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Communication for 5G Wireless using millimeter Waves and massive MIMO Technology

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إهداء

أما قبل..

بعد بسم الله الذي لا يضر مع إسمه شيء في الأرض ولا في السماء

أهدي هذا السعي إلى السادة أولي النفوس الأبية ما سما منها مكللا بفخر الشهادة ومن مازال منهم يناضل ويكابد في سبيل نصرة الحق، يرابط غير قانط من رحمة الله، إلى ذوي الأنفة العالية الذين لم يثن يقينهم مصاب، إلى الراسخين صوب ثغورهم مابان منها وما خفي في زمن كثر فيه آل جحر الضب ، حسبكم تباشير الفتاح العليم أنه مع الصابرين ،لمثلكم تهدى مساعينا الهزيلة في اللحاق بخير السابقين ثم بكم ـ مواقفا ومثالا ـ ، لمثلكم تهدى خطواتنا الصغيرة المرتجفة وأيادينا القصيرة لعلنا نبلغ مبلغكم أو ندنوا منه يوما ، مازال الطريق طويلا لكننا إن شاء الله لن نحيد حتى نخلف خلفنا أثرا يشفع لنا إلا أن يكون العمر أقصر من أن نفعل. إلى الأكارم شهداء فلسطين، شهداء أزواد وشهداء السودان، السادة المجاهدين وجميع أنصار الحق في رحاب العالم، ثبت الله أقدامكم وسدد مراميكم ونصركم.

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تمت بفضل الله ورحمته.

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إهداء

"قال رب أوزعني أن أشكر نعمتك التي أنعمت علي و على
والدي و أن أعمل صالحاً ترضاه و أدخلني برحمتك في عبادك
الصالحين"

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Résumé

Les réseaux sans fil ont transformé notre vie quotidienne en permettant aux gadgets de se connecter, d'interagir sans fil et d'accéder à Internet. Les réseaux de communication mobile à large bande 5G NR tirent parti du spectre d'ondes millimétriques (mmWave) sous-utilisé, ce qui permet de remédier à la pénurie de capacité des générations précédentes. Cette thèse aborde un sujet de recherche ouvert sur la technologie 5G NR, en se concentrant sur les communications massives MIMO et mmWave, ses caractéristiques essentielles, les mesures de performance, les propriétés du canal de propagation mmWave et ses principales difficultés et avantages. Il couvre les fondamentaux de la technologie 5G NR, ses cas d'utilisation et les fondamentaux de la communication MIMO et mmWave. Il aborde également les algorithmes et les concepts mathématiques, y compris les modes MIMO, le multiplexage spatial et les techniques de formation de faisceaux hybrides. Des simulations sont présentées pour comparer les performances de différents algorithmes de précodage .

Mots clés:-MIMO massif, mmwave, 5G, formation de faisceaux, précodage, efficacité spatiale.

Abstract

Wireless networks have transformed our everyday lives by enabling gadgets to connect, interact wirelessly, and access the internet. 5G NR broad-band mobile communication networks take advantage of the underutilized millimeter-wave (mmWave) spectrum, addressing the capacity shortage of previous generations. This thesis addresses open research topic on 5G NR technology, focusing on massive MIMO and mmWave communications, its essential characteristics, performance metrics, properties of the mmWave propagation channel, and its primary difficulties and benefits. It covers the fundamentals of 5G NR technology, its use cases, and the fundamentals of MIMO and mmWave communication. It also discusses algorithms and mathematical concepts, including MIMO modes, Spatial Multiplexing, and hybrid beamforming techniques. Simulations are presented to compare the performance of different precoding .

Keywords:-massive MIMO, mmwave, 5G, beamforming, precoding, spactral efficiency.

ملخص

غيرت الشبكات اللاسلكية حياتنا اليومية من خلال تمكين الأدوات من الاتصال والتفاعل لاسلكيًا والوصول إلى الإنترنت. تستفيد شبكات الاتصالات المتنقلة ذات النطاق العريض 5GNR من طيف الموجة المليمترية (*mmWave*) غير المستخدم بشكل كافٍ، مما يعالج نقص السعة في الأجيال السابقة. تتناول هذه الأطروحة موضوع البحث المفتوح حول تقنية 5GNR ، مع التركيز على اتصالات *m*MIMO و *mmWave* ، وخصائصها الأساسية، ومقاييس الأداء، وخصائص قناة انتشار *mmWave* ، وصعوباتها وفوائدها الأساسية. يغطي أساسيات تقنية 5GNR وحالات استخدامها وأساسيات اتصالات MIMO و *mmWave.* كما يناقش الخوارزميات والمفاهيم الرياضية، بما في ذلك أنماط MIMO ، وتعدد الإرسال المكاني، وتقنيات تشكيل الحزم الهجينة. يتم تقديم عمليات المحاكاة لمقارنة أداء الخوارزميات المسبقة المختلفة .

كلمات مفتاحية : *massive*MIMO ، *mmwave* ، 5G ، *spactralefficiency* ، الترميز المسبق ، تشكيل الحزم،

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List of Acronyms and Abreviations

mMIMO	massive multiple-input and multiple-output
mmWave	Millimeter wave
BS	Base Station
SCBs	small cells base stations
MTs	mobile terminals
DSP	digital signal processing
NR	New Radio
UE	User Equipment
AWGN	Additive White Gaussian Noise
RF	Radio Frequency
CSI	Channel State Information
MWCN	Mobile Wireless Communication Networks
QoS	Quality of service
WWWW	Wireless World Wide Web
1G	First Generation
FDMA	Frequency Division Multiple Access
AMPS	Advanced Mobile Phone System
TAC	Total Access Communications System
GSM	Global System for Mobile Communications
TDMA	time division multiple access
CDMA	code division multiple access
BTS	Base Transceiver Stations
VLR	Visitor Location Register
MSC	Mobile Switching Center
HLR	Home Location Register
AuC	Authentication Center
EIR	Equipment Identity Register
WCDMA	Wideband Code Division Multiple Access
UMTS	Universal Mobile Telecommunication System
WLAN	Wireless Local Area Network
Ev-DO	Evolution-Data Optimized
RNC	Radio Network Controller
BSC	base station controller
UE	user equipment
MS	mobile stations
PLM	Public Land Mobile Network
CG	Charging Gateway
CDR	call detail record
SGSN	Serving GPRS Support Node
BG	Border Gateway
BGP	Border Gateway Protocol
IPSec	Internet Protocol Security

OFDM	Orthogonal frequency-division multiplexing
3GPP	The Third Generation Partnership Project
TDD	Time Division Duplex
FDD	Frequency Division Duplex
LTE	long-term evolution
EPC	Evolved Packet Core
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
MME	Mobility Management Entity
S-GW	Serving Gateway
P-GW	Packet Data Network Gateway
PCRF	Policy and Charging Rules Function
SC-FDMA	single-carrier frequency division multiple access
IEEE	Institute of Electrical and Electronics Engineers
CR	Cognitive Radio
CP	Cyclic Prefix
RBs	Resource Blocks
3GPP	the 3rd Generation Partnership Project
CSI-RS	Channel State Information Reference Signal
RSRP	Reference Signal Received Power
DNRS	demodulation reference signals
SRS	Sounding Reference Signal
SNR	The signal-to-noise ratio
NB-IoT	NarrowBand-Internet of Things
KPIs	Key Performance Indicators
eMBB	Enhanced Mobile Broadband
MMTc	MASSIVE MACHINE TYPE COMMUNICATION
H2H	Human-to-human
RRM	Radio Resource Management
NOMA	Non-orthogonal multiple access
URLLC	Ultra-Reliable and Low-Latency Communication
V2V	
OMA	Orthogonal multiple access
OFDMA	Orthogonal frequency division multiple access
UL	Up link
NOMA	Non-orthogonal multiple access
DMST	Down Link multi-user superposition transmission
NAICS	Network-assisted interference cancellation and suppression
ICI	Inter-cell interference
SCMA	sparse code multiple access
PDMA	pattern division multiple access
RSMA	resource spread multiple access
MUSA	Multi-user shared access
IGMA	interleave-grid multiple access
WSMA	Welch-bound equality spread multiple access
IDMA	interleave-division multiple access
NCMA	non-orthogonal coded multiple access
ACMA	Asynchronous coded multiple access
LSSA	low code rate and signature based shared access
UGMA	user grouped
DBF	Digital Beamforming
RF	Radio frequance
ADC	analog-to-digital converters

CSI	Channel state information
TUT	Inter-User Interference

General Introduction

Because they allow us to connect gadgets, interact wirelessly, and access the internet, wireless networks have become so essential in our everyday life. sence the way we stay connected has been completely transformed by wireless technology, from the ease of Wi-Fi in our homes to the installation of wireless networks in many sectors.
The previous wireless communication generations were suffers from a lack of capacity, which is why 5G NR broad-band mobile communication networks came with the idea oo taking advantage of the underutilized millimeter-wave (mmWave) spectrum. Sufficient understanding of the mmWave propagation channel is necessary for the successful deployment of mmWave technologies. This thesis addresses open research topic about of 5G NR technology with a specific focus on massive MIMO and mmWave communications , its essential characteristics and performance metrics that set it apart as well as the properties of the mmWave propagation channel, including its primary difficulties and benefits.
we divided the document into three main chapter: Chapter 1 introduces the evolution of 5G communication systems, including 1G, 2G, 3G, 4G, and 6G. It discusses network architecture, electromagnetic spectrum, massive MIMO, and millimeter waves technologies.Chapter 2 delves into 5G NR with mmWave and mMIMO, focusing on its features like flexible spectrum, ultra-lean design, forward compatibility, and use cases like enhanced mobile broadband and massive machine type communication. Chapter 3 focuses on MIMO, beamforming, and precoding for 5G, discussing different modes, hybrid beamforming techniques, and models of precoding/combining algorithms. Simulations are presented to compare the performance of different precoding and combining algorithms.

Chapter 1

General Characteristics of 5G

1.1 Introduction

Wireless communication involves the transmission of information over a distance without the help of wires, cables or any other forms of electrical conductors. Wireless communication is a broad term that incorporates all procedures and forms of connecting and communicating between two or more devices using a wireless signal through wireless communication technologies and devices.

The mobile wireless communication networks (MWCN) have tremendous expansion. Numerous generations of cellular phone technology were deployment in tandem with the growing efficacy of wireless communication, and nowadays , several billions of people utilize them.

Although it was limited to voice conversations, the first generation (1G) of mobile communication served as the basis for all later generations of mobile technology.The second-generation (2G) digital phones facilitate communications and provide a feature-rich text messaging service. Then came the emergence of the third generation (3G) technology, which enhanced the speed of data transmission and enabled multimedia applications. compared to 3G, the fourth generation (4G) is more reliable, faster and improves quality of service (QoS) while simultaneously boosting data. The new fifth generation (5G) presents the wireless world wide web. Since in every generation are providing some techniques and support some new features [1] , and we have emerging 6G.

Wireless communications will bring about significant changes , with the developing of the modern applications such as virtual reality, the Internet of Things, etc...,. These intriguing applications have brought forth many additional difficulties, too, such as the need for low latency in massively super, dense networks and uncertain channel models [2] .

1.2 Evolution of Wireless Communication Systems

1.2.1 First Generation (1G)

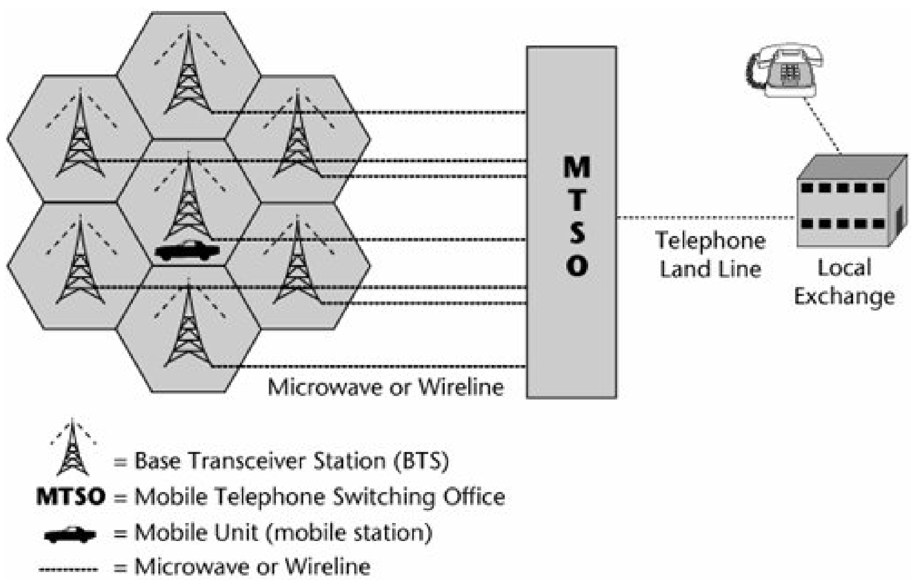

Figure 1.1: 1G AMPS architecture

1G or The first mobile network, that its architecture showed in figure 1.1 , was an analog system created in the 80s. It employs an analog radio signal with a frequency of 150 MHz; call modulation is only used to voice transmission. They are introduced as the total access communications system (TAC) and the advanced mobile phone system (AMPS). It has a 2.4 Kbps top speed. Recurrence balancing FM system is used by mobile phone systems and entire communication systems to multiplex radio communication traffic into, an frequency division multiple access (FDMA) recurrence division different access system. This generation lacks security and is unstable [1] , It has many shortcomings, such as the use of analog modulation, no encryption, poor quality, and security. Limited users because of the use of FDMA technology, insecure base station power radiation, lack of transfer procedures. Supports voice services only and divergent systems because of inadequate of consistent international standards. [3]

1.2.2 Second Generation (2G)

The second generation of mobile communication system. or what is called global system for mobile that its architecture showed in figure 1.2 communications(GSM),The later 90s saw its completion , it is Digital in nature, the 2G is still widely in use across various regions of the globe. This generation provided e-mail and SMS capabilities in addition to the voice service. it has frequency band 850-1900 MHz, and two modulation techniques are used : time division multiple access (TDMA) and code division multiple access (CDMA) , GSM technology uses eight channels per carrier in 2G, with a frame lasting 4.6 milliseconds (ms) and a gross data rate of 22.8 kbps (a net rate of 13 kbps) in the full rate channel This generation's family consists of the 2G, 2.5G, and 2.75G. [3]

After 2G close to 1995 existence the 2.5G it consists of voice with data this method development more enhanced data rate for GSM Evolution (EDGE or 2,75G). In the intermediate interval the general packet radio service (GPRS) or 2,5G was introduced which had the characteristic of packet switching which appropriate for internet. data speed up to 64Kbp, some of its significant features included short message service (SMS), photograph messages, then multimedia messaging service (MMS) in their telephones , It used digital sign for transmission instead than analog. It applied the thinking of Code Division Multiple Access (CDMA). CDMA offers each user with an exclusive code to deliver ended multiple physical channels. To communicate more and more users multiple access techniques are used, i.e. FDMA, TDMA, and CDMA. [4]

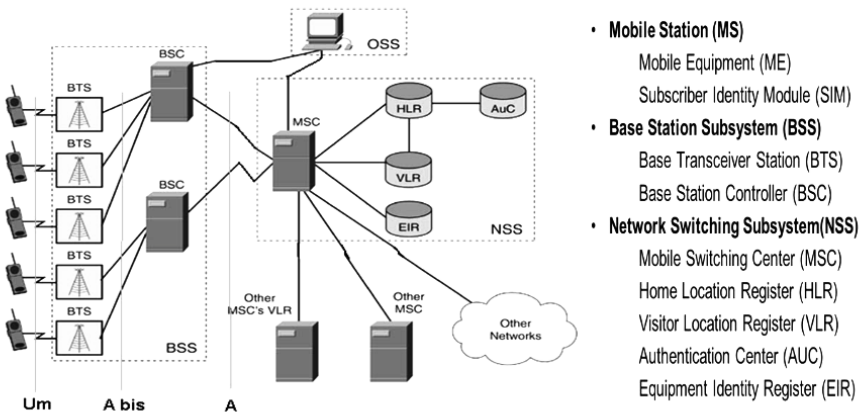

Figure 1.2: GSM architecture

- MS: Mobile Station.
- BTS: Base Transceiver Stations.
- BSC: Base Station controller.
- MSC: Mobile Switching Center.

- VLR :Visitor Location Register.
- HLR: Home Location Register.
- mobility management, and data services.
- AuC : Authentication Center.
- EIR : Equipment Identity Register.

1.2.3 Third Generation(3G)

It first appeared in late 2000. It help to enhance quality management and has supported services with higher voice quality. Third generation that its architecture showed in figure 1.3 devices provide up to 2Mbps of data. 3G is compatible with three technologies, including WCDMA, CDMA 2000, and the Universal Mobile Telecommunication System (UMTS). WLAN and Bluetooth have grown up with this generation. These methods can be used by unlicensed bands. CDMA technology was used by this generation.

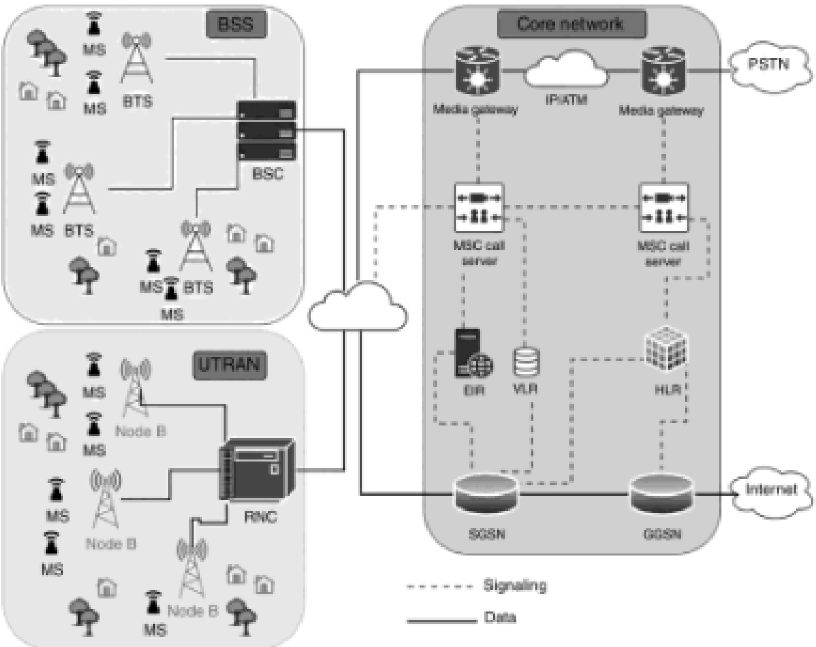

Figure 1.3: 3G architecture

The 3.5G, which feel between 3G and 4G, used High Speed Downlink Packet Access (HSDPA), High Speed Uplink Packet Access (HSUPA) and Evolution-Data Optimized(Ev-DO) technologies to deliver greater data speeds than 3G. Data rates were better in this generation compared to the previous one because high-quality video applications were possible. [5]

While designing the Universal Terrestrial Radio Access Network (UTRAN), several modifications have been made to the nomenclature, even though the fundamental elements were borrowed from GSM. Node-B and Radio Network Controller (RNC), respectively, are the names given to the buildings in 2G that are known as base transceiver station (BTS) and base station controller (BSC) in the literature. Furthermore, these devices are referred to as user equipment (UE), whilst mobile devices are called mobile stations (MS). The following is a summary of the roles in the architecture created using UMTS:

Public Land Mobile Network (PLMN): Other operators' wireless network communication services.

Charging Gateway (CG): It determines user fees by using call detail record (CDR) data. Pricing (usage) information is pulled from Serving GPRS Support Node (SGSN) and Gateway GPRS Support Node (GGSN servers).

Border Gateway (BG): The structure runs the comprehensive area network routing function called Border Gateway Protocol (BGP) and security protocols such as IPSec. [6]

1.2.4 Fourth Generation (4G)

The term 4G describes the fourth generation that its architecture showed in figure 1.4, which debuted in 2010. In addition to enabling 3G features, it offers new services. It offers access to mobile ultra-broadband internet.

4G, the next generation of wireless technology that replaces 3G, It is built on a full IP network infrastructure and uses sophisticated wireless technologies like MIMO OFDM. These standards, however, are categorized as 3.9G or Pre-4G since they do not meet the 4G bandwidth requirements, which are 1 Gbit/s for fixed operation and 100 Mbit/s for mobile operation.3GPP intends to use LTE Advanced to achieve the 4G objectives. [7]

LTE deployment started in the last of 2009 The Third Generation Partnership Project (3GPP) defines long term evolution (LTE) as having extremely high flexibility for radio interface. LTE systems are utilizing the Time Division Duplex (TDD) and Frequency Division Duplex (FDD) techniques [8]

as the 4G Network's foundational architecture network. The Evolved Packet Core (EPC) network and the Evolved Universal Terrestrial Radio Access Network (E-UTRAN) are components of the LTE architecture.

The following components make up the architecture of the 4G network:

- eNodeB
- Mobility Management Entity (MME)
- Serving Gateway (S-GW)
- Packet Data Network Gateway (P-GW)
- Home Subscriber Server (HSS)
- Policy and Charging Rules Function (PCRF) [9]

E-UTRAN's Evolution and Architecture

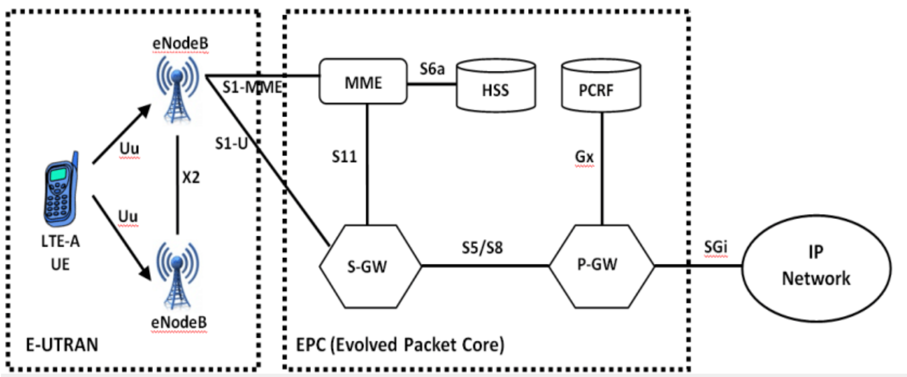

Figure 1.4: LTE architecture

E-UTRAN is a radio access network for 3GPP Long term Evolution (LTE).This novel air interface system offers high data rates, minimal latency, and is tailored for packet data. It employs OFDMA radio access for The downlink uses SC-FDMA, whereas the uplink uses SC-FDMA.

LTE utilizes two duplexing schemes: time division duplexing (TDD) and frequency division duplexing (FDD).The transmitter and receiver share a single frequency channel when using LTE-TDD . LTE-FDD requires paired spectrum with adequate frequency separation for simultaneous transmission and receiving.

The E-UTRAN Network requires high speed data rate and dependable transmissions with bandwidth efficiency, as shown in Table 1.To fulfill these requirements A multiple input, multiple output (MIMO) system with multiple antennas has been implemented [9]

1.2.5 Fifth Generation (5G)

The 5G regional advancements necessitate global collaboration to create a single 5G standard that is applicable worldwide. The regional 5G developers, including IMT-2020 (5G) PG, 5G IA, 5G forum, 5GMF, 5G Americas, and 5G Brazil, have responded to this appeal by organizing a worldwide 5G event to discuss perspectives and development status in each region. These gatherings will help develop global consensus on 5G among the world's 5G promotion groups. This series of events has focused on encouraging the use of 5G in various vertical industries and 5G ecosystems, as well as inviting major industry players, administrations, and regulators to engage in the conversation.IMT-2020 PG in Beijing hosted the first worldwide 5G event in May 2016. [10], Based on the Release 15 by 3GPP, the first version of 5G networks is comprised of the 5G Core (5GC) and 5G NR as the air interface, which will be deployed throughout the world over the wide range of frequency bands from less than 6GHz (0.45GHz-6 GHz) to mmWave (24.2-52.6 GHz). [11]

1.2.6 Sixth Generation (6G)

The sixth Generation (6G) network which differs from the 5G network in that it operates in the mmwaves frequency field (300GHz- 3THz) will focus on allowing a secure ultra agile intellectual information social order by 2030 .

6G networks are expected to provide performance superior to present 5G networks . Future 6G communication networks will be able to close gaps in 5G Key Performance Indicators (KPIs), enabling developing applications and use cases that are beyond the reach of present 5G networks. 5G offers several advantages, including ultra high data rates, ultra-low latency, and huge machine to machine connectivity. The 3GPP, an ITU agency, is working tirelessly to accelerate the global deployment of 5G and collect data for future 6G design. At the same time, IEEE is working on the latest WLAN standards, namely 802.11ax for next generation connectivity. [12]

1.3 5G Network Architecture

The core technologies of the overall 5G network architecture that its architecture showed in figures 1.5 and 1.6 include D2D, NOMA, UDN, SCA, MIMO, massive MIMO, and Cognitive Radio (CR). The goal of these technologies is to meet every 5G criteria, which is thought to be the bare minimum for 2020. The network's capacity is increased and the ultra-high user density is managed with the aid of UDN. Data traffic is offloaded and coverage is increased via SCA networks.

In order to support the greatest number of users, MIMO helps to increase the diversity gain. Massive MIMO is a useful addition to standard MIMO systems that helps to facilitate extremely high network connectivity. Another beneficial technique for making use of the spectrum's accessible bands is cognitive radio, which switches between 5G New Radio is the first standard air interface for the 5G network, according to 3GPP version 15.

Using the technology exhibited in 5G architecture, the three use cases eMBB, mMTC, and

uRLLC are deployed as part of 5G NR architecture. In 5G NR, 3GPP has designated two frequency bands. The sub-6 GHz (FR1) and above 24 GHz (FR2) frequency bands are these two. The millimeter-wave band, which uses extremely high frequencies to improve data speeds, is included in the FR2 band. 5G NR has a number of new features Excellent data rates and extensive coverage are guaranteed by the scalable numerology and flexible spectrum. Since high frequencies are typically linked to substantial propagation losses, the use of mmWave is constrained to small regions. The constraint, . Beamforming can be used to increase the antenna gain and overcome the mmWave constraint.
Using a process called beamforming, the greatest signal power is directed in the user's direction. The idea of beamforming in 5G is expanded by a number of additional beamforming techniques, such as beam merging, which combines two beams to maximize SNR, and beam broadening, which increases coverage. 5G has made possible a number of applications, including high user mobility, ultra-high definition video, fleet and logistics management, e-health, smart city, remote surgery, industrial IoT, and drone delivery. The vast interconnectedness of digital gadgets has been the emphasis of 5G networks. [11]

Figure 1.5: 5G architecture

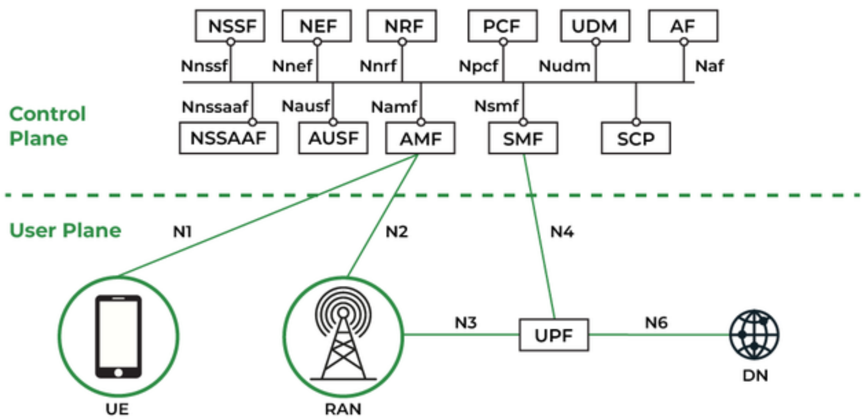

Figure 1.6: 5G architecture

1.3.1 5G Core Network (5GC)

The foundation of 5G networking is the 5G core network, which offers dependable and safe internet access together with all networking services. Many crucial mobile networking features, such as mobile administration, subscriber data management, authorization, authentication policy management, etc., are included in the 5G core network.

The 5G core network is entirely software based and native to the cloud ; it offers more deployment agility, flexibility, and cloud like infrastructure. The 5G core was created by industry specialists to facilitate the 5G network's operation. Consequently, the 3GPP standard also known as the 5G core was created, and it has the ability to regulate and oversee network operations.

5G Network Functions

The Network Repository (NRF): The Network Repository Function (NRF) houses all of the 5G network functions (NFs) which is storing centrally. 5G NFs can register and locate one another thanks to an API provided by the NRF that is based on standards. NRF is an essential component required to run the new service based architecture (SBA) in the 5G core.

Policy Control Function (PCF): makes it easier to create and apply policies in 5G networks. Because PCF was developed and designed with cloud-native principles to meet the demands of 5G services, it will assist you in harnessing the power of 5G and realizing its benefits.

BSF (Binding Support Function): The 5G Binding Support Function (BSF) is similar to the 4G Diameter Routing Agent (DRA) Session Binding Function. It becomes essential when several Policy Control Function (PCF) systems are deployed within the network.

Service Communication Proxy SCP: Service Communication Proxy (SCP) allows operators to run their 5G networks safely and efficiently by providing routing control, resilience, and observability to the core network. SCP leverages IT service mesh (ISTIO) to address many of the problems caused by the new service-based architecture (SBA) in the 5G core, and it adds essential features to make it 5G-aware.

Network Slicing Selection Function (NSSF): In a 5G environment where a range of services are provided, the NSSF system selects the optimal network slice that is available for the service that the user has requested.

user data repository (UDR) & Unified Data Management (UDM): Designed for 5G, UDM is cloud native and resembles LTE's Home Subscriber Server (HSS). It is in responsible of generating the credentials required for authentication, distributing those credentials to the other network services, and allowing access based on user subscription. It obtains the User Data Repository (UDR) credentials. The UDM network function supports several critical 5G functionalities. It generates authentication credentials in order to finish the authentication procedure. Users' subscriptions determine whether network access and roaming are permitted.

Authentication Server Function (AUSF): The authentication server function is used for 5G authentication and Key Agreement technique 5G AKA. AUSF also offers extra capabilities to handle subscription IDs that are concealed or privacy protected**. AMF** (Access and Mobility Function) is responsible for selecting the appropriate Authentication Server Function (**AUSF**) throughout the registration procedure.

Network Data Analytics Function (NWDAF): The goal of the 5G Network Data Analytics Function (NWDAF) is to enhance the end-user experience by automating the creation and usage of important network data, producing insights, and acting accordingly. With NWDAF, market fragmentation and proprietary solutions in the field of network analytics are supposed to be addressed by accelerating the generation and consumption of core network data, generating insights, and acting upon these insights.

1.4 Electromagnetic (EM) Spectrum

The electromagnetic (EM) spectrum that its architecture showed in figure 1.7 is simply the term used by scientists to refer to a broad range of radiation types when discussing them collectively. Radiation is defined as energy that moves and disperses along its path. Two examples of electromagnetic radiation are radio waves from a radio station and visible light from a bulb in your home. Microwaves, infrared and ultraviolet light, X-rays, and gamma rays are further types of electromagnetic radiation. Higher energy radiation is produced by hotter, more energetic objects and events than by colder ones. High energy radiation, such

as X-rays and gamma rays, can only be produced by extremely hot objects or particles traveling at very high speeds. [13]
Policies for spectrum allocation specify how the electromagnetic spectrum is allocated to various users. Governmental organizations usually develop these regulations to make sure that everyone may utilize the spectrum effectively and without disturbance. The circumstances under which a user is permitted to broadcast electromagnetic waves in a certain frequency range are outlined in licensing regulations. Antenna type, operation hours, and permitted power level are all frequently specified in licenses. Compliance rules make sure that electromagnetic equipment don't cause too much interference and that they run in the designated frequency range. Ensuring public safety and safeguarding the integrity of communication networks depend on these standards.

1.4.1 The electromagnetic spectrum frequencies:

Radio waves: They are created when charges in conducting wires move more quickly. The range of frequencies extends from 10^9 Hz to a few Hz. They exhibit diffraction and reflection. They are utilized in cellular phones to carry voice communications in the ultra-high frequency band, as well as in radio and television communication systems.

Microwaves: Special vacuum tubes like the Gunn diode, magnetron, and klystron are used to make it.Microwaves have a frequency range of 10^9 Hz to 10^{11} Hz.These waves can become polarized as a because of reflection. It is utilized in microwave ovens for cooking, radar systems for aircraft navigation, car speeds, and satellite-based long-distance wireless communication.

Infrared radiation: It is created by heated objects, commonly referred to as heat waves, as well as by molecules going through vibrational and rotational changes. The frequency range spans from 10^{11} Hz to 4×10^{14} Hz. It uses solar cells to supply satellites with electrical power. It is used to make dried fruits, to keep plants warm in greenhouses, as heat treatment for sprains or pains in the muscles, as a TV remote for signal transmission, to view through haze, fog, or mist, and for infrared photography or night vision

Visible light: It is released into the atmosphere by excited atoms in gases as well as by incandescent substances. The range of frequencies covered is 4×10^{14} Hz to 8×10^{14} Hz. It complies with the refraction and reflection rules. It is susceptible to diffraction, interference, and polarization. It also displays the photo-electric effect. It may be applied to the study of molecular structure and the configuration of electrons in an atom's outer shell. It results in a visual sense.

Ultraviolet radiation: It is created by arcs, the sun, and ionized gasses. It operates in the frequency range of 8×10^{14} Hz to 10^{17} Hz. Its penetration strength is reduced. It is detrimental to human health and can be absorbed by ozone in the atmosphere. It is employed in the research of atomic structure, the sterilization of surgical tools, burglar alarms, the detection of invisible writing, and finger prints to eliminate microorganisms.

X-rays: It is created via electronic transitions between atoms's innermost orbits as well as the abrupt halting of fast moving electrons at a high atomic number target. X-rays have a frequency range of 10^{17} Hz to 10^{19} Hz. Compared to UV radiation, X-rays are more invasive. X-rays are widely utilized to analyze crystal structures and the architectures of inner atomic electron shells. It is employed in the detection of bone fractures, organ illness, the creation of stones and bones, and the tracking of bone healing. Moreover, it is employed to find holes, fractures, defects, and other issues in a final metal product.

Gamma rays: It is created by decaying some elementary particles and radioactive nuclei transitioning. They result in fluorescence, ionization, diffraction, and chemical reactions on photographic plates. The range of frequencies is 10^{18} Hz and higher. X-rays and UV radiation are less invasive than gamma rays, which are non charged yet extremely hazardous to human health. Information regarding the composition of atomic nuclei may be obtained from gamma rays. It is employed in the food sector to destroy harmful microorganisms and in radiotherapy for the treatment of cancer and tumors. [14]

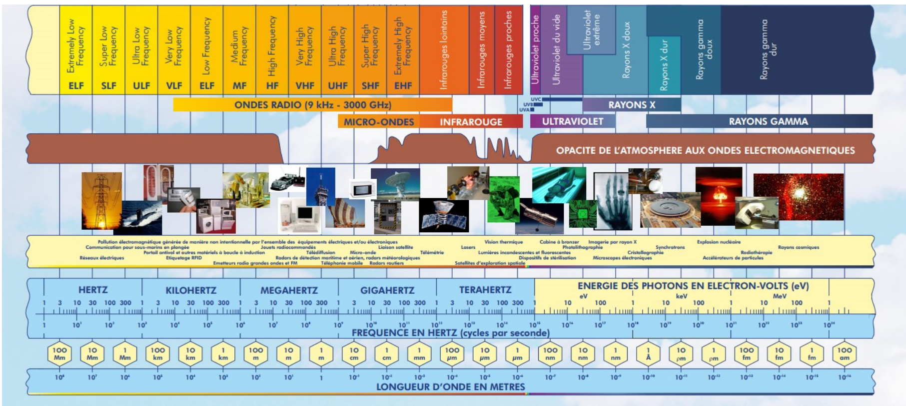

Figure 1.7: Electromagnitique srectrum

1.5 Massive MIMO

Massive multiple input multiple output, or massive MIMO, systems are multiuser communications solutions that use a large number of antenna elements practically dozens or hundreds, theoretically thousands to serve multiple users simultaneously and provide diversity gain while giving users the flexibility to choose which users to schedule for reception at any given time.

is a crucial component of 5G wireless networks. When compared to earlier generations, it greatly increases wireless communication's capacity and efficiency. [15]

1.5.1 its role in 5G communication

Massive MIMO plays a vital role in 5G communication by significantly enhancing network capacity, efficiency, coverage, and user experience. It serves as a foundation for enabling the next generation of wireless communication and supporting the ever growing demand for data usage

- Increased capacity: Enables significantly more users to connect to the network and use data simultaneously, leading to a smoother user experience.

- Improved spectral efficiency: Makes better use of the limited radio spectrum, optimizing resource utilization and reducing interference.

- Enhanced coverage: Provides better signal coverage, especially in areas with weak signals, ensuring consistent connectivity.

- Reduced power consumption: Improves user device battery life by requiring less power to transmit and receive signals, as the signal is more efficiently directed.

1.5.2 Type MIMO

► **SISO (Single-Input Single-Out put)**

Both the transmitter and the receiver use only one antenna. This is the simplest and most basic configuration, commonly found in older wireless technologies or low power applications.

▶ **SIMO (Single-Input Multiple-Output)**
The transmitter has one antenna, while the receiver utilizes multiple antennas. This configuration is less common and typically used in specific applications where diversity at the receiver side is desired. Can leverage spatial diversity to potentially mitigate fading and channel effects, improving signal reception quality.

▶ **MISO (Multiple-Input Single-Output)**
The transmitter uses multiple antennas, while the receiver only has one. This configuration is often used in base stations (cell towers) to improve coverage and signal strength for multiple users within the same area.

▶ **MIMO** offers the most advanced capabilities with multiple antennas on both sides, followed by MISO and SIMO offering specific advantages in their respective configurations. SISO is the simplest but also the most limited configuration in terms of performance.

The figure1.8 you provided shows a diagram of the different types of MIMO devices.

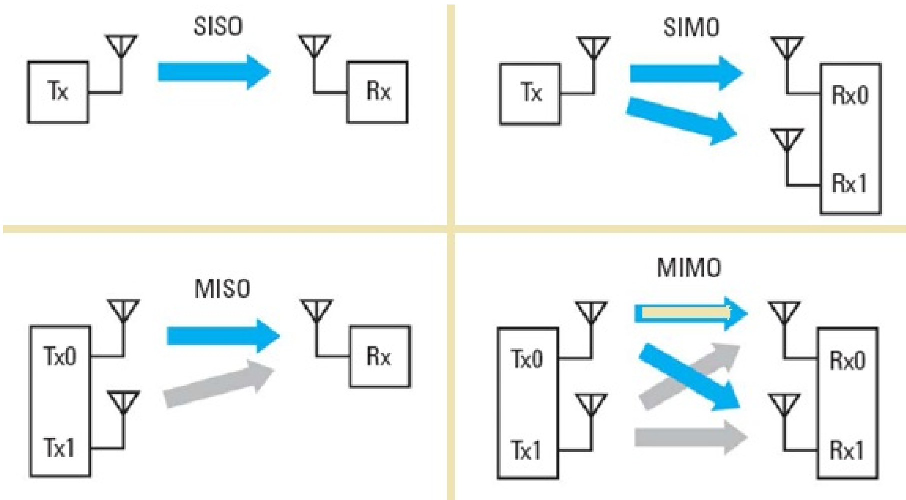

Figure 1.8: Type MIMO

1.6 Millimeter Wave (mmWave)

There are several wireless networking deployments, both present and prospective, that can make use of millimeter-wave wireless communication technologies. According to the FCC 5G NR spectrum, which has a frequency band beginning at 24 GHz and beyond, it is frequently referred to as high band 5G technology.
The exceptionally high frequency (EHF) band is another name for it given by the International Telecommunication Union (ITU). It refers to the portion of the electromagnetic spectrum that lies between 30 and 300 GHz in radio frequency. It is defined as the area between the far-infrared band and the super high frequency band, with the terahertz band being the lower section.
Given that electromagnetic waves in this spectrum have wavelengths between 10 and 1 millimeter (mm),It is sometimes referred to as the millimeter band, and the radiation that falls

inside this spectrum is called millimeter waves, or mmWave for short. The first person to study these millimeter length electromagnetic waves was the Indian physicist Jagadish Chandra Bose, who conducted experiments between 1894 and 1896, reaching a maximum frequency of 60 GHz.
Previously, only radar and satellite systems usually run by the aerospace and military industries used millimeter waves. However, the industry has realized that millimeter waves are necessary and present an opportunity for next generation mobile networks, given the explosion in data demand. In wireless networks and mobile devices, millimeter waves are employed in communications for a variety of services, as well as fast point-to-point wide area network (WAN), as it enables higher data rates than at lower frequencies, which are utilized by WiFi and modern cellular networks. [16]
The figure 1.9 shows the frequency range for cellular and millimeter waves.
The frequency range for cellular waves is from 300 MHz to 3 GHz while the frequency range for millimeter waves is from 30 GHz to 300 GHz.

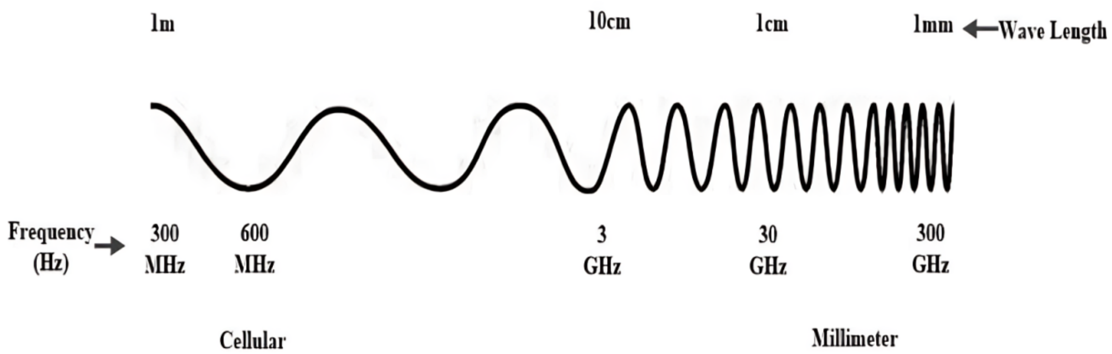

Figure 1.9: Frequency range for cellular and millimeter waves

1.6.1 The rationale behind mmWave for 5G

► **Broad bandwidth:**

A peak data rate of around 10 Gbits/s may be attained using mmWave bands, and this can rise with full duplex capabilities. Compared to 1 Gbits/s at low microwave frequencies, this is substantially greater.

► **Short wavelength:**

Compared to the microwave bands that are already in use, mmWave bands have a very tiny wavelength. This allows them to include more antennas into a compact device by enabling them to have smaller size components.

► **Slender beams:**

Highly directional steerable narrow beams may be generated in mmWave antenna arrays to accurately guide the broadcast power along desired direction to the intended consumers.

► **Enhanced protection and disruption protection from:**

Because of its restricted range and extremely directed beams, mmWave signals are more expensive and challenging to jam. Furthermore, because narrow beams may concentrate the signal's broadcast power level; they greatly reduce the likelihood of interference and noise at the receiver end of the transmission chain. [17]

1.6.2 Frequency bands allocated for mmWave in 5G NR

The figure 1.10 depicts the two distinct frequency bands identified by 3GPP for 5G New Radio (NR): FR1 (belonging to < 6GHz) and FR2 (belonging to mmwave 24.2 – 52.6 GHz).

▶ **Range of Frequency 1 (FR1):** The majority of typical cellular mobile communications traffic is carried by frequencies in the (4.1 GHz to 7.125 GHz) range.

▶ **Range of Frequency 2 (FR2):** Dive Deeply into mmWave Territory (24-100 GHz)(typically from 24 GHz to 52.6 GHz for 5G NR) : This is a defined region within 5G New Radio (NR) that focuses on short range, high data rate capabilities. Specifically, it targets the millimeter wave (mmWave) spectrum, and concentrated on high data rate, short range capabilities. [18] [19]

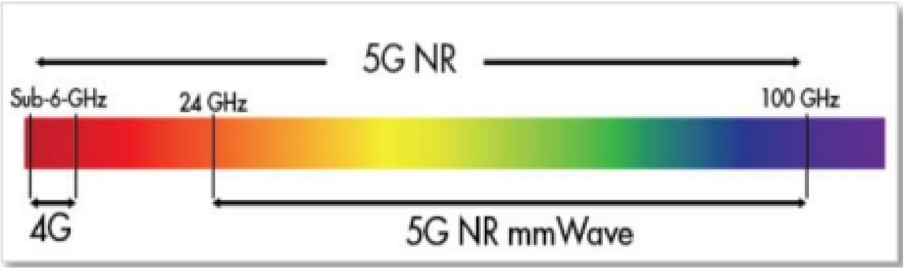

Figure 1.10: 5G NR mmwave

1.7 Conclusion

The wireless communication industry has witnessed remarkable growth and technological advancements over the generations, from the first generation (1G) analog systems to the latest 5G and anticipated 6G networks. Each generation has brought significant improvements in coverage, capacity, data rates, and the ability to support a wide range of applications and services.
Moreover, mMIMO and mmWave communications are two key enabling technologies that have played a pivotal role in unleashing the full potential of networks.

Chapter 2

Deep Dive into 5G New Radio

2.1 Introduction

This chapter highlights the key aspects of 5G NR and hints at future advancements, and the performance improvements offered by it. The world is on the cusp of a wireless revolution with the arrival of 5G New Radio (NR). This next generation technology promises to transform the way we connect, offering unprecedented speed, flexibility, and reliability. This presentation will delve into the core features of 5G NR, exploring how it utilizes innovative techniques like flexible spectrum and numerology to cater to diverse applications. We'll uncover the exciting use cases that 5G NR unlocks, from supercharged mobile broadband to enabling the vast potential of the Internet of Things(IoT). We'll then dive deeper into how millimeter wave frequencies and massive MIMO antenna systems push the boundaries of 5G NR, along with the considerations for designing and implementing these powerful technologies. Finally, we'll explore the signal processing techniques that ensure efficient data transmission in this dynamic 5G landscape.

2.2 5G NR features

2.2.1 Flexible Spectrum

The 5G NR is designed with flexible numerology and spectrum, allowing for multiple frequency bands for communication. It focuses on higher frequency channels and uses Orthogonal Frequency Division Multiplexing (OFDM) for modulation. The system architecture is versatile, serving three use cases (eMBB, MMTC, and uRLLC) in different deployment circumstances.

The OFDM is used in LTE and LTE-A systems with a 15 kHz subcarrier spacing.While NR will function on a variable subcarrier spacing ranging from 15 kHz to 240 kHz The two frequency bands used by 5G NR for operation are FR1 (low/mid bands) for greater coverage and FR2 (high bands) for extremely fast speeds. Flexible Spectrum benefits NR systems by offering solutions with reduced power and bandwidth, improving channel capacity, and ensuring efficient bandwidth use . [11]

2.2.2 Flexible Numerology

Depending on the carrier frequency, deployment circumstances, and service demand, the spacing might vary from 15 kHz to 240 kHz. The subcarrier spacing (SCS) of 15 kHz is supported in the frequency spectrum below 2 GHz. Depending on the service, the SCS will be 15/30/60 kHz at frequencies above and below 2 GHz and below 6 GHz. The SCS of 60/120/240/480 kHz will be used for the frequency range above 6 GHz.

Cyclic Prefix (CP) duration and OFDM symbol duration correspond to each SCS In 5G NR, the SCS is scaled by multiplying 15 kHz by the factor 2^n . The SCS in the LTE system is 15 kHz, and n can be any integer positive, negative, or zero. Systems with 5G support $n \in [1,2,3,4,5]$. As a result, 15 kHz, 30 kHz, 60 kHz, 120 kHz, 240 kHz, and 480 kHz will be the available spacing. The creation of mini-slots as a result of this spacing adds a feature to the NR functions. A very little packet will be successfully sent if mini-slots are available. The smallest Resource Blocks (RBs) that can be allotted to a user are called mini-slots. It is used to provide low latency communication and carries a control signal.

The 5G NR's extremely adaptable frame structure accommodates both FDD (Frequency Division Duplex) and TDD (Time Division Duplex): Supports both operation modes, offering flexibility in how uplink and downlink data are transmitted. The basic time unit T_b of NR in the temporal domain is as follows:

$$\mathrm{T}_b = \frac{1}{\Delta_{fs} \times \mathrm{N}_f} \tag{2.1}$$

In this case, Δ_{fs} represents the subcarrier spacing, which scales as a factor of 15×2^n kHz, and is the 5G NR FFT size, which is always taken to be 4096. Equation 2.1 is used to compute the frame length of T_{fd} sec, which determines how long each 5G NR frame will last. This results in:

$$T_{fd} = \left[\frac{\frac{df}{dx} \times \frac{dy}{dx}}{100} \right] \times T_b = 10m \tag{2.2}$$

The frame is then split up into ten subframes, each with a T_{sb} sec duration, as follows:

$$T_{fd} = \frac{\Delta f s \times N_f}{1000} \times Tsb = 1ms \tag{2.3}$$

As a result, a frame lasting 10 ms is split up into 10 subframes, each lasting 1 ms. Two half frames of the same size are created by combining five subframes. Because these subframes are self-contained, it is possible to decode the data in one slot without relying on the data in any other slot. Then, depending on $\frac{T_{sb}}{2^n}$, each subframe is partitioned into an arbitrary number of slots. If n = 0, the slot duration will be 1ms and there will be 1 slot; if n = 1, there will be 2 slots and the slot time will be 0.5ms.
In OFDM Frame as showed in figure 2.1, 14 OFDM symbols with varying CP lengths and subcarrier spacing make up each slot. displays the 5G NR frame structure along with the slot and subframe durations. One resource block in the frequency domain is made up of 12 subcarriers. Depending on the frequency range, 5G NR will provide a configurable spacing between these subcarriers of 15×2^n kHz.

The NR architecture offers flexibility, enabling mini-slots for lower latency communication, large subcarrier spacing to reduce interference, and improving power economy for narrowband IoT [11].

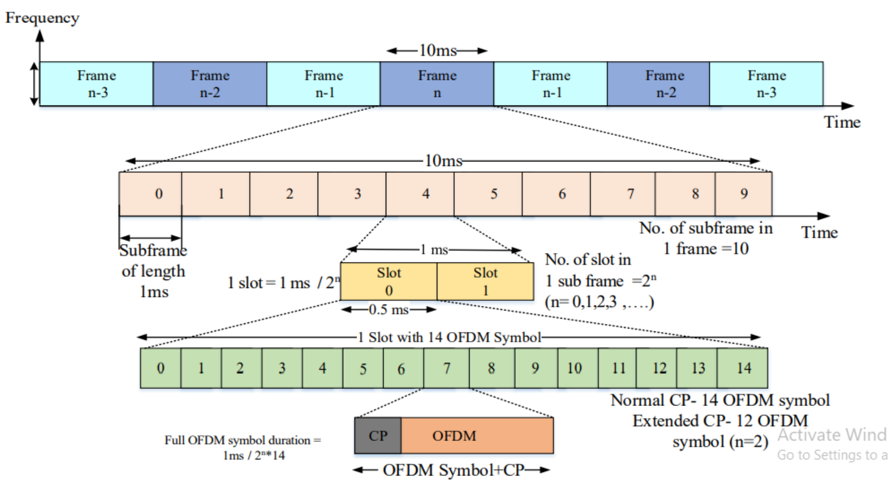

Figure 2.1: OFDM Frame

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2.2.3 Ultra-Lean Design

The 5G NR networks aim to reduce "always on" signals in mobile communication systems, such as reference, broadcast, and synchronization signals, which can negatively impact system performance due to increased user density and interferences. The ultra-lean design of these networks reduces operating costs, increases energy efficiency, reduces interference, and improves forward compatibility.
Phase tracking reference signals (PTRS), channel state reference signals (CSI-RS), sounding

reference signals (SRS), and demodulation reference signals (DMRS) are the four main reference signals in ultra-lean design. They are broadcast only when necessary. When estimating channels, the receivers employ DMRS to carry out demodulation. These signals, in both UL and DL channels, can only be beamformed in the direction of the designated user when necessary. The synchronization signals are sent together with the DMRS. In order to eliminate any inaccuracy in the phase noise of the signal, PTRS is used to track the phases of the local oscillator and offers correction at the receiver terminal. For communications over high frequencies, typically mmWave, PTRS is utilized.
Additionally user-specific, PTRS can be planned across the limited resources. There are these signals on the DL and UL channels. The UE's scheduling and sounds are provided by SRS. It is sent as one of the final six symbols of a slot. Unlike LTE, these signals are made user-specific in 5G NR networks. When the user is moving, beam measurements are taken using CSI-RS.
Through the use of CSI-RS signals, many metrics such as SNR and Reference Signal Received Power (RSRP) are evaluated. The CSI-RS signal in 5G NR can be configured in any way and can take up any slot in the OFDM symbol. Depending on the needs, these signals can be sent either regularly or aperiodically. [11]

2.2.4 Forward Compatibility

Forward compatibility is a feature in 5G NR that allows it to handle various use cases and accommodate future advancements. It involves reserving frequency and time resources flexibly and data decoding independently in a slot or beam. Key features include self contained structure, scalable transmissions, and dynamic allocation of resources based on traffic state. Forward compatibility ensures a system can work with future versions, allowing for upgrades or modifications to hardware or software. This allows for network adaptability, scalability, and uniqueness. 5G NR features flexible numerology, minimizes latency, and promotes eco-friendly communication. It also allows for numerous apps, minimizes bandwidth overuse, and offers an avenue for future technological advancements. [11]

2.3 5G New Radio Use Cases

The 5G cellular networks are intended to meet the demands of machine type Internet of things applications (mMTC), high reliability and low latency critical industrial use cases (URLLC), and higher end-user bandwidth (eMBB services). In order to accommodate these divergent needs, 5G networks utilize LTE-M and NB-IoT for mMTC services and their new radio interface (5G-NR) for eMBB and URLLC services. Release 16 of 5G networks successfully supports the highest echelons of the KPIs, which include coverage, autonomy, latency, bandwidth, and dependability. The NR-REDCAP 3GPP Study Item of Release 17 discusses a number of use cases, including wearables, industrial IoT, and video surveillance .

2.3.1 Enhanced Mobile Broadband (eMBB)

Broadband technology enables high speed data transfer and quick signal delivery through the internet, integrating computer networks, televisions, and smart devices. It provides low-cost access to electronic resources, increased productivity, and cost savings for users. The growth of mobile broadband traffic is driven by demand for data, improved network coverage, new technology, smartphones, software, and machine type communications.

Enhanced Mobile Broadband (eMBB) techniques in 5G NR focus on improving signal strength, capacity, and coverage for high data rate applications. Techniques include Massive MIMO, beamforming, diversity techniques, channel coding techniques, and modula-

tion techniques. These techniques aim to mitigate signal fading caused by multipath propagation, ensure reliable data transmission, and introduce redundancy to detect and correct errors. Modulation techniques determine how data is represented on the radio signal, impacting data rate and spectral efficiency. The goal is to provide high throughput applications for high priority services, ensuring ultra fast data rates for a seamless user experience.
The technology facilitates high definition video streaming, large file downloads, and seamless next generation VR and AR experiences, enabling real-time cloud gaming without interruptions. [20]

2.3.2 MASSIVE MACHINE TYPE COMMUNICATION (MMTC)

Machine type communication (mMTC) is a technology that facilitates efficient communication between low-power devices, with applications in smart metering, factory automation, autonomous driving, surveillance, security, and fleet management. It uses intelligent devices to analyze data and provide appropriate responses, with mMTC services handling massive IoT (mIoT) and connecting devices to the internet for independent operation.
The 5G mMTC uses high connection density of 1M devices/Km^2, increased reach, low cost IoT, and fast mobility for applications like powering IoT, remote monitoring, and supporting wearable health trackers. It supports 10 km/h indoors, 30 km/h in crowded cities, and 500 km/h outdoors. Cellular networks, initially designed for H2H communication, are inadequate for M2M communication due to the need for security and dependability. Radio Resource Management (RRM) techniques improve energy efficiency but are insufficient for M2M communication.
Congestion in distributed mMTC networks can lead to higher latency and packet loss, which is detrimental for 5G networks. A technique for managing congestion in distributed mMTC networks is developed, which allocates resources within a defined contention time, reducing energy consumption, overhead, and latency. Implementing mmWave-based NOMA for mMTC can improve outage probability and lower overhead. [11]

2.3.3 Ultra-Reliable and Low-Latency Communication (uRLLC)

One of the most important applications of 5G NR, 5G NR's uRLLC service enhances network quality and capacity for various applications. It prioritizes minimal delays and high reliability for mission critical applications. Enabling uRLLC services involves replacing existing wired links with uRLLC enabled ones,Industry 4.0 equipment, such as cooperative robots, are one example of how uRLLC enabled wireless connections are replacing conventional cable communications. In contrast, the native uRLLC connections are not the ones that have been substituted, they are completely made with uRLLC applications in mind, take V2V communication, for instance.
The 5G uRLLC offers high reliability, low latency, and minimal mobile disruption, making it ideal for applications like autonomous vehicle support, remote surgery, and industrial automation with near instantaneous responses. uRLLC is crucial for mission critical services and real time applications, including intelligent transportation, industrial automation, and remote surgery. It requires achieving tight latency requirements and ultrareliability simultaneously in 5G NR. Technologies like massive MIMO and multi connectivity are suggested, with machine learning techniques for dependability. Prediction based resource optimization is used to optimize uRLLC services, while a preemptive scheduler based on null space is suggested for instant scheduling while maintaining system capacity. However, achieving low latency is challenging due to aggressive transmission of data with eMBB transmission. [11]

2.4 OMA|NOMA Techniques in 5G New Radio

when we talk about multiple access techniques we have to mention the two types NOMA and OMA which showed in figure 2.2. The cellular system design is interested in the multiple access scheme design , wher the objective is to efficiently use spectrum, cost, and complexity to supply radio resources to many user equipments (UEs). TDMA (time division multiple access), CDMA (code division multiple access), and frequency division multiple access (FDMA) have been introduced in 1G to 3G, respectively. Then, single-carrier (SC)-FDMA and orthogonal frequency division multiple access (OFDMA) were created as orthogonal multiple access (OMA) methods by Long-Term Evolution (LTE) and LTEAdvanced. Additionally, the OFDMA waveform is used by 5G new radio (NR) for both downlink (DL) and uplink (UL) transmission. One advantage of such orthogonal designs is that simple receivers can achieve great system performance because there is no mutual interference among UEs. [21]

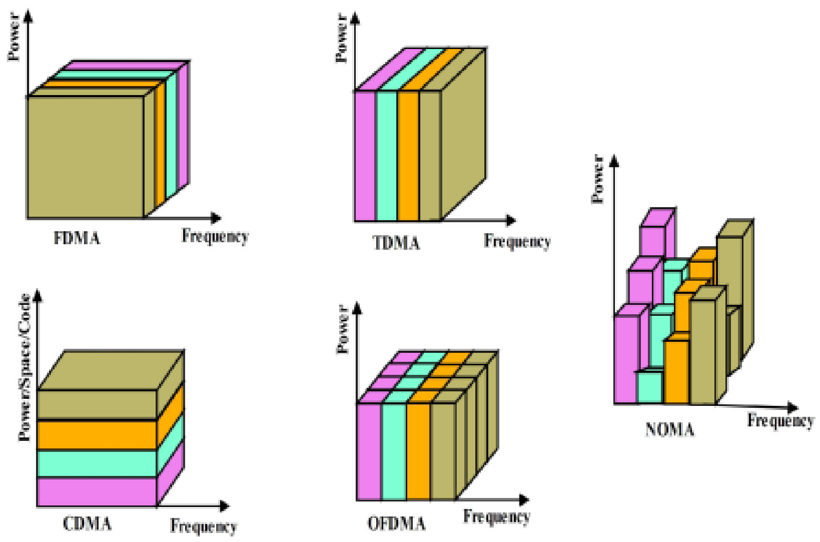


Figure 2.2: Different multiple access techniques.

Non-orthogonal multiple access (NOMA) has drawn a lot of interest as a potential multiple access method for LTE, 5G, and future 5G systems in the past several years. Multiple UEs are co-scheduled and share radio resources in terms of time, frequency, and/or coding while using NOMA. In particular, 3GPP has taken NOMA into account for many applications.
For example, NOMA has been introduced as a study item of LTE Release 13 called DL multiuser superposition transmission (DMST), and as an extension of the network assisted interference cancellation and suppression (NAICS) for inter-cell interference (ICI) mitigation in LTE Release 12. Some of the schemes that have been proposed for NOMA are : Power domain NOMA, SCMA (SC: sparse code), PDMA (PD: pattern division), RSMA (RS: resource spread), multi-user shared access (MUSA), IGMA (IG: interleave grid), Welch bound equality spread multiple access (WSMA), IDMA (ID: interleave division), NCMA (NC: non-orthogonal coded), ACMA (AC: asynchronous coded), low code rate spreading (LCRS), non-orthogonal coded access (NOCA), low code rate and signature based shared access (LSSA), and UGMA (UG: user grouped) .
These methods adhere to the superposition principle. The primary distinction between them is the design of the UEs' signatures, which is based on spreading, coding, scrambling, or interleaving distinctness, as well as variations in bit and symbol level NOMA implementation.
At the expense of receiver, UE pairing, and coordination complexity, NOMA has the potential to perform better than the current OMA approaches. These factors have led to the proposal of NOMA as a potential method for data transmission in dense networks where a

high number of UEs are requesting access and there are insufficient orthogonal resources to accommodate their requests in an OMA-based manner. In particular, 3GPP took into consideration a study item in 2018 to assess the advantages of NOMA and offer recommendations regarding whether NR should support (at least) UL NOMA in addition to the OMA. Nevertheless, it was determined not to proceed with NOMA as a work item and to save it for potential usage in the years after 5G, for many reasons. wher the NOMA Study in 3GPP for 5G NR involved simulations of transmission schemes and receivers. Three scenarios were considered: mMTC, ultra reliable low latency communications (URLLC), and enhanced mobile broadband (eMBB). Results showed significant performance degradation in non-ideal channel estimation scenarios, while channel estimation effects were more noticeable in URLLC scenarios. 3GPP decided not to continue with NOMA, leaving it for use cases with ultra-dense UEs beyond 5G. [21] we can see an example of UL and DL NOMA techniques in figure 2.3

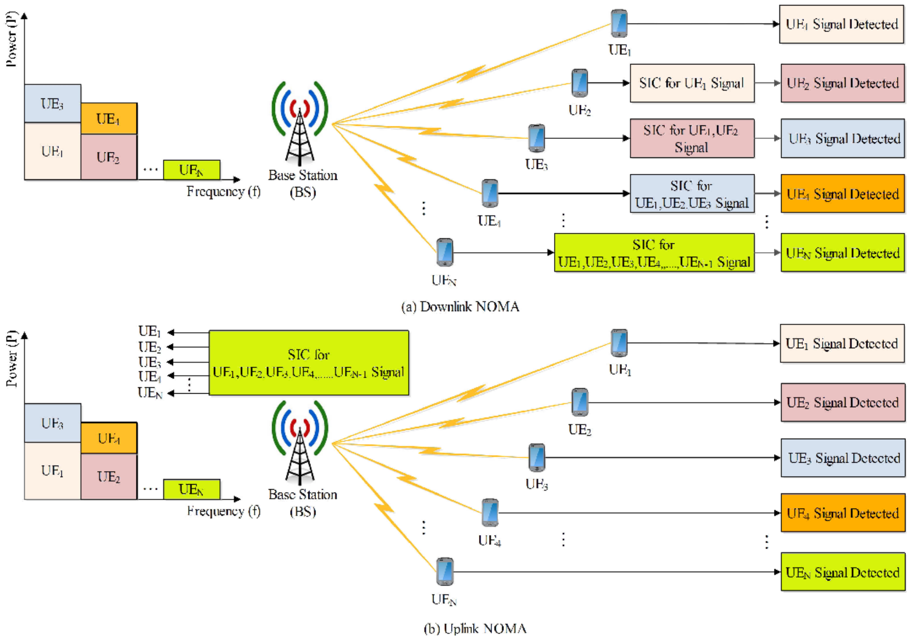


Figure 2.3: Downlink and uplink NOMA

2.5 Millimeter-Wave Massive MIMO Communication

Massive MIMO is one of the technologies to achieve 5G requirements. It has plenty of antennas at the BS which serve multiple users simultaneously , which makes the network more efficient in throughput, spectrum utilization, and energy consumption. MmWave communication is another technology with a large amount of unused bandwidth to support millions of devices at once .
Since the mmWave frequencies are highly directional as compared to lower frequencies, they can precisely handle large antenna arrays during the transmission and reception process with a beamforming strategy . On the contrary, it is challenging for long range wireless communication because of the huge path loss in the mmWave band.
To compensate for the path loss and extend the coverage, massive MIMO antennas are supposed to be deployed in mmWave communication systems.

the figure 2.4 shows to merge massive MIMO and mmWave, it dramatically improves wireless access, throughput or the quality of service in 5G cellular system . This technological combination of massive MIMO and mmWave systems has given birth to mmWave-massive MIMO which brings an opportunity to support a plethora of high speed services for bandwidth hungry applications. That is, mmWave massive MIMO has the capacity to boost user throughput, mobile network capacity, spectral and energy efficiency. [22]

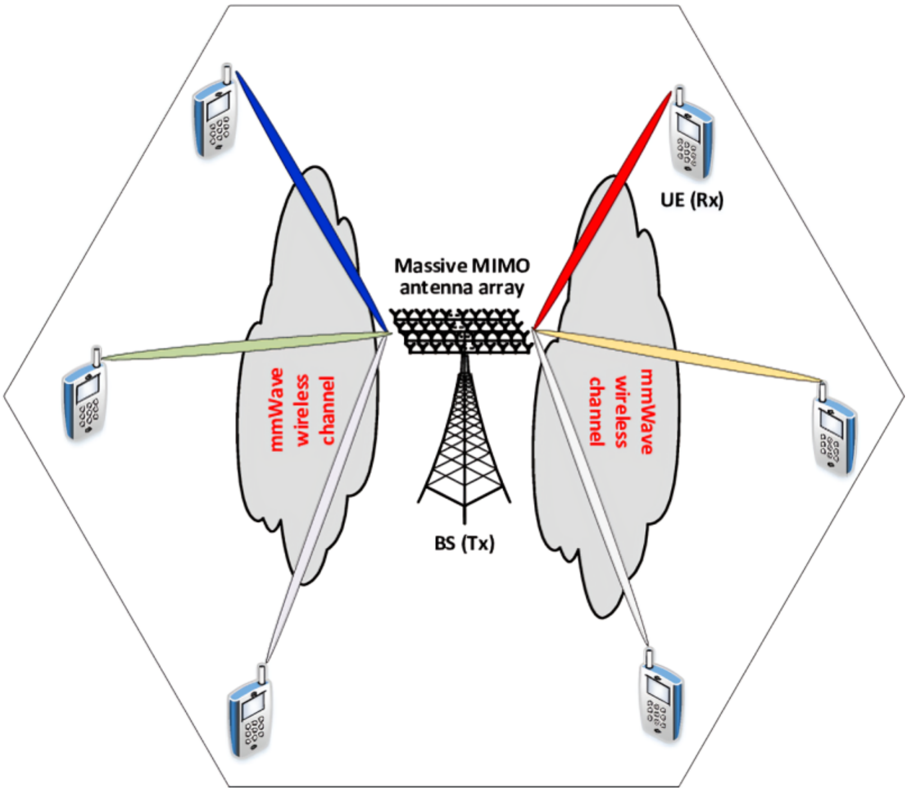


Figure 2.4: MmWave massive MIMO system

2.5.1 Key Factors for Design and Implementation mmWave mMIMO System

Leveraging millimeter wave (mmWave) frequencies and massive MIMO technology is a powerful combination for achieving the high data rates and capacity demanded by 5G networks. However, designing and implementing such a system requires careful consideration of several key factors:

- **Antenna Design** This involves creating compact and efficient antenna arrays with beamforming capabilities to handle mmWave signals.
  The system will rely on a large number of antennas at the base station. These antenna arrays need to be compact and efficient while minimizing mutual coupling (interference between antenna elements) for accurate signal processing.

- **Channel Modeling and Propagation** Understanding how mmWave signals and accounting for factors like blockage and attenuation and fast changing channels are crucial.

- **Hardware and Signal Processing** mmWave operation requires specialized components like high frequency amplifiers and converters that can handle the wider bandwidths.
  The system needs powerful digital signal processing (DSP) algorithms to handle the complex beamforming, channel estimation, and multi-user MIMO processing involved.

- **System Calibration and Optimization** Ensuring all antenna elements function optimally and implementing power saving techniques are essential.

- **Network Management and Backhaul** Efficient user scheduling, resource allocation, and a high capacity backhaul network are required to handle the increased traffic.

2.5.2 Challenges of Implementation

High cost and complexity of deploying massive antenna arrays.
Challenges in managing interference in dense urban environments with mmWaves.
Limitations of user equipment (phones, devices) to handle complex beamforming techniques.
High power consumption of mmWave and advanced signal processing.

2.5.3 Hybrid Array Technique

This is a potential solution to address some of the challenges. It combines a traditional, smaller antenna array with a simpler design for wider coverage with a secondary, high resolution array for mmWave beamforming towards specific users,and this offers a balance between cost, complexity, and performance.
By carefully addressing these key factors, engineers can design and implement a 5G communication system using mmWave and mMIMO that delivers the promised ultra fast data speeds, high capacity, and low latency for next-generation applications.

2.6 Signal Processing Techniques for mm-Wave mMIMO System

2.6.1 Beamforming

MIMO technology and the mmWave and THz frequency bands have become attractive options for next generation wireless communication systems due to the increasing demand for even higher data rates. These bands provide huge accessible bandwidths, enabling high data rates, in contrast to systems operating at frequencies below 6 GHz; nonetheless, their propagation properties (i.e., substantial attenuation in open space, absorption by atmospheric gases, and obstructions) pose considerable problems.
Beamforming techniques and the use of highly directional antennas are necessary to overcome these obstacles. By producing extremely focused beams, beamforming makes it possible for devices to communicate with one another even when there are obstructions present. The potential of mmWave and THz frequencies may now be utilized because to the advancement of beamforming techniques, which has resulted inemergence of 5G and beyond wireless communication systems .
Beamforming is a technology that allows us to adjust the radiation pattern of an antenna array. It can make the pattern more directive when needed or alter the direction of the main beam. To enhance the Signal-to-Noise Ratio (SNR), beamforming achieves this by precisely controlling the power and phase of each element in the antenna array. In contrast to the conventional method (Single-Input Single-Output, or SISO), beamforming in massive MIMO systems may be able to provide spatial multiplexing, depending on the architecture that is put into practice.
By sending distinct signals via various antennas or groups of antennas, the spatial multiplexing approach seeks to boost the channel's transmission capacity. The number of bits

broadcast over the channel per second can be multiplied by transmitting these signals simultaneously and at the same frequency. Because it requires knowledge of the channel and the separation of multipath components, this approach places a great deal of complexity on the receivers. Beamforming that showed in 2.5 can be implemented using analog, digital, or hybrid architectures, and it can be done at baseband frequencies or Intermediate Frequencies (IFs). [23]

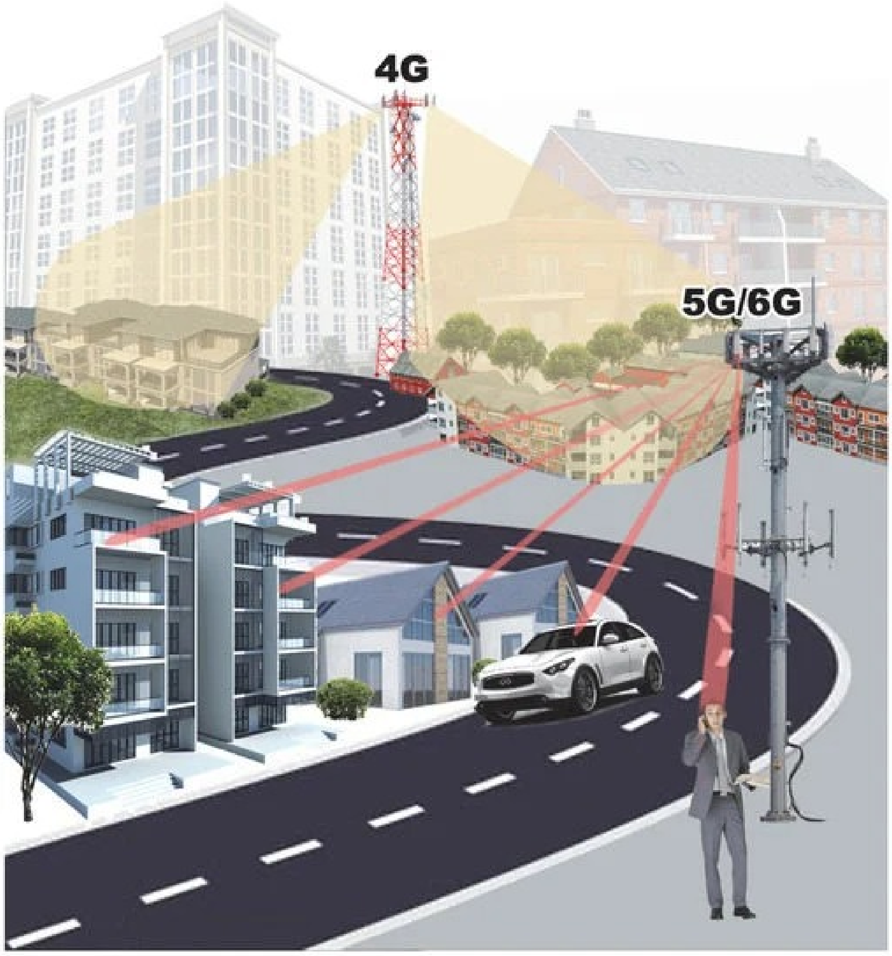


Figure 2.5: Beamforming architactur

Consider that a narrow-band signal, denoted as x(t) , is arriving at the antenna array from an angle θ relative to the axis of the array, and the signal source is located in the array's far-field. If x(t) represents the signal that would be captured at the coordinate system's origin, then the signals $x_1(t), x_2(t), ...x_M(t)$ received by the (M) sensors of the array at the time (t) can collectively be expressed as the vector [24] :

$$x(t) = [x(t-\tau_1), x(t-\tau_2), ..., x(t-\tau_M)]^T \tag{2.4}$$

where $\tau_1, ..., \tau_M$ is the time delay occurred for the signal received at each of the sensors due to the path difference. For a linear array with uniform sensor spacing d, the time delay between the adjacent sensors is given by [24] :

$$\tau = (d\cos\theta/c) \tag{2.5}$$

where c is the velocity of medium. The time delay between 1^{st} and M^{th} sensor will be [24] :

$$\tau_M = ((M-1)d\cos\theta)/c \tag{2.6}$$

If $w_1, \ldots\ldots, w_M$ are the weights to be multiplied to each of the sensor outputs which is collectively represented by the vector w, then the scalar beamformer output y(t) generated by the linear combination of x(t) and w can be represented as [24]:

$$y(t) = w^H x(t) \tag{2.7}$$

types of beamforming In 5G technology, there are three main types of beamforming techniques such as figure 2.6:
- Analog Beamforming
- Digital Beamforming
- Hybrid Beamforming

2.6.1.1 Analog Beamforming

Using inexpensive phase shifters to adjust the broadcast signal's phase at each antenna array element is the fundamental concept behind analog beamforming. The system consists of a single set of antennas, phase shifters, and an analog to digital converter (ADC) for baseband processing. Analog phase shifters, which are used to direct the signal output by the array of antennas, modify the phase of the same signal before feeding it (via the RF chain) to each antenna in this architecture. Every antenna array element in this configuration is wired up to a phase shifter.
This phase shifter is used to adjust the phase of each antenna array element so that the transmitted signal is added constructively to the receiver. These phase shifters allow the beam pattern's direction and shape to be changed. a Variable Gain Amplifier (VGA) can also be used to alter the amplitude of the input RF signal. The primary benefits of this architecture are its lower energy consumption compared to the others and the beam's increased coverage due to the antenna array's total gain.
However, these architectures are bulky, expensive, and unable to transmit multiple streams simultaneously to achieve spatial multiplexing diversity, which limits the transmission rate and flexibility of the system for applications that use high frequencies or broadband operation. Other designs that generate the transmission signal digitally are sought at in order to lessen these restrictions. [23]

2.6.1.2 Digital Beamforming

Barton suggested Digital Beamforming (DBF) in the 1980s. The transmission of digitally generated signals in each antenna array element is the foundation of this system. This allows for control over the beams' form in the digital domain. Each antenna element in this architecture has its own RF chain and ADC, and the signal that feeds it goes through separate baseband processing. There are two types of DBF: fixed and adaptable.
Every phase and amplitude control in a fixed DBF is preset and cannot be altered while a communication is in progress. Adaptive DBF, on the other hand, adjusts the control based on the requirements of the system, changing the beam shape because of obstructions, raising the SNR and directivity at certain locations, etc.
The signal processor digitally controls the amplitude and phase of each element in the baseband before converting it to the pass band in order to create the proper beam pattern for communication. This design offers more flexibility in beamforming algorithm implementation than analog ones since the control is handled in the baseband via digital signal processing.
One benefit of DBF over its analog equivalent is that it can support many beams at once, enabling spatial multiplexing. Additionally, adaptive beamforming with digital control is possible with this architecture. However, because an RF chain is required for every antenna

array element, this architecture has the drawback of higher energy consumption and higher cost. [23]

2.6.1.3 Hybrid Beamforming

In order to address the shortcomings of both analog and digital beamforming, hybrid beamforming combines the two techniques. Its goal is to reduce the complexity provided by the digital beamforming approach which consists of multiple independent ADCs and RF chains while enhancing the performance of the analog beamforming technology by permitting more streams.
A digital precoder, ADCs, RF chains, phase shifters, and N components make up the architecture. Compared to the fully digital architecture, each RF chain is less expensive and complex because it is coupled to a set of antenna elements. Furthermore, pre-encoded user data is sent into a specific radio frequency chain. As a result, a group of antenna components equipped with separate phase shifters is used to transmit the signal. Spatial multiplexing can also be implemented with hybrid beamforming.
Hybrid beamforming reduces the number of RF chains in the digital architecture by having a reduced hardware cost. Furthermore, because it has several beams and can achieve more precise beam formation than the analog architecture, it does not interfere with other users. Furthermore, if the system is outfitted with separate ADC and RF chains and the input signal undergoes independent baseband preprocessing, hybrid beamforming additionally permits spatial multiplexing. [23]

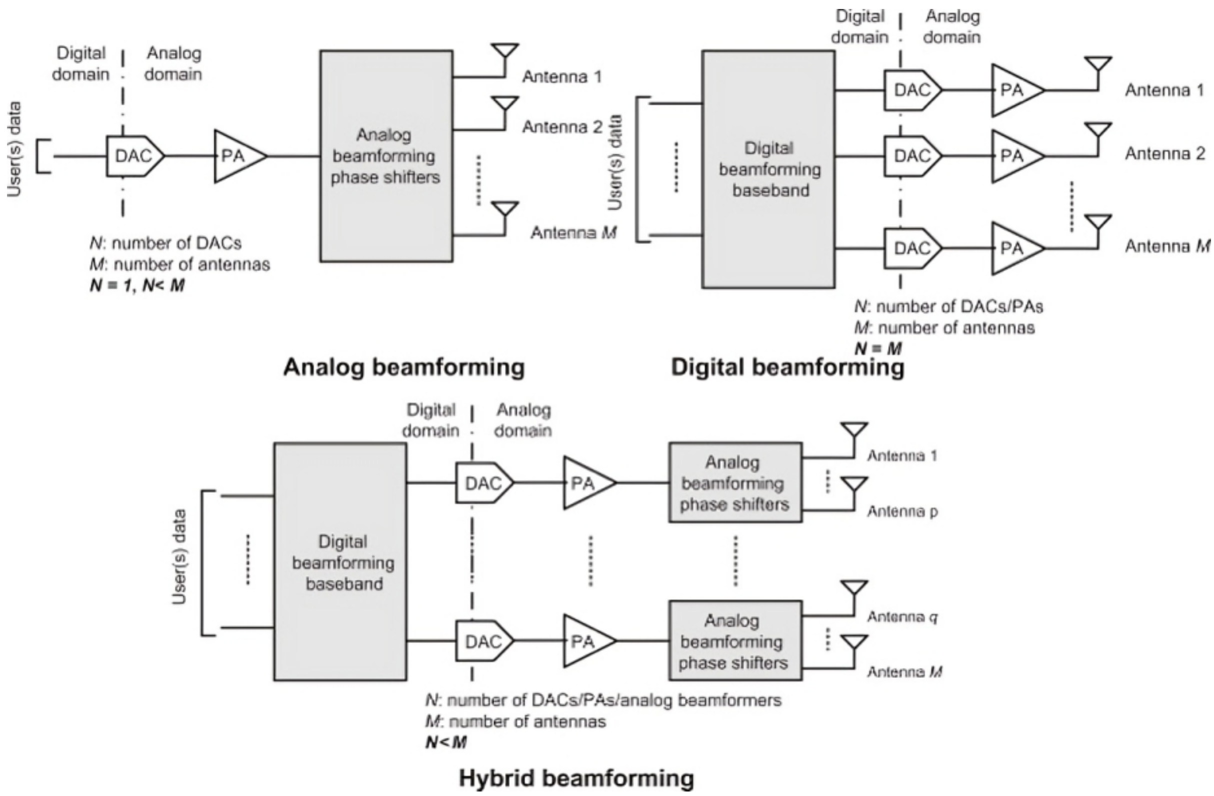


Figure 2.6: types of beamforming

2.6.2 Channel Estimation

Accurate channel estimation is crucial in 5G networks to enable coherent detection, beamforming, and other advanced signal processing techniques that improve spectral efficiency and reliability .
In large scale MIMO, signals are detected and decoded using Channel State Information

(CSI). CSI is a measure of the communication link's status, calculated by adding the effects of fading, scattering, and other variables. If a huge MIMO system has a perfect CSI and a few extra transmitting or receiving antennas, whichever is lower, it will function better. [5]
The figure 2.7 shows a diagram of Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) modes, which are two methods to allow for two-way communication between a base station and a user equipment (UE). In a FDD, CSI estimation is crucial for both uplinks and downlinks. The base station determines the channel to be used during UL with the assistance of orthogonal pilot signals supplied by the user terminal.
During the DL, the user receives a pilot signal from the base station, and they acknowledge the estimated channel information for the transmission. When it comes to large MIMO systems with several antennas, the DL channel estimate approach in FDD is extremely complicated and practically impractical. TDD operation was the initial plan for MIMO systems. [5]
Pilot contamination is a major issue during mMIMO channel estimation since there is a finite quantity of orthogonal pilots that may be reused from one cell to another. The base station selects the channel to be used for the UL. [25]

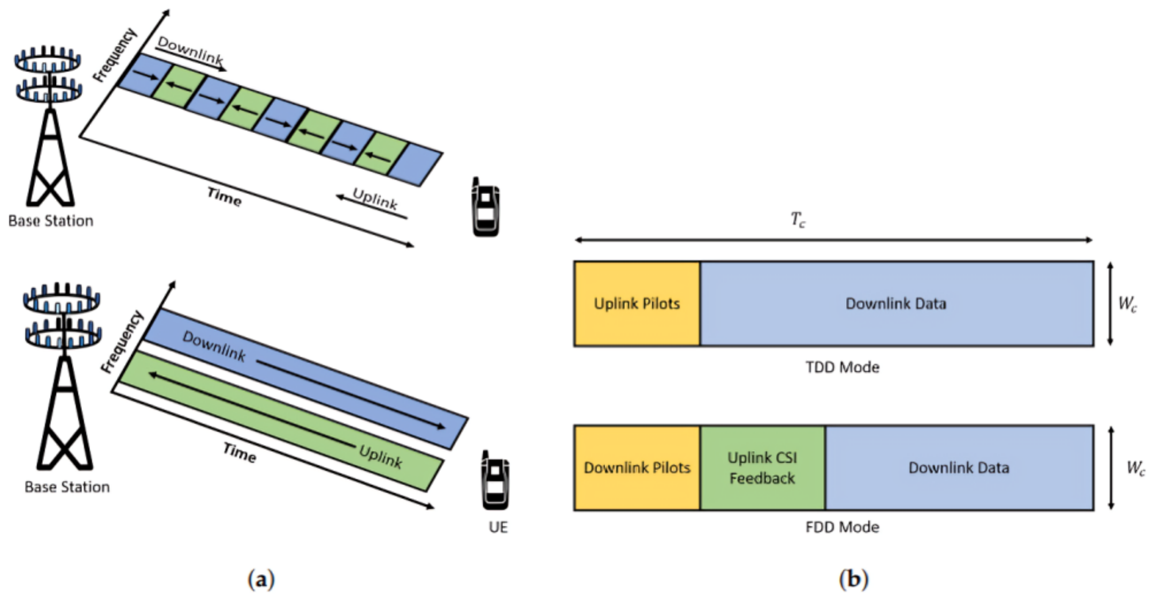


Figure 2.7: (a) Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) mode: Massive works best in TDD mode. (b) Typical pilot transmission and CSI feed back mechanism in FDD and TDD mode.

Accurate channel estimation helps steer the beams precisely towards users, maximizing signal strength, minimizing interference and improve transmission parameters, like power levels and coding schemes, to ensure reliable data delivery.
The basic system model equation to estimate the channel of Multiple-Input Multiple- Output (MIMO) system:

$$\begin{pmatrix} y_1 \\ \vdots \\ y_M \end{pmatrix} = \begin{pmatrix} h_{11} & \cdots & h_{1N} \\ \vdots & \ddots & \vdots \\ h_{M1} & \cdots & h_{MN} \end{pmatrix} \begin{pmatrix} x_1 \\ \vdots \\ x_N \end{pmatrix} + \begin{pmatrix} n_1 \\ \vdots \\ n_M \end{pmatrix} \tag{2.8}$$

y (vector): This represents the received signal at the M receive antennas.
H (matrix): This is theMxN channel matrix. It captures the complex gains and phase shifts experienced by the signal as it propagates from each of the N transmit antennas to each of the M receive antennas. In essence, H encodes the characteristics of the communication channel.

x (vector): This represents the transmitted signal vector with N complex values, one for each transmit antenna.
n (vector): This is the additive white Gaussian noise (AWGN) vector.

Channel estimation aims to recover the channel matrix (H) because it holds crucial information about the signal propagation. Knowing H allows us to:

Equalize the received signal: Since the channel can distort the signal, we can use H to compensate for these distortions and recover the original transmitted data more accurately.

Perform beamforming: By manipulating the transmitted signal based on the estimated channel (H), we can focus the signal energy towards the desired receiver, improving communication efficiency and reducing interference.

2.6.3 Precoding technology

Research interest in mobile communications has increased significantly due to massive MIMO systems. Using precoding techniques at the basestation lowers the complexity of signal processing among massive MIMO evaluation cases and design issues. Precoding methods address signal processing complexity and minimize interference as shown in figure2.8.
To steer a data transmission spatially, precoding involves delivering the signal from each antenna at a different phase and amplitude. Utilizing the CSI available at the transmitter is the goal of precoding. The inability to lessen Inter-User Interference (IUI) is what worries it; Many precoding strategies have been used to lower IUI. [22]

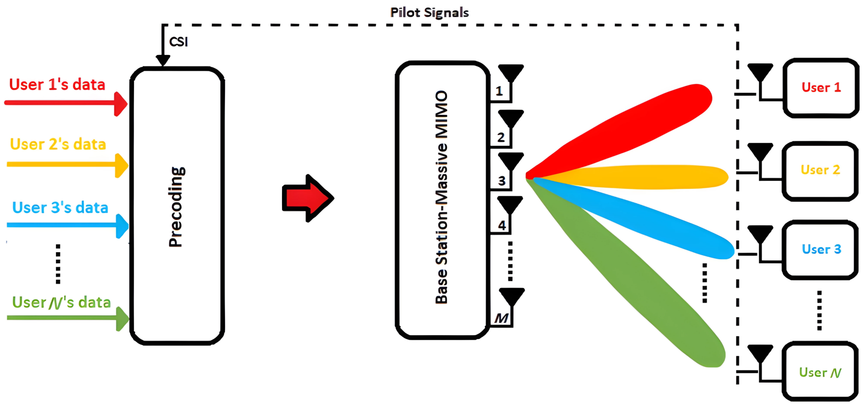


Figure 2.8: Precoding in a massive MIMO system with M antennas at base station communicating with N users

Three main types of beamforming architectures are typically investigated : hybrid, digital, and analog beamforming systems.

Linear and non-linear schemes which showed in figure 2.9 are further classifications for digital precoding techniques. Different precoding matrices are assigned to users at the transmitter in linear precoding. The transmit signal from each antenna is produced independently in the digital baseband, providing complete signal production freedom.
As the name suggests, data is transferred linearly in linear precoding, which results in less complexity and better performance. On the other hand, non-linear precoding approaches have greater promise than linear systems but are more difficult to apply. Theoretical results indicate that non-linear approaches are the best since they enable the highest system sum rates. Nevertheless, their increased cost and complexity render them unfeasible in realistic systems. Linear methods should be preferred over non-linear ones if achieving low complexity is the aim. linear precoders function flawlessly as the quantity of base station antennas increases. [22]

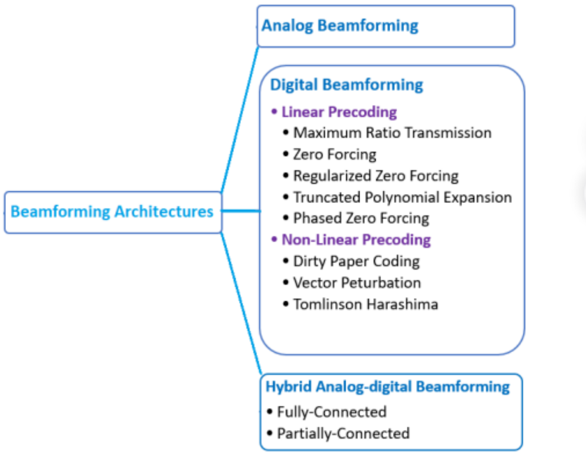


Figure 2.9: Linear and non-linear classifications for digital precoding techniques in massive MIMO systems

The figure 2.10 shows precoding matrixs (W) of linear precoding techniques in massive MIMO [22] :

$$W = \begin{cases} H^H, & RMT \\ H^H(HH^H)^1, & ZF \\ \beta(HH^H + \alpha I_K)^{-1}H^H, & RZF \\ \sum_{j=0}^{j-1} w_j (H^T H^*)^j H^T, & TPE \\ H_{eq}^H \left(H_{eq} H_{eq}^H\right)^{-1} \lambda & PZF \end{cases}$$

Figure 2.10: Precoding equations

2.6.4 signal detection

the figure 2.11 shows the signal detection: is the process of accurately identifying and extracting the desired signal transmitted by the user equipment (UE) from the received signal at the base station (BS) . It's a crucial initial step for successful communication in 5G due to the complex nature of 5G signals and the challenging channel environment.
Because of the numerous antennas in huge MIMO systems, UL signal identification becomes computationally challenging and lowers the throughput that can be achieved. The UE transmits signals that travel over distinct wireless paths and overlap at the BS, causing interference. This leads to a decrease in throughput and spectral efficiency, as well as complicated and ineffective signal recognition at the BS.
Good performance is obtained using traditional non-linear detectors such as the Sphere Decoder (SD) and Successive Interference Cancellation (SIC). However, as the number of antennas rises, the computing complexity does too, rendering huge MIMO systems unfeasible. [25]
For UL detection in mMIMO, a number of linear detectors, including Maximum Likelihood (ML), Zero-Forcing (ZF), and Minimum Mean Square Error(MMSE), have been investigated. Although ML is the best detector for mMIMO and reduces error probability, the technique is too complicated for big antenna systems.

$$\widehat{x}_{ML} = \underset{x \in O^K}{\arg\min} \|y - Hx\|_2^2 \tag{2.9}$$

The ZF techniques reduce inter-antenna interference, but additive noise increases for ill conditioned channel matrices [25]
projecting each stream into the orthogonal space of the inter user interference entirely eliminates the multiuser interference. More specifically, the pseudo-inverse of the channel matrix H is multiplied by the received vector as: [26]

$$\tilde{y} = (H^H H)^{-1} y = \sqrt{p_u} x + (H^H H) H^H n \tag{2.10}$$

Because it takes noise power into account while detecting, the MMSE detector performs better than the ZF detector. with the MMSE detection, the weighting matrix is set as:

$$W_{MMSE} = (H^H H + \frac{1}{\gamma} I_K)^{-1} H^H \tag{2.11}$$

Where:
γ : is the signal-to-noise ratio (SNR) value.
I_K : denotes the identity matrix with size $K \times K$.

While the ML, MMSE, and ZF detection algorithms offer the best throughput performance, they are computationally inefficient for large antenna mMIMO systems because they need matrix inversion during processing. [25]
Signal detection is considered a major challenge in mMIMO systems, which are a key technology for achieving the high data rates and capacity promised by 5G networks.

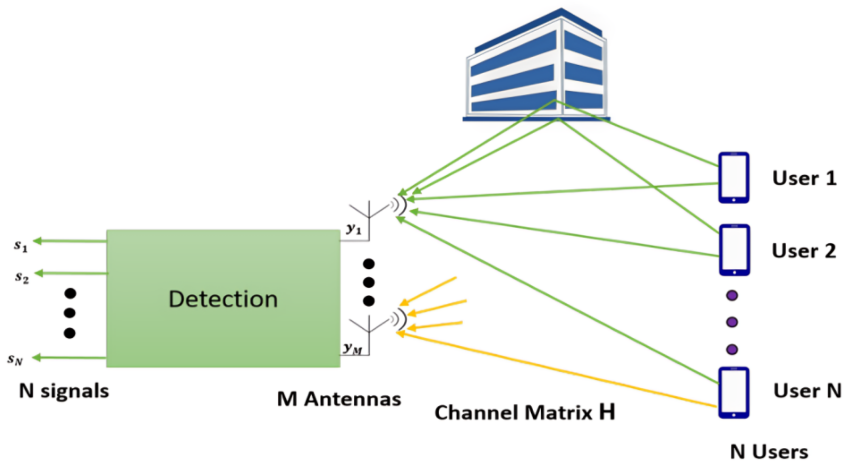


Figure 2.11: Signal detection in massive MIMO uplink

2.7 Conclusion

This chapter explored the innovative technologies of millimeter wave (mmWave) and Massive MIMO, which are fundamental building blocks for achieving the high-capacity and low-latency communication demands of 5G networks.
We saw how mmWave and Massive MIMO work in synergy to unlock the full potential of 5G. By combining the high capacity of mmWave with the beamforming capabilities of Massive MIMO, we can achieve exceptional communication performance in dense urban environments and support a multitude of applications.

Chapter 3

Beamforming, precoding and combining for 5G new radio.

3.1 Introduction

In order to achieve high data rates and dependable communication in 5G NR systems, this chapter explores the technological details involved. We examine beamforming, spatial multiplexing, and spatial variety as well as the idea of multiple-input multiple-output (MIMO) technology. Next, as a crucial component of 5G NR, the chapter concentrates on beamforming methods created especially for millimeter wave (mmWave) communication. We talk about several beamforming techniques, such as hybrid, digital, and analog schemes. We also discuss many more hybrid beamforming methods, including lens antenna-based beamspace MIMO and codebook-based, sparse hybrid beamforming using compressive sensing. The chapter investigates various precoding and combining techniques in order to maximize signal transmission and reception. We examine beamsteering techniques ranging from simple analog methods to complex ones such as Zero-Forcing (ZF) and Minimum Mean Squared Error (MMSE) precoding, as well as hybrid precoding systems that combine Kalman filtering and sparse methods. The chapter concludes with simulated examples that allow the performance of different precoding and combining techniques to be compared.

3.2 MIMO techniques modes

3.2.1 Spatial multiplexing(SM)

Spatial multiplexing (SM) that showed in figure 3.1, is a technique that breaks an outgoing signal stream into multiple parts and transmits each piece concurrently and in parallel on the same RF channel over separate antennas. This increases communication system throughput by allowing receivers to reconstruct the original transmitted sequence using an estimate of channel state information (CSI). Closed loop SM uses feedback to transfer CSI from the receiver back to the transmitter, while open loop SM uses direct measurement without feedback. IEEE 802.11ac expands SM concepts with wider RF channel bandwidths, eight MIMO spatial streams, and four downlink MUMIMO clients. [27] Wide area network technologies like IEEE 802.16e/m, 4G cell LTE, and LTE-A enable closed loop and open-loop SM. SM works best in high SNR regimes and over bandwidth limited radio networks. It requires enough diversity in the channel to accommodate multiple spatial streams. However, SM is not very helpful at low SNR operating locations, as the transmitter must divide power across multiple streams, weakening each stream and reducing overall capacity benefits. [27]

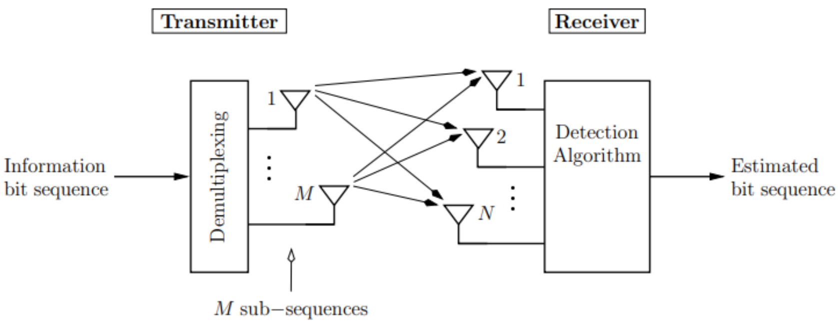


Figure 3.1: Basic principle of spatial multiplexing.

Consider this spatial multiplexing system [28] :

- The system uses multiple transmit antennas (M_t) and receive antennas (M_r) with a 1:M multiplexer.
- The channel is flat-fading and slowly time-varying. It's unknown at the transmitter but known at the receiver.

- A low bandwidth, zero-delay, error-free feedback link provides limited channel information from the receiver to the transmitter.

.

Signal Transmission

- At one symbol time, M input symbols with unit energy, from the same constellation, are multiplexed to produce the $(M_t \times 1)$ vector symbol S_x for transmission over M transmit antennas.

- The subset of $M \leq Mt$ transmit antennas is determined by a selection algorithm operating at the receiver via a feedback path.

Received Signal

- The received signal is represented by the equation:

$$x_n = \sqrt{\frac{E_s}{M_t}} H_p S_n + v_n \tag{3.1}$$

where:

- x_n is the received signal vector $(M_r \times 1)$.

- E_s is the total maximum power transmitted on all M antennas at one symbol time.

- H_p is the $M_r \times M$ submatrix corresponding to the transmit antenna subset p.

- S_n is the transmitted signal vector $(M_t \times 1)$.

- v_n is the noise vector $(M_r \times 1)$, with entries that are independent and identically distributed (i.i.d.), $v_n(K) \sim \mathscr{CN}(0, N_0)$, independent over k.

Signal Estimation

- An $M \times M_r$ matrix equalizer G_p is applied to x_n to obtain an estimate s_n as follows:

$$\hat{s_n} = G_p x_n = \sqrt{\frac{E_s}{M_t}} G_p H_p S_n + G_p v_n \tag{3.2}$$

where G_p is the equalizer matrix.

3.2.2 Spatial Diversity

Spatial diversity is a technique used to enhance wireless communication reliability by exploiting multiple antennas at both the transmitter and receiver. By transmitting redundant streams of information along different spatial paths, spatial diversity increases the chances of maintaining reliable communication even when some paths experience fading or interference [29].

The basic idea:

▶ Multiple Antennas

- In a massive MIMO system, we have multiple antennas at both ends (transmitter and receiver).

- These antennas are spaced apart, allowing them to capture different versions of the transmitted signal due to their different locations.

▶ Phase Differences:

- When signals arrive at these antennas, they experience different phase delays due to their spatial separation.
- These phase differences result in different fading conditions for each antenna.

▶ Diversity Gain:

- By combining the received signals from multiple antennas, we can achieve diversity gain.
- Diversity gain refers to the improvement in reliability due to the statistical independence of fading across different antennas.
- Even if some antennas experience deep fading, others may still provide usable signal quality.

By giving the receiver numerous independently faded copies of the transmitted signal, multiple antennas were traditionally used to increase link dependability by providing spatial diversity to combat channel fading. A maximum of MN random fading coefficients must be averaged over during the reception of a single symbol in a MIMO channel equipped with M transmit and N receive antennas. This results in a maximal diversity order of MN. Slope of the average error probability against SNR curve at high SNR, or the SNR exponent of the average error probability, is the mathematical definition of diversity gain. Furthermore, the utilization of numerous antennas at the transmitter and receiver simultaneously allows for the independent operation of many parallel channels. This characteristic results from the ergodic capacity of the MIMO channel, which can be roughly described in the high SNR regime as [30] :

$$\mathrm{C(SNR)} \approx \min \mathrm{M,N} \log\left(\frac{\mathrm{SNR}}{\mathrm{M}}\right) \tag{3.3}$$

where:

- (C(SNR)): This represents the channel capacity (in bits per second) as a function of the signal-to-noise ratio (SNR).
- (M): number of transmit antennas
- (N): number of receive antennas.
- (minM, N): The minimum value between (M) and (N).

.

▶ Applications:

- Spatial diversity is particularly useful in rich scattering environments (e.g., urban areas with reflections and multipath propagation).
- It helps combat fading caused by destructive interference.

.

The equation for spatial diversity doesn't have a single specific form, but the underlying principle involves using multiple antennas to improve reliability. If we consider a simple case with two antennas, the received signal can be expressed as [29]:

$$y = \sqrt{p_t}\mathrm{H}s + n \tag{3.4}$$

where

- Y: the received signal after application of spacial diversity.
- p_t: the symbol average transmit power (from the source).
- H: channel matrix (channel gain ,accounts for fading, path loss, etc.).
- s: transmit signal
- n: Noise power (usually modeled as additive white Gaussian noise).

.

Wireless communications will efficiently use link capacity and spectrum efficiency with this unique multiplexing technology. The system performance will be greatly improved if more antennas are added. This idea, sometimes referred to as antenna (spatial) diversity or multi-input multi-output (MIMO), can boost the system's data rate (throughput). This technology has a further benefit in that, in addition to making the system resistant to fading, it can effectively reduce retransmission in the event that it occurs. Because 1 ms latency includes the time needed to process data at both the transmission and reception terminals, as well as the time needed for retransmission in the event that the receiver is unable to decode symbols or parquets for any reason, this will lower the overall latency. [29]

3.3 Hybrid beamforming techniques

3.3.1 Code book based hybrid Beamforming

A codebook is a group of beams that collectively occupy the entire area and cover a certain direction in space for each beam. To be more precise, it is really a N × K matrix, where K represents the number of beam patterns and N the number of antenna components. The weights of the components that steer the beam in the azimuth/elevation domain are included in the k − th column vector w_k in the codebook. [31]
Feedback-assisted codebooks are an effective way to accomplish beamforming in mmWave systems. Each code vector in the codebook is created to minimize the mean square error (MSE) between the code vector's beam pattern and the ideal beam pattern that corresponds to it. [32]

The unit norm transmit beamforming codeword, or $c = Fv \in \mathbb{C}^{M_t}$, is the product of a baseband beamforming vector v and an analog beamsteering matrix $F = [f_1, ..., f_{N_{RF}}] \in \mathbb{C}^{M_t \times N_{RF}}$ with N_{RF} unit norm beamsteering vector columns, subject to the restriction $\|Fv\|_2^2 = 1$.
The analog beamsteering vector $f_n \in \beta_{M_t}$ produced by each set of RF phase shifters is subject to the limited equal gain subset:

$$\beta_{M_t} = \{w \in \mathbb{C}^{M_t} : (ww^H)_{\ell,\ell} = 1/M_t, 1 \leq \ell \leq M_t\}. \tag{3.5}$$

The baseband beamforming weight vector $v \in \mathbb{C}^{N_{RF}}$ is merged with the beamsteering vectors to achieve baseband beamforming. Hybrid beamforming is the term for this combination beamforming approach.
In this study, we'll suppose that codebook $C = \{c_1, ..., c_{2^B}\}$ has 2^B codewords , each of which is provided as $c_q = F_q v_q$. The codewords should be appropriately created by taking the channel characteristics and antenna construction into consideration in order to cover a wide variety of probable channel situations.
Furthermore, the codewords must be created with the hybrid beamforming arrangement in mind by modifying F and v. [33]

3.3.2 Sparse hybrid Beamforming (compressive sensing techniques)

. Compared to conventional techniques, compressive sensing (CS) requires substantially fewer samples in order to gather and reconstruct a sparse signal. The signal of interest $f \in \mathbb{C}^{N_f}$ must be sparse with respect to some dictionary ψ, which might be a basis or frame, in order to use CS. To be more precise, we can expand the signal f as follows:

$$f = \sum_{i=1}^{I} \psi_i x_i = \psi x \tag{3.6}$$

where $x = [x_1, ..., x_I]$ and $\psi = [\psi_1, ..., \psi_I]$is the expansion vector . Because of f sparsity, only a tiny percentage of x components are important, with the remainder being zero.
The signal f is measured using the CS framework as follows:

$$y = \phi f + n = \phi\psi x + n = Vx + n \tag{3.7}$$

where φ is the measurement matrix of size $M_f \times N_f (M_f \ll N_f)$. There are M_f measurements overall since each row of φ generates one measurement, $V \stackrel{\Delta}{=} \phi\psi$ is referred to as the effective dictionary, and n is the noise vector.
It is possible to build the measurement matrix φ by selecting each item i.i.d from a random distribution, such as the Bernoulli or Gaussian distributions. [34]
Compressive sensing has been used to design hybrid beamformers that can adapt to changing channel conditions. This involves formulating the beamformer design problem as a sparse recovery problem, which can be solved using CS algorithms.
This approach leverages compressive sensing to achieve efficient channel estimation and beamforming in hybrid beamforming systems and achieve efficient beamforming in large antenna arrays. The RF combiner for each user is independently designed based on channel decomposition.
sparse hybrid beamforming with compressive sensing offers a promising approach to improve the efficiency and performance of hybrid beamforming in mmWave communication systems. It reduces pilot overhead and enables faster beamforming, but careful codebook design and robust compressive sensing algorithms are necessary for optimal performance.

3.3.3 Beamspace MIMO (using lens antennas)

Recently, the idea of beamspace MIMO has been put up, which can use lens antenna array to drastically cut down on the number of RF chains needed for mmWave large MIMO systems without obviously sacrificing performance.

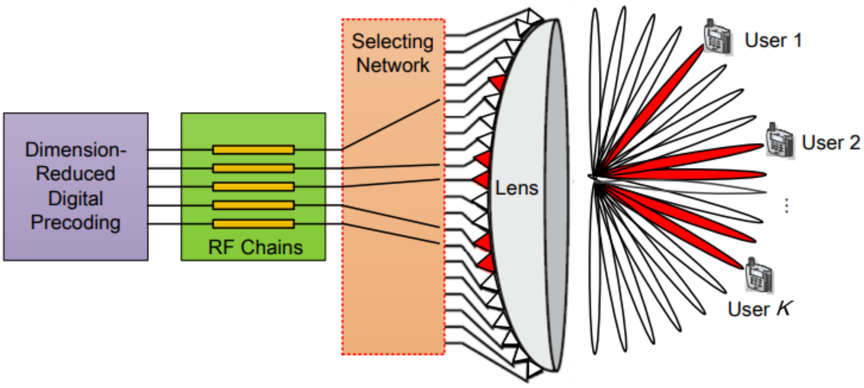


Figure 3.2: beamspace MIMO

As Figure 3.2 illustrates, The spatial channel can be converted to the beamspace channel in beamspace MIMO by using a lens antenna array. In particular, the lens antenna array's mathematical role is to carry out the spatial discrete Fourier transformation using the N × N transform matrix U, which has the array steering vectors of N directions that span the whole space in the following manner:

$$\mathrm{U} = \left[a(\bar{\theta}_1), \ldots\ldots, a(\bar{\theta}_\mathrm{N})\right]^\mathrm{H} \tag{3.8}$$

where the preset spatial directions are denoted by $\bar{\theta}_n = \frac{1}{\mathrm{N}}(n - \frac{n+1}{2})$ for each n=1,2,..,N. After that, in beamspace MIMO systems, the received signal vector $\bar{y}$ may be expressed as:

$$\bar{y} = \mathrm{H}^\mathrm{H}\mathrm{U}^\mathrm{H}\mathrm{WP}s + \bar{\mathrm{H}}^\mathrm{H}\mathrm{WP}s + v, \tag{3.9}$$

where the beamspace channel matrix $\bar{\mathrm{H}}$ is defined as:

$$\bar{\mathrm{H}} = \mathrm{UH} = [\mathrm{U}h_1, \mathrm{U}h_2, .., \mathrm{U}h_\mathrm{K}] = \left[\bar{h}_1, \bar{h}_2, ..., \bar{h}_\mathrm{K}\right] \tag{3.10}$$

where the beamspace channel vector between the BS and the kth user is $\bar{h}_k = \mathrm{U}h_k$, which is the spatial channel vector hk transformed Fourierically [35] .

3.4 Algorithms used for precoding/combining

3.4.1 Analog-only beamsteering

Analog-only beamsteering algorithm focus on manipulating the direction of a radio signal using physical components, without the need for digital processing. An amplitude modulator and a phase shifter for each antenna branch can serve as a representation of the primary component for analog precoding. Each antenna branch's amplitude modulator and phase shifter may be independently regulated. Equal gain combining/precoding is well known to be able to accomplish most of the gain with a relaxed per-antenna peak power constraint (essential for mmWave MIMO communications in the GHz frequency region) for large numbers of antenna elements. For this reason, as well as the additional expense of controlling the amplitudes independently in the analog domain, one can often set a fixed modulus constraint for all antenna branches and only make independent adjustments to the phase shifters. This explains why phased arrays are so common in mmWave systems. [36] Two common architectures of analog precoders are the fully-connected structure (FS) and the partially connected structure (PS), which are determined by the mapping techniques of the precoders.

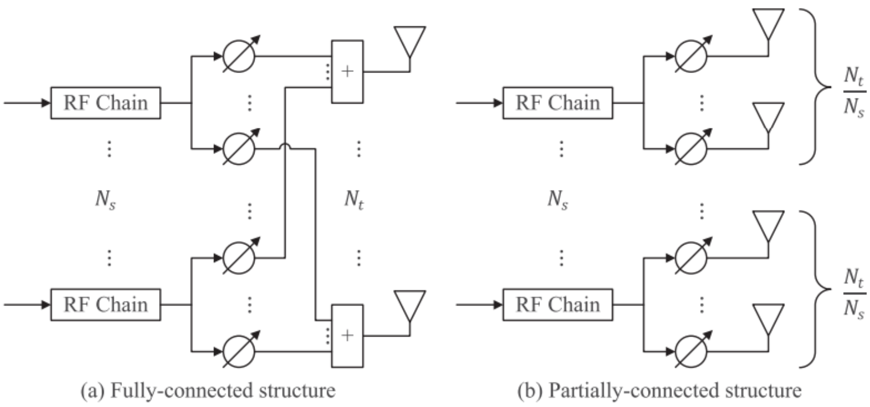


Figure 3.3: Two architectures of analog precoding system

3.4.1.1 System Model

Figure 3.3 shows the single-user mmWave MIMO system with analog precoder and combiner. N_t and N_r antennas are installed in the transmitter and receiver, respectively. The number of RF chains (NRF) and the number of data streams (Ns) in this model are equal. It is necessary to satisfy the restrictions $N_s < N_t$ and $N_s \leqslant N_r$ in order to achieve multi-stream transmission. The initial signal, represented by the symbol s, meets the normalized power requirement

$$\left(\mathbb{E}[ss^H]\right) = \frac{1}{N_s} I_{N_s} \tag{3.11}$$

The analog precoding matrix is indicated by the Nt × Ns matrix, or F. Consequently, x = Fs can be used to represent the sent signal x. The received signal can be expressed as follows:

$$y = \sqrt{\rho} W^H H F s + W^H n \tag{3.12}$$

if the receiver also uses an analog combiner for signal processing. ρ denotes the average received power in the equation. W is an RF combining matrix of size Nr × Ns. The channel matrix is denoted by H . [37]
In figure 3.4 we can see a general view architecture of mmWave communication system with the mention of precoder and combiner.

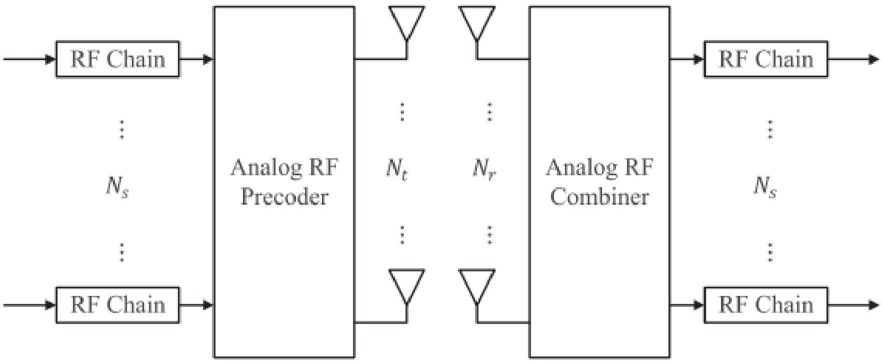


Figure 3.4: The architecture of mmWave communication system

3.4.2 Fully Digital Precoding

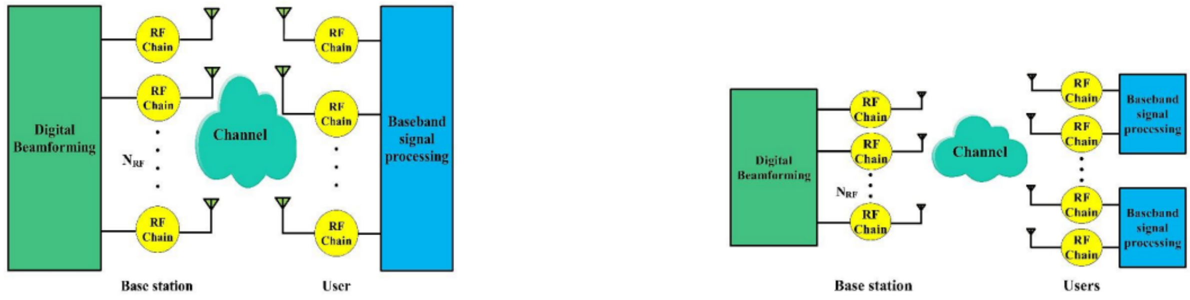
Due to the challenges of achieving full-digital processing at mm-Wave frequencies with large bandwidths and enormous antenna arrays, precoding and combining processing play a crucial role. Digital precoding allows the creation of independently controlled beams, enhancing reliability and preventing the failure of one or more antenna components.

Single-User Fully Digital Precoding Consider a scenario where there are N_t antenna array elements at the base station and N_s data streams. On the user side, there are N_r antenna elements (where $N_t < N_r$). The transmitted signal can be represented as: $x = L_s$. Here, S is an $N_r \times 1$ vector representing the original signal with normalized power. The base station (BS) applies a $N_t \times N_r$ digital precoder matrix L using its N_t^{RF} chains. The received signal y, an $N_r \times 1$ vector, is given by [38], [39], [40], :

$$y = \sqrt{\rho} W^H H F s + W^H n \tag{3.13}$$

ZF precoding is commonly used to mitigate interference across different data streams. The digital precoding matrix L can be expressed as:

$$L = \sqrt{\frac{N_r}{tr(FF^H)}} F \tag{3.14}$$



(a) single-user

(b) multi-user

Figure 3.5: Structure of single-user multi-user fully digital precoding for mmWave MIMO wireless system

Where

$$F = H^H (HH^H)^{-1} \tag{3.15}$$

ZF precoding, while effective, may increase noise power compared to the ideal channel capacity.

Multi-User Fully Digital Precoding When multiple users share the same antenna at each terminal, reducing signal interference becomes challenging. ZF precoding is a standard solution, but if terminals have more than one antenna, the block diagonalization (BD) method is preferable. For a base station (BS) with N_t antennas serving K terminals, the received signal for the i-th terminal can be expressed as [38], [39], [40] :

$$y_i = H_i \sum_{k=1}^{K} P_k^{BD} x_k + n_i \tag{3.16}$$

Where:

- H_i is the channel matrix
- P_k^{BD} is the BD precoding matrix
- x_k represents the source signal
- n_i denotes the noise

MMSE-Based Multiuser basic precoding technique To address the limitations of BD precoding, MMSE-based strategies have been proposed. The goal of MMSE precoding is to create a transmit precoder that yields a received signal vector $\hat{s} = [\hat{s}_1, ..., \hat{s}_K]^T$ close to the original signal vector s. Instead of using fully digital RF chains, a $Nt \times N_r^{RF}$ precoder matrix ${F_i}^{MMSE}$ is employed. Let $T = [T_1, ..., T_K]$ be the unnormalized MMSE precoder, and let be the power gain factor. The unitary matrices V_i and U_i split the block channel $H_i T_i$ into parallel subchannels. The baseband equalizer W_{B_i} at MS-i is given by $\sqrt{\gamma} U_i$. The fully digital MMSE precoder ${F_i}^{MMSE}$ for MS-i is constructed as $\sqrt{\frac{1}{\gamma}} T_i V_i$. The estimated symbol vector at MS-i is given by [38], [39], [40] :

$$\hat{s}_i = U_i^* \tilde{H}_i T_i V_i s_i + U_i^* \tilde{H}_i \sum_{j \neq i}^{K} T_j V_j s_j + \sqrt{\gamma} U_i^* \tilde{z}_i \tag{3.17}$$

Zero Forcing (ZF) basic precoding technique ZF precoding directs the signal toward the targeted user while nulling other users' directions to eliminate interference. The ZF precoder matrix WZF is given by [38], [39], [40] :

$$W_{ZF} = \sqrt{\alpha} H^* (H^T H^*)^{-1} \tag{3.18}$$

The corresponding received signal vector is:

$$y_{ZF} = \sqrt{\rho\alpha}H^T H^* (H^T H^*)^{-1} s + n \tag{3.19}$$

where:

- ρ :The average transmit power at the BS is The $W \in C^{M\times K}$ linear precoding matrix.
- H:represents the channel matrix $C^{M\times K}$.
- K: receiver terminals
- $n \in C^{K\times 1}$: represent Interference and noise .
- α: is Scaling factor used to standardize signal power.
- $s \in C^{K\times 1}$:denote The transmitted source information prior to precoding.

The diagonal elements of the Gram matrix formed by the term $H_T H^*$ indicate a power imbalance among the channels

3.4.3 MMSE hybrid precoding

Minimal squared mean error Minimizing the sum-MSE off data streams $\|s - \hat{s}\|^2$ is the goal of the hybrid precoder. This section explains an orthogonal matching pursuit algorithm that makes obtaining it simple. Considering V_{BB} as unnormalized digital precoder and γ a power gain actor such that $F_{BB} = \sqrt{1/\gamma}V_{BB}$. With $V = F_{RF}V_{BB}$ taken into account, the sum-MSE equation is as follows: [41]

$$E\|s - \hat{s}\|^2 = \|I - HF_{RF}V_{BB}\|_F^2 + K\gamma\sigma^2 \tag{3.20}$$

Through the following optimization, the hybrid precoder that minimizes this sum-MSE may be found:

$$\min_{F_{RF}, F_{BB}, \gamma} imize Tr\left\{(I - HF_{RF}V_{BB})(I - HF_{RF}V_{BB})^H\right\} + K\gamma\sigma^2 \tag{3.21}$$

subject to

$$\|F_{RF}F_{BB}\|^2 = Ns$$

the MSE matrix is defined as

$$E = \left(\mathbb{E}[(x - \hat{x})(x - \hat{x})^H]\right) = W^H R_y W - W^H HF - F^H H^H W + I_{N_s} \tag{3.22}$$

where $R_y = \left(\mathbb{E}[yy^H]\right) = HFF^H H^H + \sigma_n^2 I_{N_r}$ is the correlation matrix of the received signal y. Accordingly, the sum MSE across all data streams is given by tr[E]. To achieve MMSE, the optimal linear equalizer W_{opt} is the well-known Wiener filter, i.e.,

$$W_{opt} = R_y^{-1}\mathbb{E}\left[yx^H\right] = (HFF^H H^H + \sigma_n^2 I_{N_r})^{-1} HF. \tag{3.23}$$

Therefore, plugging (3.23) into (3.22), the MSE matrix can be simplified as :

$$E = I_{N_s} - F^H H^H (HFF^H H^H + \sigma_n^2 I_{N_r})^{-1} HF = (I_{N_s} + F_{BB}^H F_{RF}^H R_H F_{RF} F_{BB})^{-1} \tag{3.24}$$

where $R_H = \frac{1}{\sigma_n^2} H^H H$ and the matrix inversion lemma

$$[(A + CBC^H)^{-1} = A^{-1} - A^{-1}C(B^{-1} + C^H A^{-1} C)^{-1} C^H A^{-1} \tag{3.25}$$

is used to arrive at (3.24). We are interested in designing a hybrid precoder such that the sum MSE is minimized. The problem is thus formulated as:

$$\min_{F_{RF},F_BB} .tr\left[\left(I_{N_s}+F_{BB}^H F_{RF}^H R_H F_{RF} F_{BB}\right)^{-1}\right] \tag{3.26}$$

.

$$s.t.F_{RF} \in f_{RF}, \|F_{RF}F_{BB}\|_F^2 = P_T.$$

It is shown in (3.24) that the unconstrained optimal precoder F_{opt} renders diagonal the post- and pre-processed channel $W^H HF_{opt}$. Denote the eigenvalue decomposition (EVD) of R_H as :

$$R_H = [U_{opt}, U_2]\, D[U_{opt}, U_2]^H \tag{3.27}$$

the r nonzero eigenvalues
$D = diag\{\lambda_1, ..., \lambda_r\}$ are assumed to be in non-increasing
order, and the columns of U_{opt} are the eigenvectors that correspond to the N_s largest eigenvalues. [42]

3.4.4 ZF hybrid precoding

ZF precoding, a type of digital linear precoder, is frequently employed in conventional communication systems to remove interference. However, in order to carry out frequency translation and A/D conversion, the ZF precoder needs Nt RF chains, which is equal to the number of antennas. Since several antennas are used in mmWave systems, this is actually too costly to accomplish. An approach to balance hardware costs and system performance is hybrid precoding, which employs digital processing in the baseband and analog processing in the RF domain.
Using zero-forcing theory based on QR-decomposition, a hybrid precoding approach is presented as follows. It is believed that the transmitter already knows the channel matrix H, which can be obtained via feedback in an FDD system or by utilizing the channel's reciprocity in a TDD system. The conventional ZF precoding matrix is shown as [43]:

$$F_{zf} = H'(HH')^{-1} \tag{3.28}$$

where F_{zf} stands for the dimension $N_t \times N_r$ ZF precoding matrix. Let us assume that $N_t \geq N_r$. The formula for F's QR-decomposition is as follows:

$$F_{zf} = Q \times R \tag{3.29}$$

where $\sum$ is an upper triangular matrix of dimension $N_t \times N_r$, 0 denotes a null matrix of dimension $N_t \times N_r$, and $Q = [q_1, q_2, .., q_{N_t}]$ is a unitary matrix of dimension $N_t \times N_t$. Additionally , $q_i, 1 \leq i \leq N_t$ represents the i^{th} column vector of $Q.R = \begin{bmatrix} \Sigma \\ 0 \end{bmatrix}$. Define $Q_1 = [q_1, q_2, .., q_{N_r}]$ is rewriteable as follows: [43]

$$\begin{aligned} F_{zf} &= Q \times R \\ &= [q_1, q_2, .., q_{N_t}] \times \begin{bmatrix} \Sigma \\ 0 \end{bmatrix} \\ &= [q_1, q_2, .., q_{N_r}] \times \Sigma \\ &= Q_1 \times \Sigma \end{aligned} \tag{3.30}$$

Zero-Forcing (ZF) hybrid precoding is technique to improve signal quality and reduce interference. Unlike MMSE (Minimum Mean Square Error) precoding, which minimizes the mean squared error between the desired signal and the received signal, ZF aims to completely eliminate interference directed towards other users.

3.4.5 Hybrid sparse precoding and combining via orthogonal matching pursuit (OMP)

Sparse Precoding and Combining:

- In massive MIMO (multiple-input, multiple-output) systems, where the number of antennas at the base station (BS) is large, fully digital precoding and combining can be computationally expensive.
- Sparse precoding and combining aim to reduce this complexity by exploiting the sparsity of the channel.
- Instead of using all antennas for transmission and reception, sparse techniques select a subset of antennas to achieve similar performance.

Orthogonal Matching Pursuit (OMP):

- OMP is an algorithm used for sparse signal recovery.
- It iteratively selects columns from a dictionary (representing possible precoder or combiner vectors) that best match the received signal.

In the context of hybrid precoding and combining:

- OMP helps find an efficient approximation of the optimal precoder and combiner.
- It reduces the computational complexity compared to exhaustive search methods.
- By selecting only a few dominant paths, OMP achieves performance close to fully digital techniques.

Benefits:

- **Reduced Complexity:** Hybrid sparse precoding and combining significantly reduce the number of required RF chains compared to fully digital approaches.
- **Trade-off:** It strikes a balance between performance and complexity.
- **Massive MIMO:** Particularly useful in massive MIMO scenarios where the number of antennas is large.

In summary, hybrid sparse precoding and combining via OMP provide an efficient compromise between performance and computational complexity, making them suitable for practical implementation in modern wireless communication systems.

Algorithm Overview [44]:

- The algorithm aims to find the optimal hybrid precoder by iteratively selecting antennas and adjusting the precoder coefficients.

►Problem Setup:

- We have a multi-antenna communication system with a transmitter (base station) equipped with N_t antennas.
- Our goal is to design a hybrid precoder that combines analog and digital processing to optimize the transmitted signal.
-

Table 3.1: **Algorithm: Hybrid Precoder Design through Orthogonal Matching Pursuit (OMP)**

Require: F_{opt}
1. $F_{rf} = \{\}$
2. $F_{res} = F_{opt}$
3. for $i = 1$ to N_t^{rf}
4. $\psi = A_t^* F_{res}$
5. $K = \arg\max_I = 1, \ldots, N_{cl} N_{ray} (\psi\psi^*)_I, I$
6. $F_{rf} = [F_{rf} | A_t^{(k)}]$
7. $F_{bb} = (F_{rf}^* F_{rf})^{-1} (F_{rf}^* F_{opt})$
8. $F_{res} = \frac{F_{opt} - F_{rf} F_{bb}}{\|F_{opt} - F_{rf} F_{bb}\|_F}$
9. end for
10. $F_{bb} = \sqrt{N_s} \left(\frac{F_{bb}}{\|F_{rf} F_{bb}\|} \right)$
11. Return (F_{rf}, F_{bb})

►**Algorithm Steps:**

Initialization:

- Initialize an empty set F_{rf} to store the selected antennas.
- Set F_{res} equal to the optimal precoder F_{opt}.

Main Loop:

- For each iteration $i = 1$ to N_t^{rf}:
- 1. Compute the effective channel ψ by multiplying the conjugate transpose of the antenna array matrix A_t with F_{res}.
- 2. Find the index K that maximizes the product of channel gains $\psi\psi^*$ for a specific path.
- 3. Add the corresponding antenna $A_t^{(k)}$ to the set F_{rf}.
- 4. Compute the digital precoder F_{bb} using the selected antennas:
- $F_{bb} = (F_{rf}^* F_{rf})^{-1} (F_{rf}^* F_{opt})$.
- 5. Update the residual precoder F_{res} by subtracting the interference caused by the selected antennas:
- $F_{res} = \frac{F_{opt} - F_{rf} F_{bb}}{\|F_{opt} - F_{rf} F_{bb}\|_F}$.

Normalization:

- Normalize the digital precoder F_{bb} to ensure a power constraint:
- $F_{bb} = \sqrt{N_s} \left(\frac{F_{bb}}{\|F_{rf} F_{bb}\|} \right)$.

►**Output:**

- Return the hybrid precoder (F_{rf}, F_{bb}).

In summary, this algorithm efficiently combines analog and digital processing to achieve beamforming in multi-antenna systems while minimizing complexity. It leverages OMP to select antennas and optimize the precoder

3.4.6 Kalman-Based Hybrid precoding

Phase recovery and carrier frequency synchronization are two physical layer applications that have made use of the powerful Kalman filter. This section describes the hybrid precoding approach based on Kalman filtering. The predicted signal at the receiver is $\hat{s} = [\hat{s}_1,..,\hat{s}_M]^T$, where s(n) is the training vector at iteration n. Base station (BS) broadcasts a preamble message s. By minimizing the mean squared error of the training vector between the estimated signal $\hat{s}$ and the transmitted signal s, the Kalman filer method achieves its goal. $E\|s-\hat{s}\|^2$

$$\min_{F_{RF},F_{BB}} imize\, E\|s-\hat{s}\|^2 \tag{3.31}$$

subject to

$$\|F_{RF}F_{BB}\|^2 = Ns$$

Given that $\hat{s} = [\hat{s}_1,..,\hat{s}_M]$ at the MS allow for the definition of the observation vector at iteration n as $\hat{s}_m(n) = (w_m^H H_m F_{RF} F_{BB}) s(n) + n_m(n)$, the minimization issue may be written as:

$$\min_{F_{RF},F_{BB}} imize\, E\,\|I - H_e F_{BB}(n|n-1)\|_F^2 \tag{3.32}$$

subject to

$$\|F_{RF}F_{BB}\|^2 = Ns$$

H_e is the effective channel in this case. Nevertheless, the issue is nonconvex because of the multiplication of the variables F_{RF},F_{BB}, and W_{RF}. Nevertheless, in order to compute F_{BB} and solve the optimization problem, this work fixes F_{RF} and W_{RF}. The computation of the RF precoder and combiner matrices maximizes the signal power for the MS. The next stages are used to compute the F_{BB} once the analog precoder and combiner have been adjusted. $F_{BB}(n|n)$ The Kalman filter state equation may be written as follows when using the baseband digital precoding F_{BB}: [41]

$$F_{BB}(n|n) = F_{BB}(n|n-1) + K(n)E\{diag\,[e(n)]\} \tag{3.33}$$

where the e(n) is the error at the n-th Kalman iteration, K(n) represents the Kalman gains and $E\{diag\,[e(n)]\}$ is the respresentation of the error $s(n) - \hat{s}(n)$. Expanding the equations:

$$F_{BB}(n|n) = F_{BB}(n|n-1) + K(n)\frac{I - H_e F_{BB}(n|n-1)}{\|I - H_e F_{BB}(n|n-1)\|_F^2} \tag{3.34}$$

$$K(n) = R(n|n-1)\,H_e^H\left[H_e R(n|n-1)\,H_e^H + Q_n\right]^{-1} \tag{3.35}$$

$$R(n|n) = [I - K(n)\,H_e]\,R(n|n-1) \tag{3.36}$$

In this case, $Q_n = (1/SNR) \times I$ represents the covariance matrix of the noise n(n) , and H_e stands for the corresponding channel. [41]

Algorithm 1: Kalman Based Hybrid Beamforming

1.**Input:** BS RF codebook F, MS RF codebook W

2. **Output:**F_{BB} ,F_{RF} and $W_m \forall m = 1, .., M$

3.**Step 1 - RF Analog design:** Single-user F_{RF} and $W_m \forall m$

4. BS and MS-m select $\tilde{V}_m$,$\tilde{g}_m \forall m$ so that

5. $\tilde{g}_m, \tilde{V}_m = \underset{\forall g_m \in w, \forall v_m \in f}{\arg\max} \left\| g_m^H H_m v_m \right\|$

6. BS sets $F_{RF} = \left[\tilde{V}_1, .., \tilde{V}_M\right]$ and MS-m sete $V_m = \tilde{g}_m \forall m$

7.**Step 2 - BB Digital design:** Multi-userF_{BB}

8. $MS - m$estimates $\tilde{h}_m^H = w_m^H H_m F_{RF}$ and qantizes $\tilde{h}_m$ using a codebook $H \forall m$

9. $MS - m$ calculate and sends to BS $\hat{h}_m \forall m$ where

10. $\hat{h}_m = \underset{\hat{h}_m \in H}{\arg\max} \left\| \tilde{h}_m^H \hat{h}_m \right\|$

11. BS sets $H_D = \hat{H}_e = \left[\hat{h}_1, ..., \hat{h}_M\right]^H$

12. At BS: **for** $n \leq N$ **do**

13. $\in (n) = \frac{I - H_D F_{BB}(n|n-1)}{\|I - H_D F_{BB}(n|n-1)\|_F^2}$

14. $F_{BB}(n|n) = F_{BB}(n|n-1) + K(n) \in (n)$

15. $K(n) = R(n|n-1) H_D^H \left[H_D R(n|n-1) H_D^H + Q_n\right]^{-1}$

16. $R(n|n) = [I - K(n) H_D] R(n|n-1)$

17.Normalize $F_{BB} = \sqrt{P} \frac{F_{BB}}{\|F_{RF} F_{BB}\|_F}$

explain algorithm:

The RF beamforming and combining vectors, f_{RF_m} and w_m, are initially calculated by the BS and each MS-m by optimizing the signal power for the MS-m (line 3-6 in Algorithm 1).
The BS is now using the effective channels $h_m^H = w_m^H H_m F_{RF} \forall m$. The original channel matrix H_m had a size of $N_{MS} \times N_{BS}$, whereas each effective channel vector h had a dimension of M × 1, significantly less . After quantizing its effective channel response using a codebook H, each $MS - m$ transmits the quantized channel vector's index to the BS (line 8–10 in Algorithm 1).
Lastly, the BS uses the quantized channels (lines 11–18 in Algorithm 1) to create its Kalman-based digital precoder F_{BB}.

3.5 Simulation examples

After providing helpful theoretical information about the precoding and combining techniques used for mmWave MIMO systems, the rest of this chapter will illustrate some simulation examples to compare the performance of different schemes

3.5.1 Example1

In this example, we compare the SVD full digital precoder with the full analog precoder in a massive MIMO system. The parameters used in this scenario are as follows: number of streams (Ns) = 2, number of clusters (Nc) = 8, number of rays per cluster (Nray) = 10, number of RF chains (NRF) = 3, number of transmit antennas (Nt) = 256, number of receive antennas (Nr) = 64, standard deviation of the angles in azimuth and elevation for both the receiver and transmitter (anglesigma) = 10/180pi, normalization factor based on the number of antennas and clusters (gamma) = sqrt((NtNr)/(Nc*Nray)), and the scaling factor for

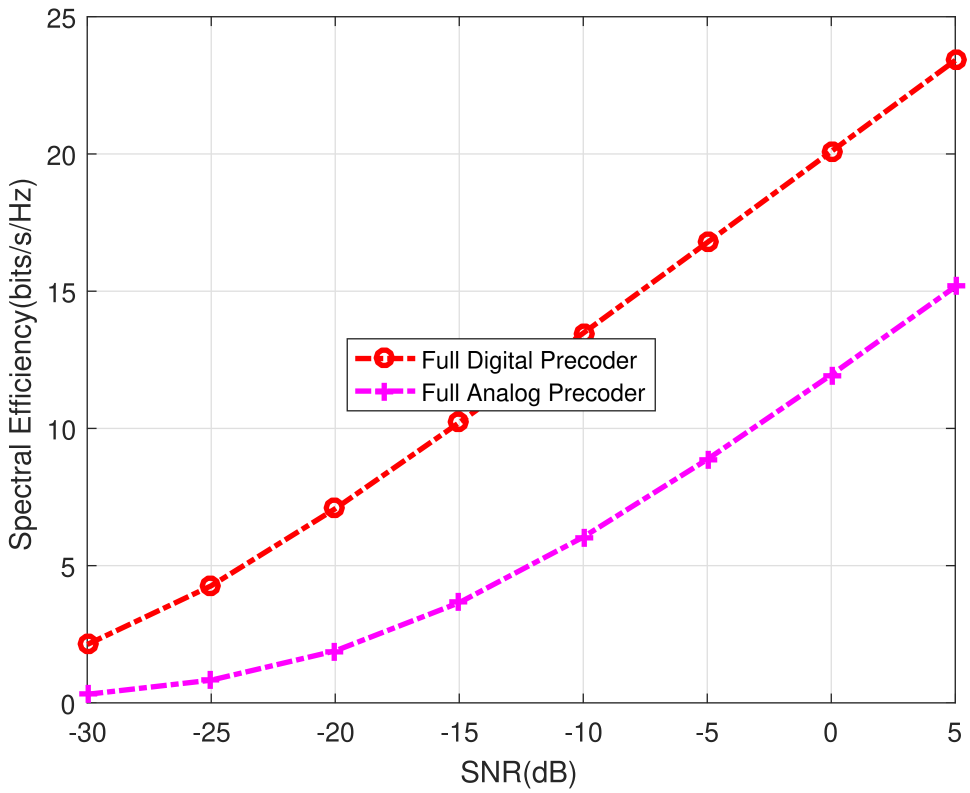


Figure 3.6: Comparison between the analog and the digital precoders.

the H channel matrix sigma is set to 1.

The results of figure 3.6 compare the spectral efficiency of two different precoding techniques: full digital precoder and full analog precoder, as a function of the Signal to Noise Ratio (SNR) in dB.
Spectral efficiency quantifies how efficiently data is transmitted over a communication channel. Higher spectral efficiency indicates more data can be transmitted within a given bandwidth.
The Full Digital Precoder outperforms the Full Analog Precoder in terms of spectral efficiency across the entire range of SNR values presented in the graph.
Digital precoders generally offer higher spectral efficiency compared to analog precoders due to their ability to adapt to channel conditions and provide fine- grained control over the signal.
Analog precoders may be suitable for simpler systems where complexity and cost are primary concerns. However, their limited adaptability can lead to lower spectral efficiency.

3.5.2 Example2

.

In order to compare the Spectral Efficiency (SE) versus Signal-to-Noise Ratio (SNR) for three different precoding techniques: Zero Forcing (ZF), Minimum Mean Square Error (MMSE), and Maximum Ratio Combining (MRC). We consider a system based on these parameters: :

- Number of Streams (Ns): 2
- Number of Clusters (Nc): 8
- Number of Rays per Cluster (Nray): 10

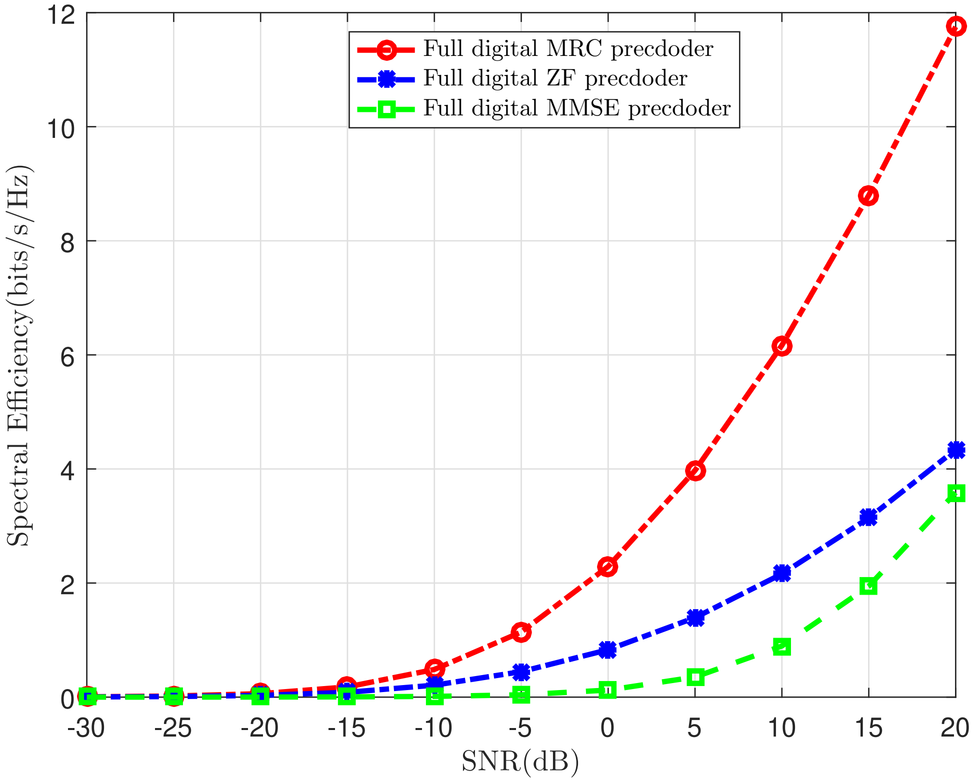


Figure 3.7: Spectral efficiency versus SNR for three different precoding techniques: ZF, MMSE and MRC.

- Number of RF Chains (NRF): 3
- Number of Transmit Antennas (Nt): 256
- Number of Receive Antennas (Nr): 32
- Angle sigma: 10/180π (Standard deviation of the angles in azimuth and elevation both of Rx and Tx)
- gamma: Calculated as $\sqrt{\frac{N_t \cdot N_r}{N_c \cdot N_{\text{ray}}}}$, Normalization factor sigma = 1; According to the normalization condition of H
- realization: 150 (Number of Realizations)

ZF is a linear precoding technique that nullifies interference by projecting the transmitted signal onto the null space of the channel matrix. MMSE (Minimum Mean Square Error) is a more sophisticated precoding technique that minimizes the mean square error between the transmitted and received signals, considering noise and interference. MRC (Maximum Ratio Combining): a diversity technique that combines multiple received signals with different weights to maximize the received power.
From the figure 3.7 we can see that as SNR increases, SE improves for all techniques. In fact, the MRC pecoding algorithm begins its ascent near -15 dB, surpasses ZF just before -10 dB, and continues to rise steadily. In addition, the ZF algorithm starts rising as SNR increases after about -10 dB but at a slower rate than MRC. The MMSE algorithm rises sharply after around 0 dB and continues steeply upwards. The graph shows that the full digital MRC precoder achieving the highest spectral efficiency at low SNR due to its focus on maximizing signal strength.. The full digital ZF precoder comes in second at little more SNR, and the full digital MMSE precoder has the lowest spectral efficiency that increases with the increase of SNR where it might almost equal to ZF after 20 dB .

3.5.3 Example3

In this example we focuse on the analysis of the hybrid sparse precoding and combining via OMP. The graphs of figure 3.8. show the spectral efficiency (bits/s/Hz) versus SNR (dB) for three different precoding and combining techniques in a millimeter wave (mmWave) system. The system parameters used in this example are:

- Nt = 256: Number of transmit antennas
- Nr = 64: Number of receive antennas
- Ns = [1]: Number of data streams (single stream)
- NumRF = 4: Number of RF chains for precoding and combining
- NumCluster = 8: Number of clusters
- NumRay = 10: Number of rays per cluster
- AS = 7.5: Angular spread of 7.5 degrees
- SNR(dB) = -25:5:5: Range of SNR in dB
- ITER = 150: Number of channel generations

The optimal SVD precoding and combining is the ideal approach that achieves the maximum spectral efficiency possible. However, it requires full digital processing at both the transmitter and receiver, which is complex and expensive to implement.The hybrid OMP precoding and combining is a more practical approach that uses a combination of analog and digital processing. It achieves good spectral efficiency with lower complexity than optimal SVD. The eam steering is the simplest approach, where the antenna arrays are steered to focus the signal in the direction of the receiver. It has the lowest spectral efficiency of the three approaches.

The curve of the optimal SVD precoding and combining shows a steady increase in spectral efficiency with increasing SNR. It has the highest spectral efficiency because it can exploit all the spatial channels to transmit data efficiently. The curve of the hybrid OMP precoding and combining also shows an increase in spectral efficiency with increasing SNR, but it does not reach the same level of performance as optimal SVD at high SNR values. This is because the hybrid approach uses fewer RF chains than the optimal approach, which limits its ability to exploit all the spatial channels. How ever, the hybrid approach achieves a good trade-off between performance and complexity. The curve of the beam steering has the lowest spectral efficiency because it does not perform any spatial filtering. It simply transmits the signal in a fixed direction. As a result, the signal is more susceptible to interference and path loss.

The results of figure 3.9 show the spectral efficiency (bits/s/Hz) versus angular spread (degrees) for three different MIMO processing techniques: optimal SVD precoding and combining, hybrid OMP precoding and combining, and beam steering. We are based on these parameters to compare: Nt = 256; Number of transmit antennas Nr = 64; Number of receive antennas Ns = [1]; Number of data streams NumRF = 4; Number of RF chains for precoding and combining NumCluster = 8; Number of clusters NumRay = 10; Number of rays per cluster AS(values) = 0:3:15; Angular spread from 0 to 15 degrees fixed SNR(dB) = -5; Fixed SNR in dB ITER = 150; Number of channel generations.

Both of optimal SVD precoding and combining and hybrid OMP precoding and combining curves are almost start from the pointe (0 ; 11),whille the beam steering curve start

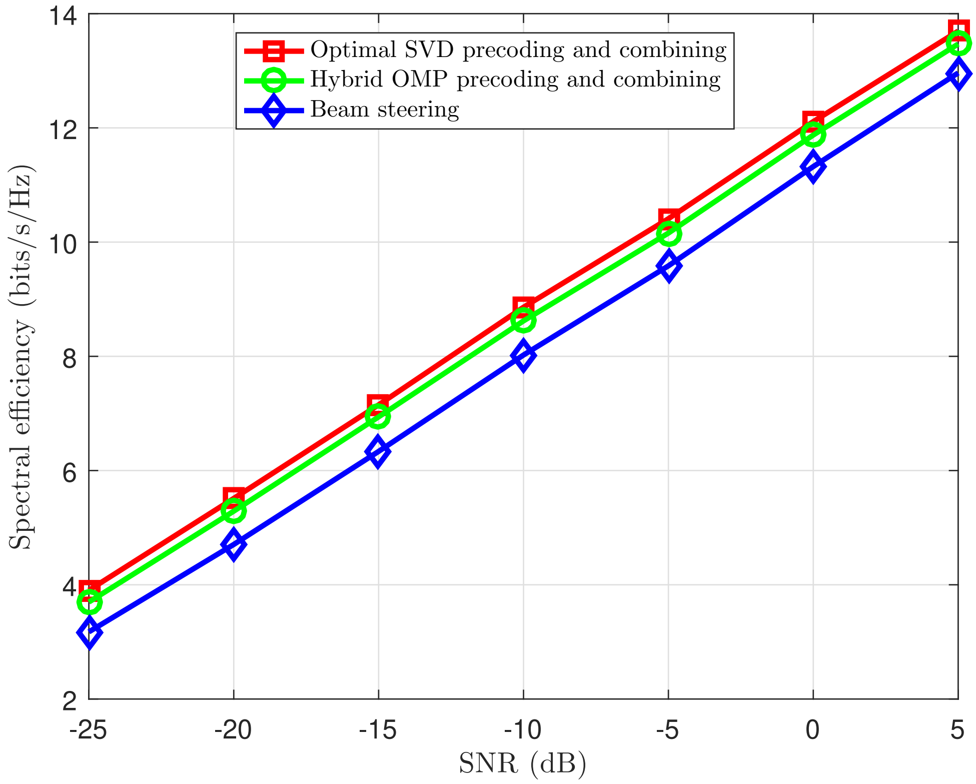


Figure 3.8: 256 x 64 mmWave system with 4 RF chains for different precoding and combining approaches

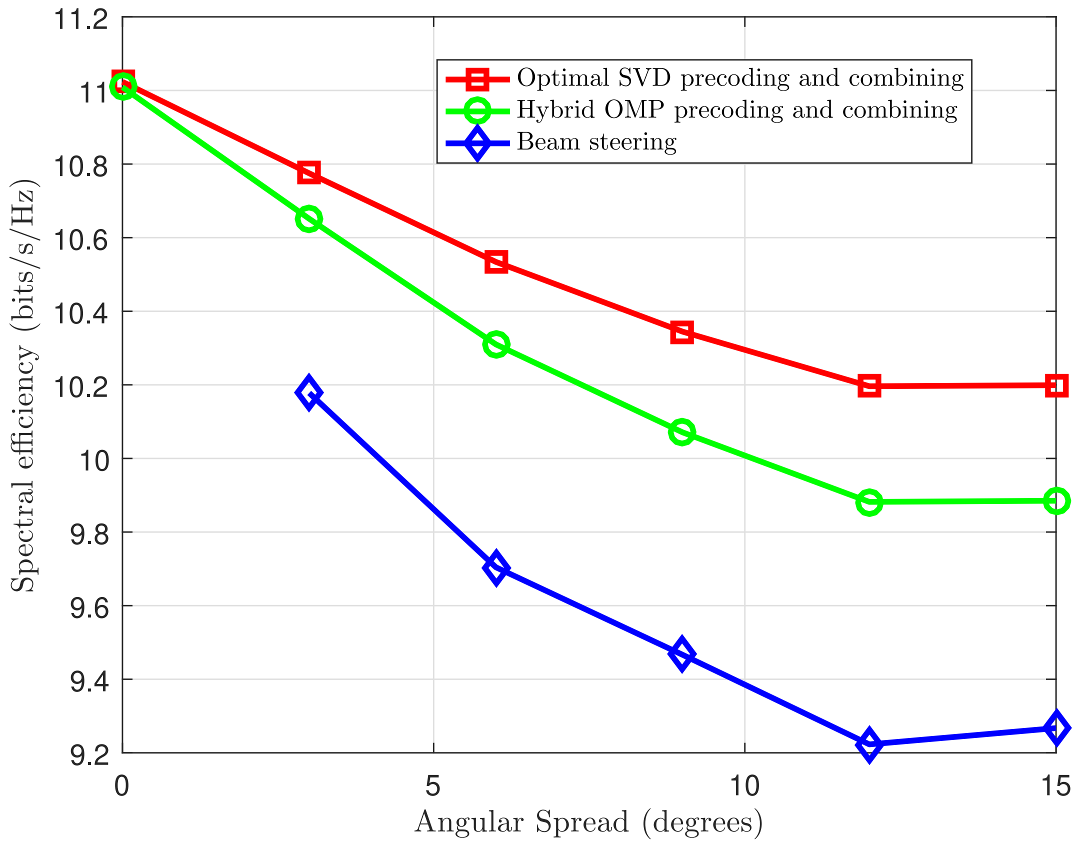


Figure 3.9: Spectral Efficiency vs. Angular Spread (Fixed SNR = -5 dB)

from the point (3 ; 10,2). As Angular Spread increases, the performance of all three methods degrades. The beam steering curve shows the worst performance in terms of spectral efficiency across all angular spreads. This is because beam steering focuses all the transmit power towards a single direction, which may not be optimal when the channel has a large angular spread. With a large angular spread, the signal energy is spread out over a wider range of angles, and beam steering may not be able to effectively capture all of it. The hybrid OMP precoding and combining curve shows better performance than beam steering at all angular spreads. Hybrid precoding combines digital and analog precoding to improve spectral efficiency compared to pure analog beam steering. This allows for more flexibility in shaping the radiation pattern and directing the signal energy towards the desired users. The optimal SVD curve shows the best performance among the three techniques at all angular spreads. SVD precoding is a more sophisticated technique that exploits the full channel state information (CSI) to create a precoding matrix that maximizes the received signal power while minimizing interference. This requires more complex computations compared to hybrid OMP, but it can achieve higher spectral efficiency, especially in channels with large angular spreads.

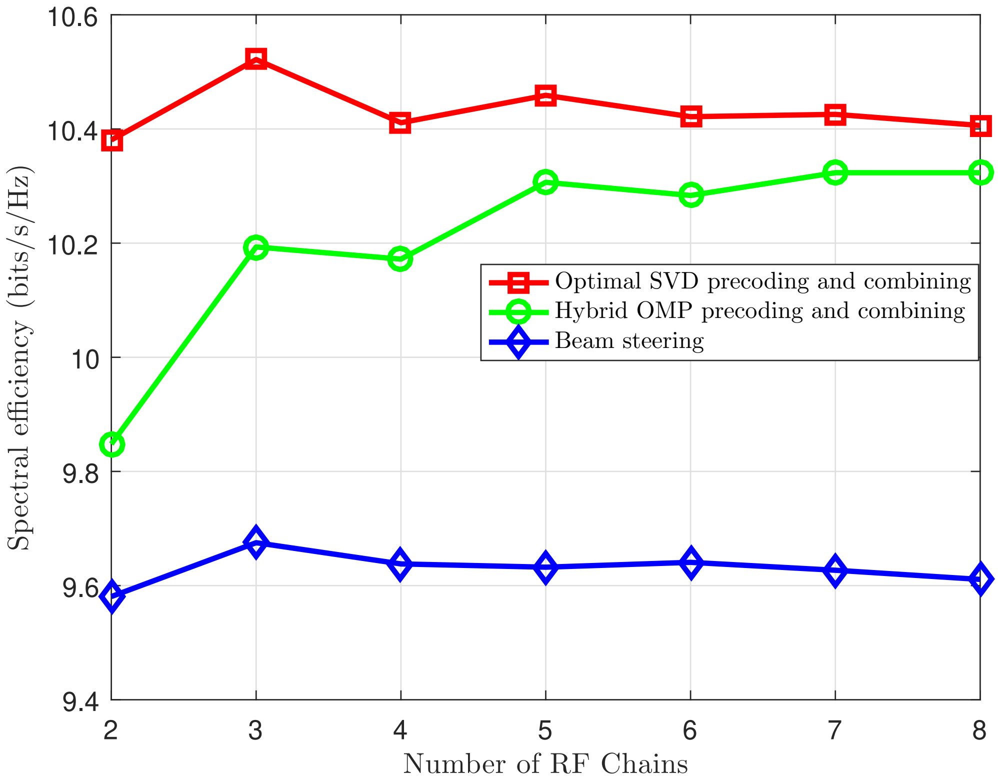


Figure 3.10: Spectral Efficiency vs. Number of RF Chains (Fixed SNR = -5 dB)

The curves of figures 3.10 show the spectral efficiency (bits/s/Hz) versus the number of RF chains for three different precoding and combining techniques which are optimal SVD, hybrid OMP, and beam steering. To show the influence of the number of chain RF on the spectral efficiency of the three studied methods , we use these parameters:

- Nt = 256; Number of transmit antennas
- Nr = 64; Number of receive antennas
- Ns = 1; Number of data streams
- NumRF(values) = 2:1:8; Number of RF chains for precoding and combining

- NumCluster = 8; Number of clusters
- NumRay = 10; Number of rays per cluster
- AS = 7.5; Angular spread of 7.5 degree
- fixed SNR(dB) = -5; Fixed SNR in dB
- ITER = 150; Number of channel generations

All curves show an increasing trend in spectral efficiency as the number of RF chains increases, but the rate of increase slows down for all three methods as more RF chains are added. The optimal SVD curve shows the highest spectral efficiency for all values of RF chains. It also has the most significant increase in spectral efficiency with the addition of more RF chains: The Hybrid OMP curve shows a lower spectral efficiency than optimal SVD but higher than beam steering for all values of RF chains. The increase in spectral efficiency with additional RF chains is smaller than that of optimal SVD. The Beamsteering curve shows the lowest spectral efficiency among the three methods. The increase in spectral efficiency with additional RF chains is also the smallest. Overall, the graph suggests that using a larger number of RF chains can improve the spectral efficiency of all three precoding and combining methods. However, the benefit of adding more RF chains diminishes as the number of RF chains increases. Additionally, optimal SVD outperforms the other two methods in terms of spectral efficiency.

3.5.4 Example4

In this simulation, we will try generally to reproduce the results obtained by [45] to evaluate the performance of the Kalman analog/digital precoding algorithm. We consider a system with a base station (BS) using an 8x8 uniform planar array (UPA) and associated with 5 mobile stations (MSs), each having a 4x4 UPA. We assume both single-path channels and multi-path channels. The number of users in the system is set to 5, which could represent multiple devices attempting to communicate simultaneously.

The number of channel paths is set to 5, which indicates a multipath channel where the signal reaches the receiver through multiple distinct paths. SNR Range in dB (from -20 dB to 15 dB in steps of 5 dB). The nuumber of iterations is set to 15, this could represent the number of simulation runs or algorithm iterations performed at each SNR level to obtain statistically significant results. The number of Kalman iterations is set to 10, This suggests the potential use of a Kalman filter or a related algorithm, which might involve iterative updates based on received signals and state estimates.

The figure 3.11 shows a graph of Spectral Efficiency (in bits/s/Hz) versus Signal to Noise Ratio (SNR) (in dB). The graphs compare the Kalman hybrid precoder with several analog, digital and hybrid solutions: The graph shows that the Single user (No Interference) technique achieves the highest spectral efficiency across all SNR values . it is an ideal scenario without interference from other users. It might serve as a baseline for comparison. The MMSE digital precoding is able to achieve performance closer to the single user , which means it is offer more flexibility and control over the transmitted signal. the hybrid precoding (ZF, MMSE, Kalman) techniques aim to improve spectral efficiency by manipulating the transmitted signal before it reaches the antenna elements. While they can be effective, their performance might not be as good as pure MMSE digital precoding in terms of interference mitigation, depending on the specific algorithm and implementation. The analog beamsteering the lowest, as it less precise control over the signal. It might not be able to dynamically adapt to channel variations or create nulls as effectively as other precoding technique, leading to potentially higher interference levels.

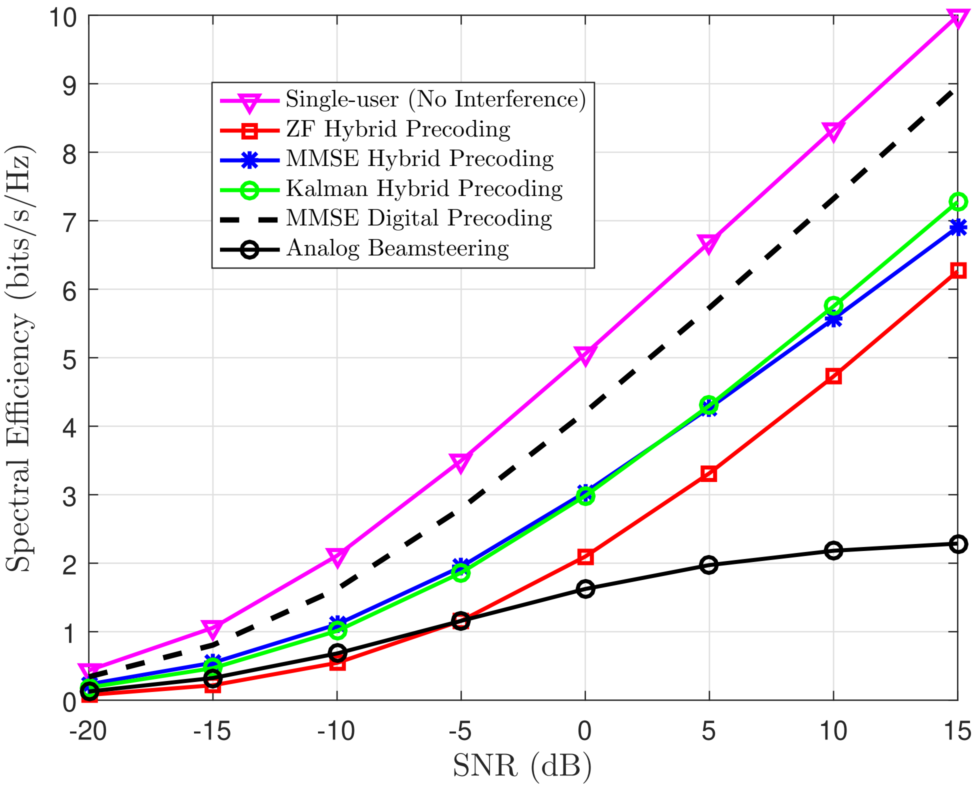


Figure 3.11: Comparison of the Kalman hybrid precoder with several analog, digital and hybrid solutions.

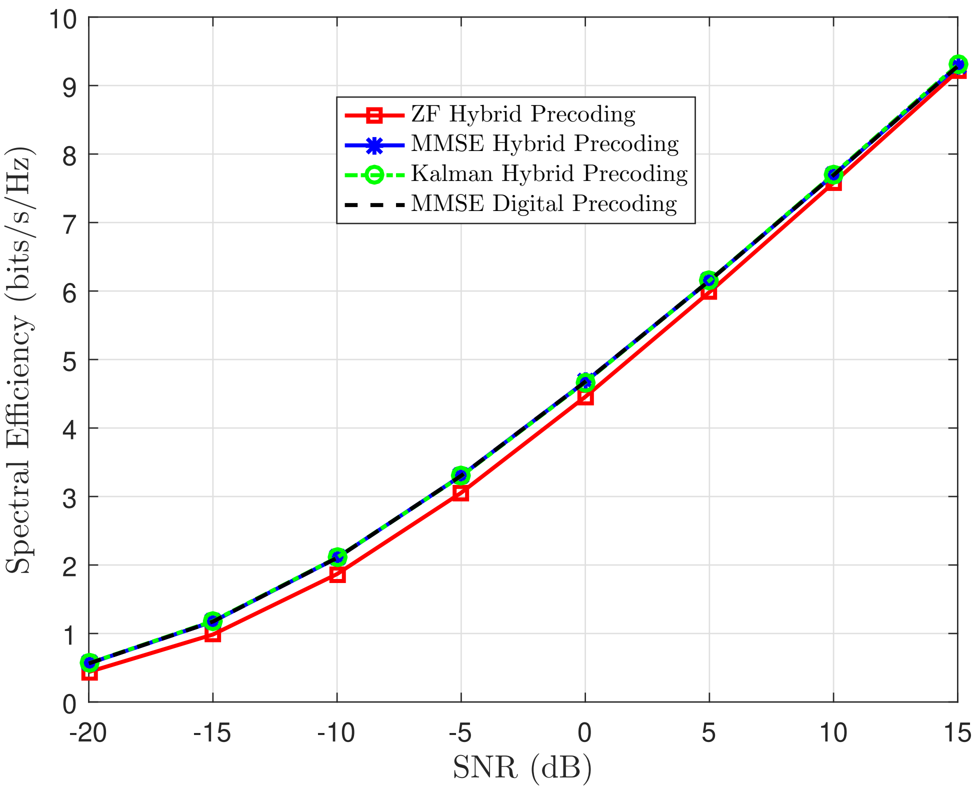


Figure 3.12: Comparison of the Kalman hybrid precoder with several analog, digital and hybrid solutions with single path channels (L=1).

From the results illustrated by Figure 3.12 , we can see that, all four techniques exhibit similar trends in spectral efficiency across varying SNR levels. In fact, the curves for MMSE Hybrid Precoding, Kalman Hybrid Precoding, and MMSE Digital Precoding nearly match in the graph indicates that they have similar performance in terms of spectral efficiency.
The MMSE digital precoding is the most significant improvement in a single-path scenario due to its ability to adapt to channel conditions. while, the ZF hybrid precoding where interference from other users is minimal due to the absence of multiple paths, the primary benefit of ZF (interference cancellation) becomes less crucial in a single path scenario.

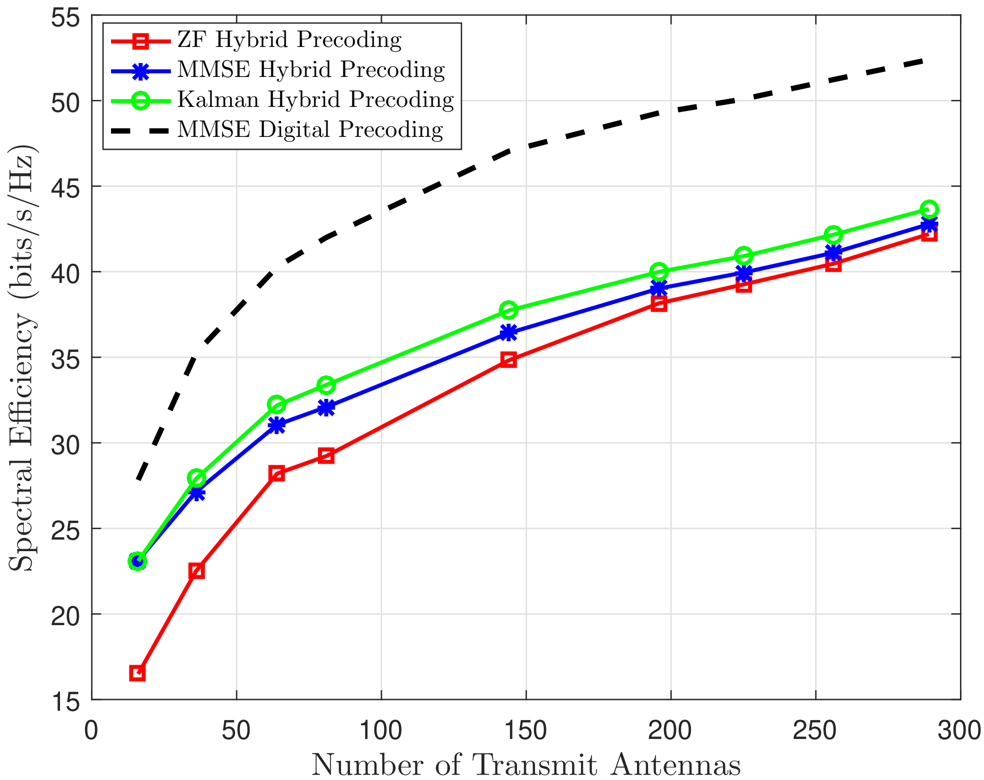


Figure 3.13: Comparison of the Kalman hybrid precoder with several analog, digital and hybrid solutions there are 5path, SNR=5dB, 4 receive antennas.

From the results illustrated by Figure 3.13 we can say that the general trend suggests that spectral efficiency improves for all precoding techniques as the number of transmit antennas increases. This is because using more antennas allows for more control over the transmitted signal, potentially leading to better spatial diversity and improved signal strength at the receiver. It can be seen that MMSE digital precoding clearly outperforms the rest of the technology across all antenna values sent because it offers the most flexibility and control over signal processing. This flexibility allows it to exploit the benefits of multiple antennas more effectively. while Kalman Hybrid and MMSE Hybrid show close and superior performance over ZF Hybrid.

The graphs in Figure 3.14 show the spectral efficiency as a function of the number of receiving antennas. The MMSE digital precoding technique consistently outperforms the others across all antenna configurations, because it offers greater flexibility and control over signal processing. The hybrid Kalman and the hybrid MMSE share the goal of improving the signal to noise ratio (SNR) at the receiver. They might achieve similar performance once there are enough receiving antennas to capture a good representation of the channel. While the hybrid ZF while aiming for complete interference cancellation, in a multi-path scenario, increasing receive antennas can potentially provide more information to help separate the desired signal from interfering signals. This could explain its convergence with the other

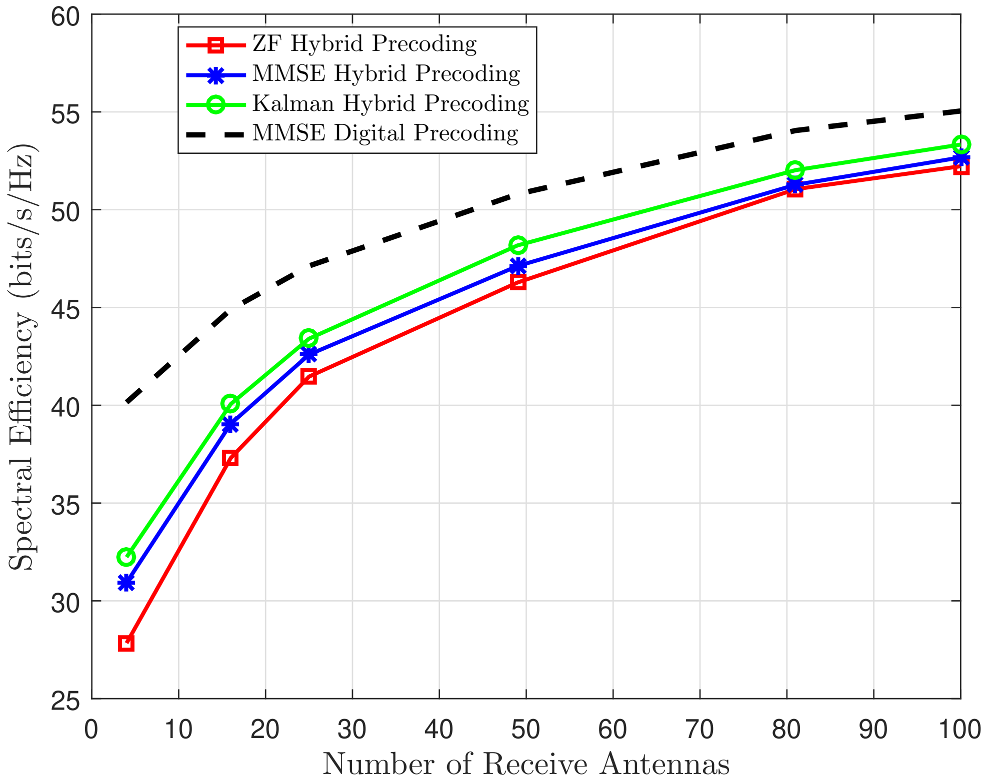


Figure 3.14: Comparison of the Kalman hybrid precoder with several analog, digital and hybrid solutions where there are 5 paths, SNR = 5 dB, and 64 transmit antennas

hybrid techniques as the number of receiving antennas increases.

3.6 Conclusion

In this chapter we comprehensively examined MIMO techniques, analyzing their potential for increased data rates (spatial multiplexing) and improved robustness (diversity modes). we also delved into various hybrid beamforming approaches, including codebook based methods for efficient beam selection, sparse hybrid beamforming leveraging compressive sensing for reduced complexity, and even beamspace MIMO utilizing lens antennas for spatial filtering. we then explored a range of precoding and combining algorithms, from the simple analog-only beamsteering to the sophisticated fully digital precoding. Furthermore, we investigated performance enhancing techniques like MMSE and Zero-Forcing (ZF) precoding, along with cutting edge sparse methods like OMP for hybrid precoding and combining. Finally, we showcased a series of simulation examples that meticulously compare the spectral efficiency of these techniques under diverse channel conditions (e.g., massive MIMO, millimeter wave) and system configurations (e.g., SNR, varying number of RF chains, single-user vs. multi-user scenarios, path delays). These comparisons will providevaluable insights into the effectiveness of each approach, allowing for informed decisions in real world MIMO system design.

General Conclusion

We embarked on a journey through the remarkable advancements of wireless communication, tracing its evolution from the first generation's (1G) analog systems to the cusp of 6G networks. Each generation witnessed significant strides in coverage, capacity, data rates, and the ability to support a growing array of applications and services. Notably, millimeter wave (mmWave) and Massive MIMO emerged as two key enabling technologies, unlocking the full potential of networks and paving the way for 5G's high capacity and low latency communication demands. we meticulously explored the synergy between these technologies, demonstrating how mmWave's high capacity seamlessly integrates with Massive MIMO's beamforming capabilities to achieve exceptional communication performance in dense urban environments, ultimately supporting a multitude of applications.

Delving deeper, we comprehensively examined Multiple-Input and Multiple-Output (MIMO) techniques, analyzing their potential to significantly increase data rates through spatial multiplexing and enhance robustness through diversity modes. It then ventured into the realm of various hybrid beamforming approaches, exploring codebook based methods for efficient beam selection, sparse hybrid beamforming that leverages compressive sensing for reduced complexity, and even beamspace MIMO utilizing lens antennas for advanced spatial filtering. The thesis further investigated a comprehensive range of precoding and combining algorithms, encompassing the fundamental analog only beamsteering to the sophisticated fully digital precoding. It meticulously explored performance enhancing techniques like MMSE and Zero-Forcing (ZF) precoding, along with cutting edge sparse methods like OMP for hybrid precoding and combining.

Finally, to solidify these theoretical findings, we presented a series of meticulously designed simulation examples. These simulations compared the spectral efficiency of the aforementioned techniques under diverse channel conditions (e.g., massive MIMO, millimeter wave) and a multitude of system configurations (e.g., varying Signal to Noise Ratio (SNR), number of RF chains, single-user versus multi-user scenarios, and path delays). These comparisons provided invaluable insights into the effectiveness of each approach, ultimately allowing for informed decisions when designing real world MIMO systems for future generations of wireless communication, ensuring continued advancements in network capacity, robustness, and user experience.

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