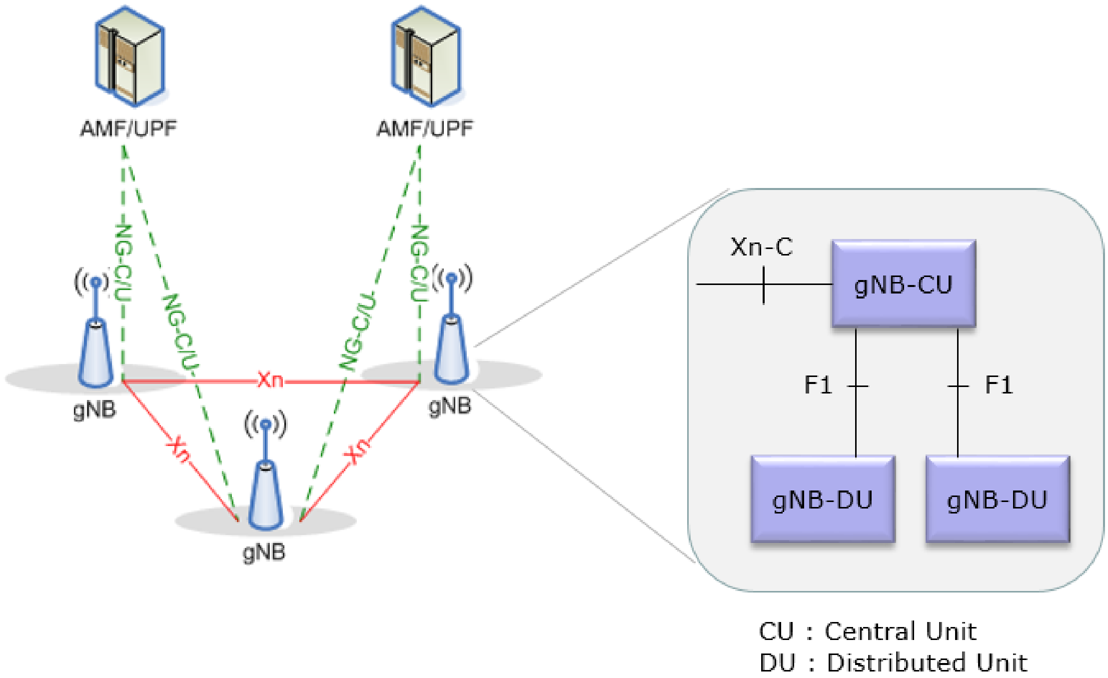


***Figure 2.*** *5G RAN network elements.* [1]

In 5G RAN, the base station is called next generation nodeB (gNB). The gNB architecture is made of two main elements: the central unit (CU) and the distributed unit (DU). The DU is responsible for processing the baseband signals received from the gNB and generating the signals to be transmitted to the UE. It includes the digital signal processors, the memory and storage components, and the fronthaul interface. The CU is responsible for managing the overall operation of the gNB. It includes the control plane functions, such as call setup and handover, and the user plane functions, such as data transmission and reception. Figure 2 [1] provides an overview of the 5G RAN architecture. The division of the control and user planes is a crucial aspect of the versatile 5G Radio Access Network (RAN) due to its alignment with Software-Defined Networking (SDN) and Network Function Virtualization (NFV) methodologies, for example the implementation of service chaining. An overview of various possible RAN split options for the gNB is presented in Figure 3 [1]. Brief explanation of the split options can be found in Appendix A. The gNB will then be connected with the 5G core network through an interface called NG-interface, which is responsible for carrying both user data and control signalling between these two [1].

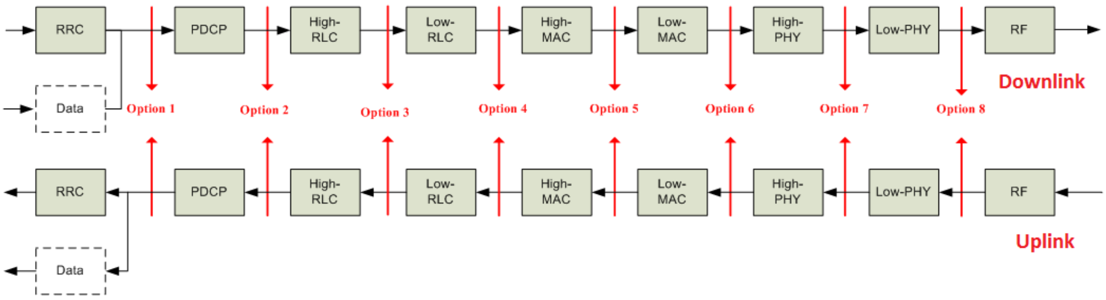


***Figure 3.*** *5G RAN network split options.* [1]

Through the process of function decomposition, isolation, and the establishment of well-defined interfaces, operators have the ability to segregate software and hardware components. The specific way that New Radio (NR) functions are split in the architecture is determined by factors such as the deployment scenarios of the radio network, imposed limitations, and the desired range of supported services.

## 3.2 Antennas

An antenna is a device used to transmit and receive radio frequency (RF) signals in a mobile network. It is an essential component of any wireless communication system, including mobile networks. [15]

In a mobile network, the antenna is typically located on the top of a base station, also known as a cell tower. The antenna is responsible for transmitting and receiving signals between the base station and mobile devices, such as smartphones, tablets, and other wireless devices. At mmWave frequencies, antennas are physically small and can be integrated into chip arrays with 4-8 elements, which offer high gain and the ability to support multiple beams. To ensure optimal data connectivity in all directions around the mobile device, it is crucial to establish high-quality data links. This is accomplished by achieving a high User Equipment Effective Isotropic Radiated Power (UE EIRP) while simultaneously maintaining an acceptable power consumption level. To achieve this delicate balance, it becomes necessary to employ antennas with high gain and the ability to dynamically steer the beam in the desired direction, thereby ensuring sustained link performance [2]. The overall antenna gain and UE EIRP are determined by the number of antenna elements present in the array, and the utilization of beamforming techniques allows for increased antenna gain and enhanced performance. Antennas are arranged in an array and phased to concentrate radiation in a narrow beam, as in this function: $G_{\text{total}} = G_N + 10\log(N)$, where $N$ is the number of elements and $G_N$ is the element gain, which applies in both uplink and downlink. Figure 4 [1] shows a typical diagram for such antennas. Integrating the antenna in the device behind a cover presents challenges, as the cover significantly affects the radiating performance of the antenna at mmWave frequencies. Techniques employed for Radom design within the aerospace sector have been adapted and implemented here [20]. By manipulating the geometry of plastic or glass covers, antennas can be effectively integrated behind them, with the cover acting as a localized lens. Additionally, electromagnetic windows based on the principles of Frequency Selective Surfaces (FSS) can be incorporated to facilitate antenna integration behind metal covers. The compact physical dimensions of mmWave antennas, made possible by their shorter wavelengths (λ) in comparison to lower frequency ranges, offer an alternative means of integration through slot-based designs in the metal rim of the phone [3].

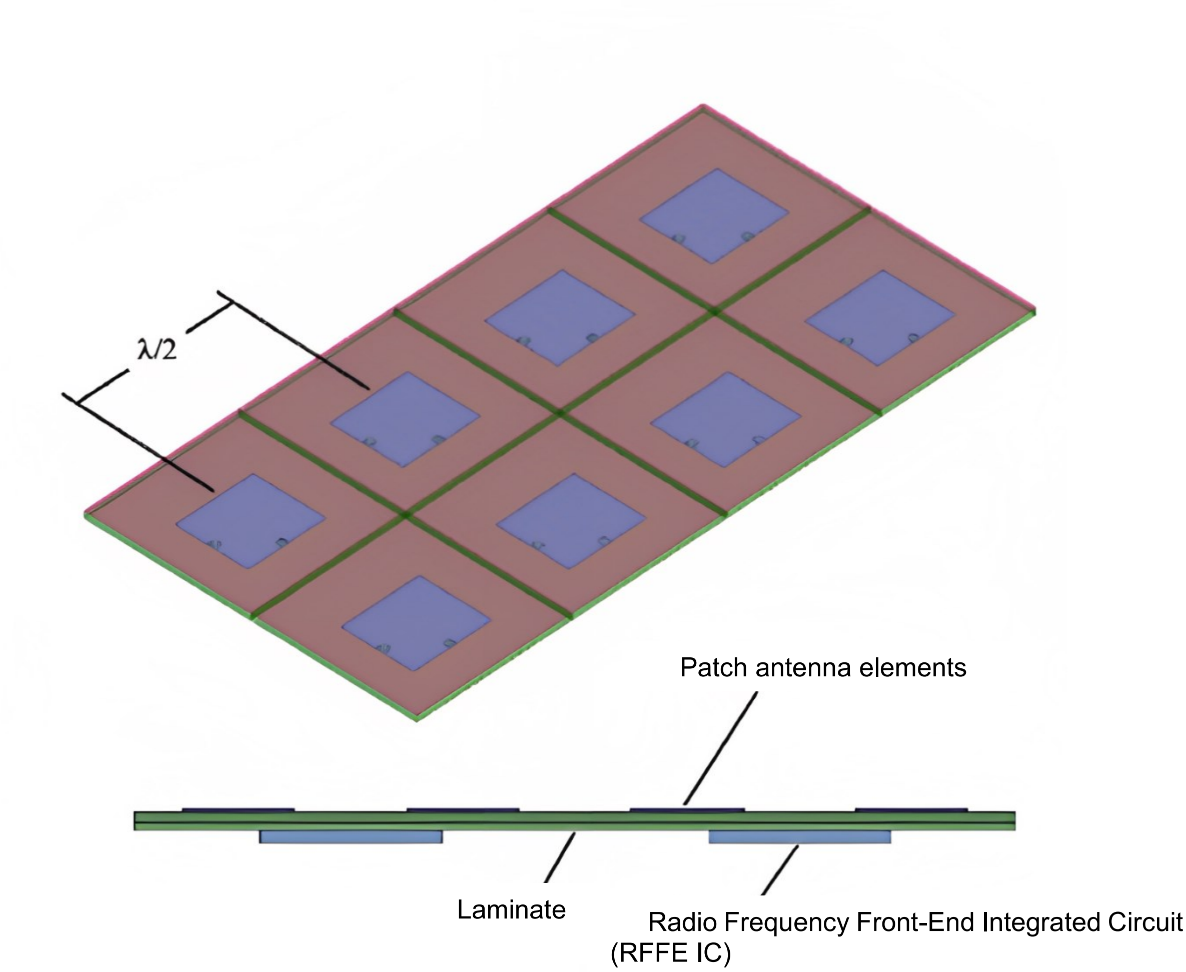


***Figure 4.*** *Typical antenna design for mmWave smartphone.* [1]

## 3.3 Beamforming

Beamforming is a key technology used in 5G mmWave networks to enhance the communication performance of user equipment (UE) by directing the transmitted signals toward the intended receiver. The use of mmWave frequencies in 5G networks presents a unique challenge due to their limited coverage area and high susceptibility to attenuation and blockage. Therefore, focusing the transmitted energy in the desired direction is essential to ensure reliable communication links.

Beamforming provides several benefits for 5G mmWave networks. By directing the energy towards the receiver, the signal strength at the receiver is increased, which results in better signal quality and increased throughput. Additionally, beamforming enables multiple beams to be formed simultaneously, allowing multiple users to be served simultaneously with a very low amount of interference. This results in better spectral efficiency, which is critical in mmWave networks due to their limited bandwidth.

One of the key challenges in implementing beamforming in 5G mmWave networks is the need to accurately estimate the channel characteristics, such as the angle of arrival and the path loss, in real-time. This is necessary to determine the optimal beamforming parameters and steer the beam toward the intended receiver. To address this challenge, advanced signal processing techniques, such as channel estimation and tracking, are used to estimate the channel parameters accurately and adjust the beamforming parameters accordingly.

To achieve effective beamforming, each antenna necessitates an amplitude controller, phase shifter, or time delay element. The arrangement of these components, combined with the geometry of the antenna array, establishes a distinct beamforming architecture. Within mmWave communications, three widely used beamforming architectures are the Analog Phase Array (APA), Hybrid Phase Array (HPA), and Fully Digital Architecture (FDA). While FDA is a common choice for sub-6 GHz massive MIMO communications, it may not be as appropriate for mmWave frequencies due to factors such as channel sparsity and high propagation loss. In terms of performance and cost tradeoffs, HPA and APA are typically the preferred architectures for mmWave. However, there are pending advancements in circuit technologies that may make FDA a viable option as a next generation architecture for mmWave [4].

HPA is a type of antenna array that combines analog and digital processing to optimize performance. In this architecture, the received signal is first converted into the digital domain, where it is processed by a digital beamforming algorithm. The resulting signal is then converted back into the analog domain and amplified before being transmitted. This approach offers good flexibility and scalability, making it suitable for a range of applications.

APA, on the other hand, relies solely on analog processing to adjust the phase of the signals at each antenna element. This allows for greater control over the beam direction and beamwidth but limits the flexibility and scalability of the system. APA is a cost-effective solution for mmWave applications that require relatively simple beamforming capabilities.

FDA is a fully digital architecture that relies on digital signal processing to perform beamforming. This approach offers the highest level of flexibility and scalability, as well as the ability to implement advanced algorithms for interference mitigation and channel estimation. However, FDA may be more complex and costly to implement compared to HPA and APA.

To compensate for the substantial pathloss encountered in mmWave frequency bands, it is necessary to employ beamforming techniques that yield considerable gain, which is needed to achieve a satisfactory signal-to-noise ratio (SNR) and ensure a favourable user experience. The continuous alignment of these beams between the cellular site and the user equipment (UE) is crucial for sustaining the communication link, as illustrated in Figure 5 [1]. However, achieving consistent beam alignment poses a significant challenge in dynamic mobile environments, where the potential for obstructions and blockages is constant. Moreover, mmWave signals have a narrow beamwidth, which means that the beam must be accurately pointed towards the target, which requires high precision and accuracy in aligning the beam. The mmWave transmitter cannot overcome this with more transmission power or beamforming gain, so it must find alternative paths or spatial channels.

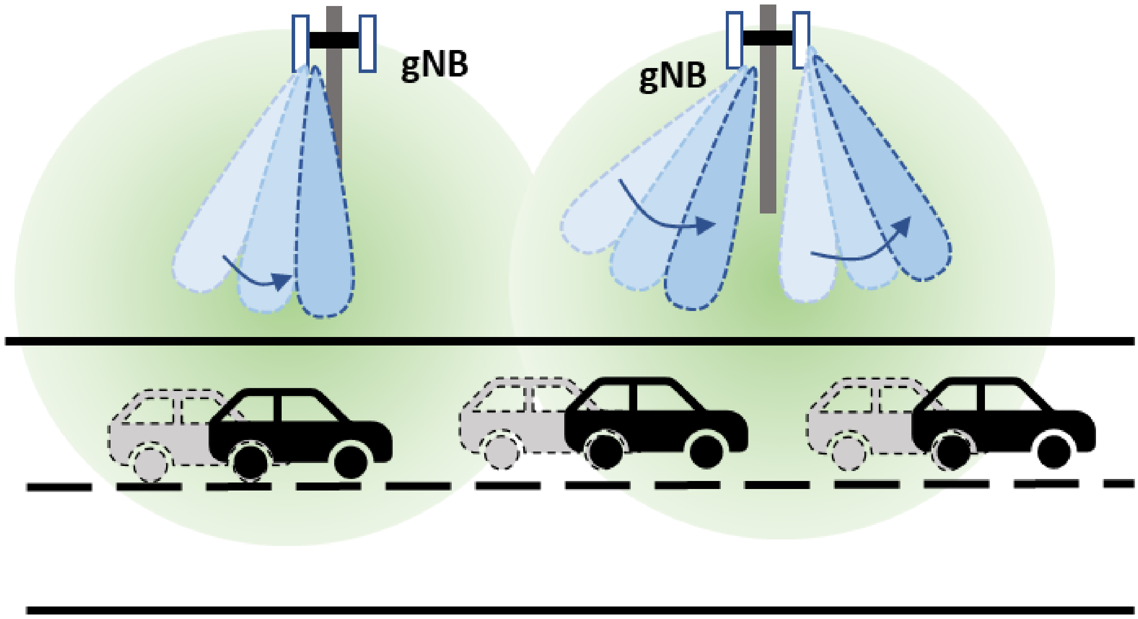


***Figure 5.** Base station beam tracking for sustaining communication link with vehicles.* [1]

APA and HPA beamforming solutions periodically adjust the direction of the beams to follow the movement of the mobile station, but this process can reduce throughput by increasing overhead. On the other hand, FDA solutions use omnidirectional antenna elements to transmit and receive signals in all directions and can form directional and narrow beams that cover the entire space simultaneously. With FDA, the transmitter and receiver can dynamically identify the best beamforming vector without increasing latency. Additionally, the receiver can use blind beam tracking to constantly monitor the best beam direction without requiring pilots.

In mmWave systems, a significant challenge lies in the beam acquisition for mutual beam detection between the base station and the user side. The 5G NR standard tackles this problem by facilitating periodic transmission of synchronization signals employing directional transmission and receiver beam sweeping techniques. However, beam acquisition can take longer for APA/HPA systems due to the exhaustive search over possible beam combinations. This initial access latency can be reduced to only seconds with FDA systems, as they can examine all possible receive directions and determine the best beam. [1]

# 4. MMWAVE CHARACTERISTICS AND PERFORMANCE

This chapter provides an overview on key characteristics of mmWave that need to be considered when implement system design. There is also an example study at the of the chapter that evaluates the performance of a mmWave system.

## 4.1 Signal transmission characteristics

The mmWave frequency range, with small wavelengths ranging from 1 mm to 10 mm, has transmission characteristics that are considerably different from the conventional cellular band.

Fellers discussed the use of mmWave frequency for cellular network in 1956 [5]. He investigated the 30–300 GHz frequency range and concluded that these ranges can be used where high gain, huge bandwidth, and high directional antennas are needed for communication. However, high-frequency signals do not cover long distances, and directional antennas are necessary to alleviate the strong signal attenuation that occurs at mmWave signals [6]. Furthermore, mmWave-based communication systems are susceptible to blockages. Conventional cellular bands can also share the same characteristic but suffer a less severe effect. Experiments have been conducted to estimate transmission characteristics in various scenarios [7]. Some of the key characteristics include differences between line-of-sight and non-line-of-sight links, higher attenuation and sparse multipath scattering for mmWave, large wall penetration losses, and the need for dense base station deployment with directional antennas to mitigate signal attenuation. It is necessary to note these key points when system design is considered.

## 4.2 System design implications

Previous chapters have highlighted the advantages of mmWave bands in providing improved quality of services for 5G and beyond cellular networks. However, due to several reasons like different cell coverage and backhaul connections, varying operating frequency bands, environmental impairments, and transmission protocols, modelling and analyzing mmWave cellular networks is a complex task. Therefore, developing frameworks capable of capturing the characteristics of the mmWave bands and meeting the requirements of 5G and beyond networks is a major challenge. It can be concluded from the discussed characteristics of mmWave that a fundamental difference between traditional cellular networks and mmWave-based networks is the susceptibility to blockages. All those aforementioned aspects should be taken into account when we consider system modeling for the cellular network.

First element to be considered is to identify the system scenario and operating frequency. The transmission characteristics of mmWaves are not uniform across different scenarios, including indoor, outdoor, or a combination of both. Additionally, these transmission characteristics are influenced by the specific operating frequency bands utilized by mmWaves, such as 28 GHz, 38 GHz, 60 GHz, 72 GHz, among others. As a result, it is crucial to develop a suitable channel model based on the chosen operating frequency and scenario to accurately represent the transmission characteristics of mmWaves.

### 4.2.1 Blockage

The transmission of wireless signals is impacted by blockages (shadowing effects), which can include phenomena like reflection, refraction, scattering, diffraction, and absorption. Compared with sub-6GHz signals, mmWave signals are more sensitive to obstacles in the environment as the wavelength is less than a centimeter [7]. The prevalence of diffuse scattering is more pronounced in mmWave signals compared to specular reflection, which is predominantly observed in sub-6GHz signals. When mmWave signals interact with large objects, they exhibit reduced diffraction but a higher degree of scattering and reflection than microwaves. Consequently, mmWave signals experience significant attenuation in signal strength when compared to microwaves. The cumulative impact of amplified diffuse scattering and diminished diffraction results in more pronounced shadowing effects on mmWave signals in contrast to sub-6GHz signals.

In cellular networks, these effects are often modeled statistically, assuming a log-normal distribution to account for shadowing. In traditional homogeneous cellular systems, blockages were considered a secondary effect, as most signals were assumed to be non-line-of-sight (NLOS) due to long communication links. Experiments have shown that in outdoor millimeter wave (mmWave) systems, stationary obstructions like buildings and trees can cause significant variations in the path loss law between line-of-sight (LOS) and NLOS links [8]. Because mmWaves experience reduced diffraction, a larger portion of signal energy is scattered, resulting in a much higher path loss exponent for NLOS mmWave links. Blockages also affect interference signals, but most are likely to be blocked in dense environments. Various blockage models are available, including random shape theory, 3GPP blockage model, LOS ball model, and Poisson line model [9], but blockage is typically modeled as a large-scale variation around the path loss, and the composite large scaling propagation loss can be expressed as a function of the path loss component and shadowing loss. To alleviate shadowing severity, mmWave communication systems leverage high gain and narrow beamforming antenna arrays. Overall, blockage is an essential factor to consider when modelling the mmWave channel and needs to be accounted for in link budget calculation and determining the time variance of the mmWave channel.

### 4.2.2 Multipath fading

Multipath fading is another critical aspect that needs to be considered in mmWave system modeling. Due to the shorter wavelength of mmWave signals, they tend to experience more severe multipath fading compared to lower frequency bands [10]. Multipath fading occurs when there are multiple paths between the transmitter and receiver due to reflections and scattering from objects in the environment, resulting in constructive or destructive interference. Figure 6 [11] illustrates the phenomenon.

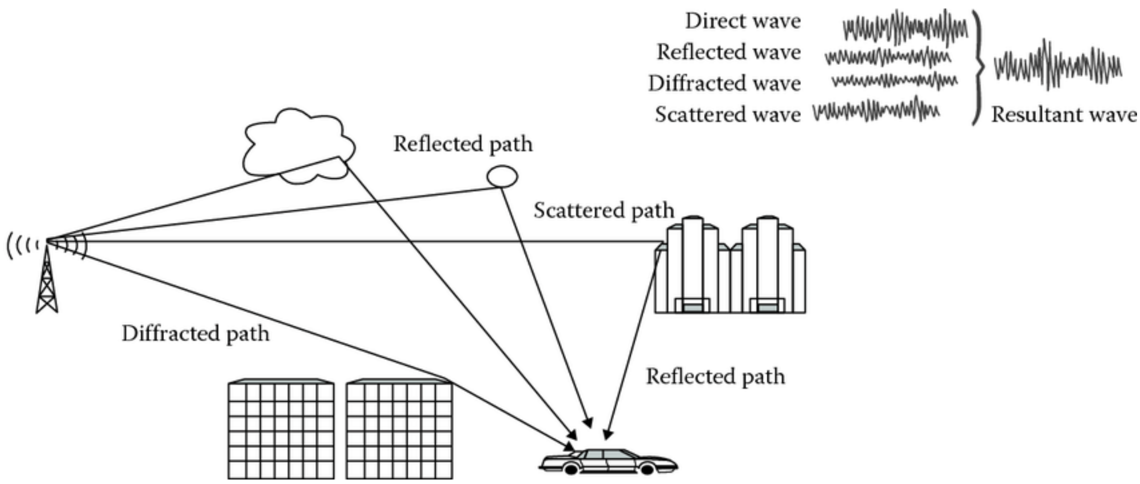


***Figure 6.*** *Different type of interference waves in multipath propagation.* [11]

The mmWave channel is highly sensitive to the spatial position of objects in the environment, and therefore, the channel state changes rapidly as objects move or when there are changes in the environment. This makes it challenging to model and predict the behavior of the channel accurately. As a result, the channel needs to be modelled stochastically using statistical methods [12]. Various stochastic models are available, including the Saleh-Valenzuela (SV) model [13] and the 3GPP 3D channel model [14], which can capture the spatial characteristics of the mmWave channel.

To mitigate the effects of multipath fading, beamforming techniques are commonly used in mmWave systems to direct the energy toward the intended receiver. Beamforming can be performed using analog or digital techniques, depending on the system requirements.

In summary, modeling and analyzing mmWave cellular networks is a complex task that requires consideration of various factors, including blockage and multipath fading. Accurate modeling of the mmWave channel is crucial for developing suitable frameworks that can capture the characteristics of the mmWave bands and meet the requirements of 5G and beyond networks. Beamforming techniques can be used to mitigate the effects of blockage and multipath fading and direct the energy toward the intended receiver.

## 4.3 Performance – example case study

This part will cover an example study on mmWave network performance [17], considering various scenarios and providing a comparison to 4G network at the same location.

### 4.3.1 Case study scenarios and networks settings

This study focuses on simulations conducted in a suburban area spanning 6.85 km² in Ghent, Belgium (Figure 7 [17]). The simulations consider the following reference scenarios:

i. Scenario I represents a 4G network operating at 2.6 GHz with a 20 MHz bandwidth and no employment of MIMO.
ii. Scenario II involves a 5G network operating at 60 GHz with a 500 MHz bandwidth. Under Scenario II, multiple sub-scenarios are explored:

(1) Scenario II.a examines the 5G network without beamforming,

(2) Scenario II.b explores the 5G network with beamforming implemented solely at the base station, with varying numbers of antennas (8, 16, 32, 64, and 256),

(3) Scenario II.c investigates the 5G network with beamforming implemented at both the base station and the mobile station, considering changing numbers of antenna elements at the base station (8, 16, 32, 64, and 256) and a fixed number of antenna elements (four) at the mobile station.

***Figure 7.*** *Study area with location of base stations.* [17]

The scenarios are set so that they focus on the beamforming aspects, based on the above assumptions, but the results can also be interpreted as a comparison between the mmWave network and the 4G network. Other parameters like link budget and power model parameters, energy efficiency metrics and path loss model are set to be suitable for the study.

A flowchart (Figure 8 [17]) below shows the generation process of the 5G network. Step 1 and 2 in the flowchart create the network for each individual time interval, based on the traffic information. Step 3 then provides evaluation of the distance between new users in the selected area with an enabled base station. This distance will be used to compare with the maximum allowable path loss (MAPL). The user will be connected to the base station if the distance is lower than MAPL in Step 4, or if it is higher, a new base station will be activated so that it has the lowest path loss possible in Step 5. Step 6 provides a check if the users already connected to a base station should be connected to the newly activated base station, so that they may experience lower path loss. These steps are then repeated for new users.

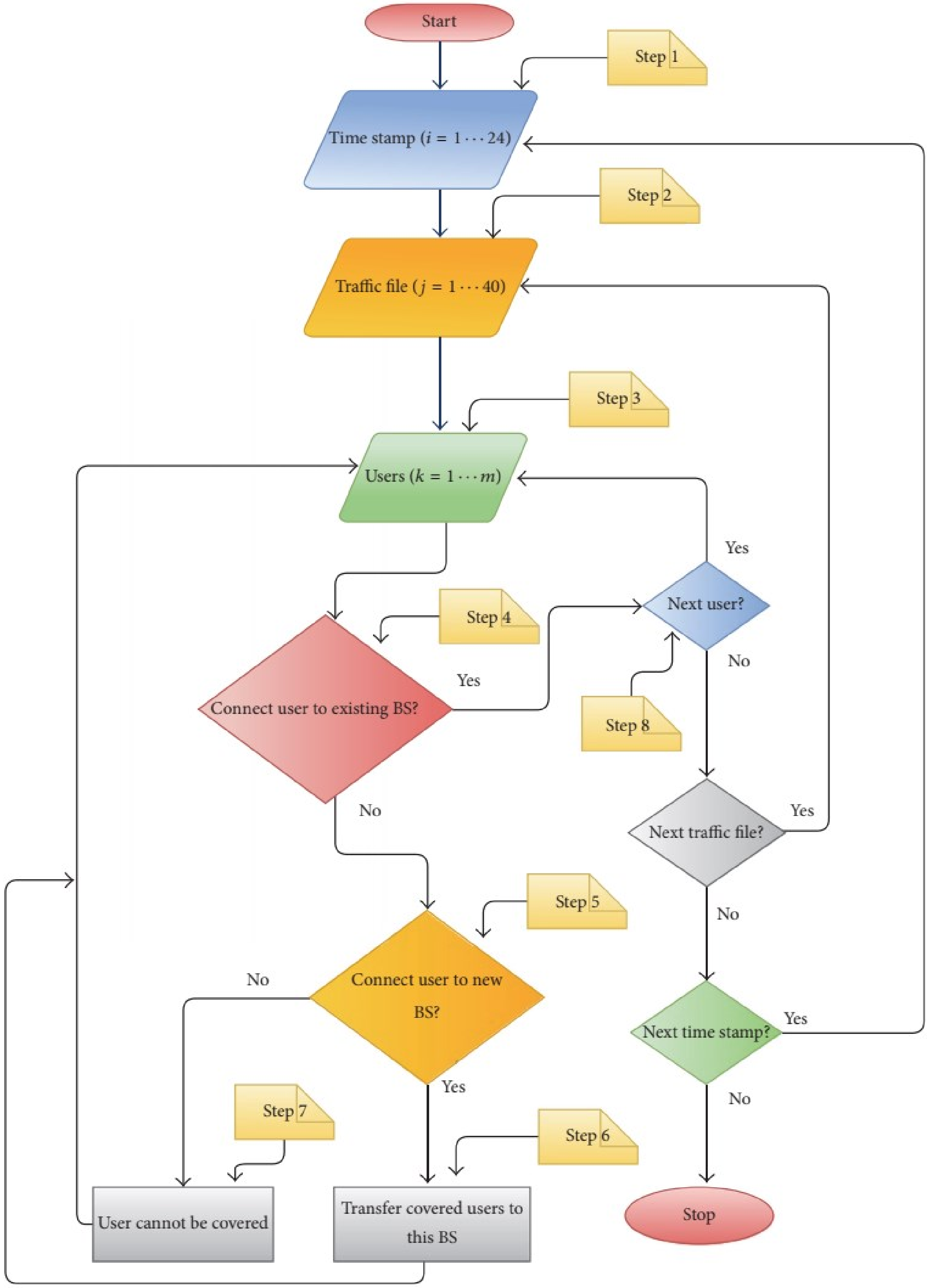


***Figure 8.*** *Network generation flowchart.* [17]

### 4.3.2 Case study results and analysis

The below figure 9 [17] and shows the performance metrics obtained from the study, including the power consumption, the number of base stations (BSs) used, percentage of served user and network capacity, for different aforementioned scenarios.

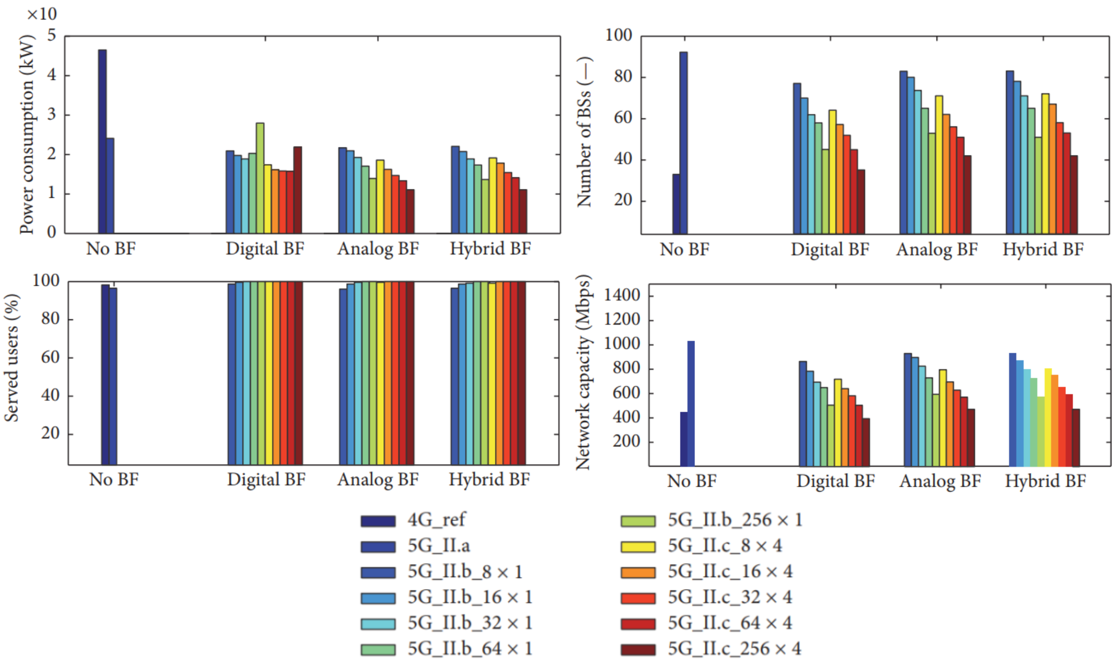


***Figure 9.*** *Summary of case study results.*
*Top left: Power consumption, top right: Number of base stations, bottom left: Served users, bottom right: Network capacity* [17]

From the figure, it can be concluded that in the 5G scenario where there is no implementation of beamforming, the number of base stations required is much higher than that of reference 4G scenario, which is in line with conclusions made about beamforming in earlier chapters. All 5G scenarios also offer around 50% less power consumption, and at the same time provides around twice the network capacity, compared to the reference 4G scenario.

# 5. MMWAVE APPLICATIONS AND FUTURE

This chapter explores the considerations and implications of utilizing mmWave spectrum for various use cases, such as multimedia, virtual reality, IoT, and automotive applications. Additionally, the chapter delves into the future prospects of mmWave technology, including the potential of hybrid sub-3GHz and mmWave networks, as well as the importance of spectral, energy, and cost efficiency in optimizing the performance and deployment of mmWave networks.

## 5.1 Applications considerations in mmWave Spectrum

The integration of multiple networks in 5G, serving various sectors and applications such as multimedia, virtual and augmented reality, machine-to-machine communication, internet of things, smart city, and automotive applications, requires operators to provide diverse 5G networks that meet the service requirements for data rate, latency, reliability, and other parameters. One of the key features enabling 5G is the use of mmWave spectrum with network densification and massive MIMO, which provides ultra high speed access and backhaul systems. Mobile edge computing (MEC) is also necessary to enable applications in mmWave spectrum by bringing information and processing closer to mobile users, resulting in high-speed and low-latency communications. The range of mmWave spectrum supports large bandwidths and high data rates, making it ideal for increasing the capacity of wireless networks. However, the propagation challenges in mmWave spectrum make it suitable for short-range transmissions, and small cells are practical means to deliver communication in this band. Supporting mobile operation is a major challenge for using mmWave in 5G, but advancements in antenna processing and beam-steering techniques are being used to address this issue. The use of reflected signals and supplementing the line of sight signal can also improve channel capacity, making it practical to deploy mmWave on existing cell sites for higher channel throughputs over relatively short inter-site distances.

## 5.2 Future of mmWave

There are some future research directions, that can offer enhancements to the performance of the current mmWave networks.

### 5.2.1 Hybrid sub 3Ghz-mmWave network.

As the deployment of mmWave networks continues to evolve, a promising approach for the future is the integration of hybrid sub-3GHz and mmWave networks. While mmWave offers high data rates and capacity, it is limited in terms of coverage and penetration through obstacles. On the other hand, sub-3GHz frequencies provide wider coverage and better penetration, albeit with lower data rates. By combining the strengths of both frequency ranges, a hybrid network can provide seamless connectivity with wide coverage and high-speed capabilities [8]. This approach allows for optimal utilization of spectrum resources while ensuring a balance between coverage and capacity requirements.

### 5.2.2 Spectral, energy, cost efficiency.

Efficiency considerations are crucial for the future of mmWave networks [18]. With the increasing demand for data and the proliferation of connected devices, efficient utilization of spectrum resources becomes essential. The wide bandwidth available in mmWave spectrum enables high data rates, but it also requires efficient spectrum management techniques to avoid interference and maximize spectral efficiency. Advanced spectrum sharing mechanisms, such as dynamic spectrum access and cognitive radio, can play a significant role in optimizing spectrum utilization and enabling coexistence between different services and technologies.

Energy efficiency is another important aspect to address in future mmWave networks [18]. The deployment of massive MIMO and small cells in dense urban areas can consume significant amounts of energy. Therefore, innovative techniques for energy harvesting, power optimization, and network optimization should be explored to minimize energy consumption and enhance the sustainability of mmWave networks.

Cost efficiency is a key consideration for network operators. The deployment of mmWave infrastructure involves the installation of a large number of small cells to provide coverage in dense urban environments. The cost of equipment, site acquisition, and maintenance can be substantial. Therefore, exploring cost-effective solutions such as infrastructure sharing, virtualization, and network slicing can help reduce the deployment and operational costs associated with mmWave networks.

# 6. CONCLUSION

This thesis has explored the topic of mmWave communication for 5G mobile networks. The thesis began by providing an overview of 5G technology, including the different frequency bands that are being used. It then delved into the enabling technologies for mmWave, such as the RAN architecture, antennas, and beamforming techniques, including beam acquisition and tracking.

It also discussed the characteristics and performance of mmWave communication, including its signal transmission characteristics, system design implications, and physical limits such as blockage and multipath fading. Additionally, it examined the use cases and future of mmWave technology, including its potential commercial applications and the possibilities for hybrid sub-3GHz/mmWave networks that offer increased spectral, energy, and cost efficiency.

Overall, mmWave communication has emerged as a promising technology for 5G mobile networks, with the potential to provide faster data rates, improved capacity, and reduced latency. However, it also presents unique challenges, such as the need for careful system design and the mitigation of physical limitations. As humanity move into the future, it will be important to continue exploring the possibilities of mmWave technology and finding new ways to overcome its challenges.

In conclusion, this thesis has provided a comprehensive overview of mmWave communication for 5G mobile networks and has contributed to our understanding of this important and rapidly evolving field.

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# APPENDIX A: RAN SPLIT OPTIONS

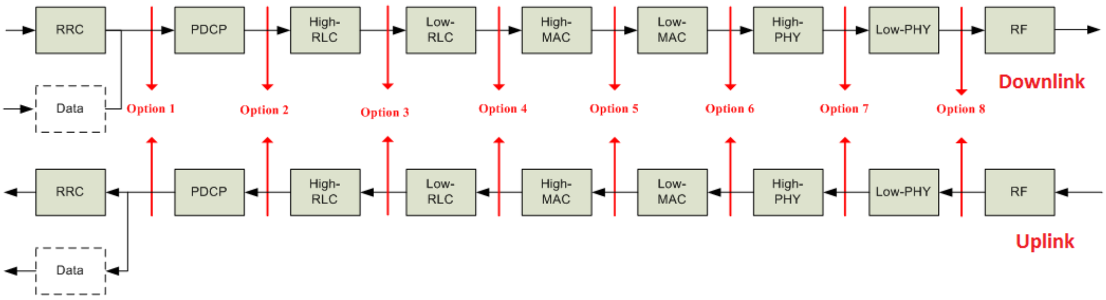


***Figure 10.*** *5G RAN network split options.* [1]

- Option 1 (RRC/PDCP, 1A-like split): This split configuration places the Radio Resource Control (RRC) component in the central unit, while the Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC), Medium Access Control (MAC), physical layer, and Radio Frequency (RF) are located in the distributed unit. As a result, the entire user plane resides in the distributed unit.

- Option 2 (PDCP/RLC split): Option 2 serves as a potential foundation for a design resembling X2, mainly due to similarities in the user plane. However, certain functionalities, such as the C-plane, may differ, necessitating the introduction of new procedures. This option offers two possible variants:

  Option 2-1 Split U-plane only (3C-like split): In this split option, the central unit houses the RRC and PDCP components, while the RLC, MAC, physical layer, and RF are located in the distributed unit.

  Option 2-2: In addition to the central unit housing the RRC and PDCP components, this split option separates the RRC and PDCP for the CP stack and the PDCP for the UP stack into different central entities. The RLC, MAC, physical layer, and RF remain in the distributed unit.

- Option 3 (High RLC/Low RLC Split): Option 3 explores two approaches based on real-time/non-real-time functions split:

  Option 3-1 split based on Automatic Repeat Request (ARQ): The Low RLC handles segmentation functions, while the High RLC manages ARQ and other RLC functions. This split configuration separates the RLC sublayer into High RLC and Low RLC sublayers. The High RLC, residing in the central unit, performs all RLC functions for Acknowledge Mode (AM) operation, while the Low RLC, in the distributed unit, conducts segmentation using available MAC PDU resources.

Option 3-2 Split based on TX RLC and RX RLC: The Low RLC encompasses transmitting Transparent Mode (TM) RLC entity, transmitting Unacknowledged Mode (UM) RLC entity, a transmitting side of AM, and the routing function of a receiving side of AM, primarily related to downlink transmission. On the other hand, the High RLC includes the receiving TM RLC entity, receiving UM RLC entity, and a receiving side of AM, excluding the routing function and reception of RLC status reports, primarily related to uplink transmission.

- Option 4 (RLC-MAC split): In this split option, the RRC, PDCP, and RLC components are located in the central unit, while the MAC, physical layer, and RF are situated in the distributed unit.
- Option 5 (Intra MAC split): This option involves distributing the following components:

  RF, physical layer, and lower part of the MAC layer (Low-MAC) in the distributed unit.

  Higher part of the MAC layer (High-MAC), RLC, and PDCP in the central unit.

  With this split, the MAC layer services and functions are distributed between the central unit (CU) and the distributed unit (DU). The High-MAC sublayer in the CU handles centralized scheduling and inter-cell interference coordination, while the Low-MAC sublayer in the DU focuses on time-critical functions and radio-specific tasks related to downlink transmission.
- Option 6 (MAC-PHY split): The MAC and upper layers reside in the central unit (CU), while the PHY layer and RF are located in the distributed unit (DU). The interface between the CU and DU handles data, configuration, and scheduling-related information.
- Option 7 (Intra PHY split): This option offers multiple realizations, including asymmetrical options that provide independent benefits for uplink (UL) and downlink (DL).
- Option 8 (PHY-RF split): This alternative provides the capability to separate the RF (Radio Frequency) layer from the PHY (Physical) layer. By implementing this split, it becomes possible to centralize processes across all protocol layer levels, leading to highly coordinated operations within the Radio Access Network (RAN). This centralization facilitates effective support for advanced functionalities like Coordinated Multipoint (CoMP), Multiple Input Multiple Output (MIMO), load balancing, and mobility management.