# KEY TECHNOLOGIES AND ARCHITECTURE OF 5G WIRELESS NETWORKS: MIMO WIRELESS COMMUNICATION TECHNOLOGY

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***ABSTRACT***

***Fifth generation wireless communication technologies have the potential to dramatically transform communications thanks to their previously unheard-of speed, capacity, and reliability. This article provides a comprehensive overview of 5G technology, including its history as well as important ideas like millimeter-wave spectrum use and multiple-input multiple-output. MIMO wireless communication technique makes use of multiple antennas on both the transmitter and receiver ends. This method enables data transfer via radio broadcasts with less errors, maximum data speeds, and greater capacity by utilizing several signal paths simultaneously. In this post, we'll discuss multiple access, which makes use of shared multiplexed channels to facilitate continuous communication between numerous users at once. Time-division multiple access (TDMA), code-division multiple access (CDMA), and frequency-division multiple access (FDMA) are among the communication and data transmission methods that will be covered by this.***

***Keywords: MIMO, FDMA, TDMA, CDMA.***

## 1. INTRODUCTION

In today's constantly linked world, where there is an increasing need for quicker, more dependable, and more effective communication, 5G wireless technology is a game-changer. 5G, the fifth generation of wireless networking, has the potential to completely change the way we interact. It will provide previously unheard-of speed, capacity, and connection that could upend whole sectors, spur creative thinking, and improve our day-to-day existence.

In many significant ways, 5G represents a significant improvement above 4G LTE and its predecessors. It delivers amazing data transfer rates with theoretical peak speeds of up to several gigabits per second. This allows for fast file downloads, uninterrupted high-definition video streaming, and nearly latency-free game play. This amazing speed is made possible by the use of cutting-edge technologies such as massive MIMO [1] (Multiple Input Multiple Output), beamforming, and millimeter-wave frequencies.

Moreover, 5G networks are far more capacious, allowing for a significant increase in the number of connected devices per unit area. An enhanced connection would facilitate the proliferation of Internet of Things (IoT) devices, therefore realizing the potential of intelligent transportation systems, networked smart homes, and smart cities.

However, the impact of 5G extends beyond mere speed and capacity improvements. It also introduces network slicing, a revolutionary concept that enables the creation of multiple virtual networks within a single physical infrastructure. This capability enables tailored network configurations to meet the diverse requirements of different applications, ensuring optimal performance, security, and reliability for each use case.

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## 2. LITERATURE REVIEW

It is commonly recognized that two primary objectives of Multiple-Input Multiple-Output (MIMO) wireless systems are high data rate and good performance. The transmission and detection methods of MIMO systems, with a focus on spatial modulation (SM), are the subject of this thesis. SM is a recently designed multiple antenna system transmission method. The idea behind SM is to map a block of bits of information into two portions, represented independently by the symbol selected from constellation points and the index of the active transmitter. The SM principle serves as the foundation for all four of the transmission strategies this thesis presents. The first approach, known as spatial phase shift keying (SPSK) modulation, exhibits a gain of 2 dB over a transmission technique based on SM and is based on the principle of spread spectrum (SM). However, it makes use of several active transmitters. ABPM, or antenna beam pattern modulation, is the second method that is suggested. Information is sent via the antenna beam patterns in this technology. This scheme's contribution is to increase data rate by employing various beam patterns, which adds another dimension to the constellation diagram. The system performs better when the beam pattern design is optimized. A sub-optimal detection approach based on lattice reduction (LR) is utilized to lower the computational complexity in contrast to the optimal maximum likelihood (ML) method, in addition to all the benefits of ABPM at the transmission design. The goal of this suggested sub-optimal detection approach (LR) is to get a complexity that is reasonable while achieving performance comparable to the ML scheme. When compared to SM-based transmission approaches, ABPM exhibits a gain of greater than 2 dB. Antenna pattern shift keying (APSK) modulation is the third approach. Because the active transmitters' indices and antenna beam patterns both convey the symbol selected from a constellation diagram, this technique integrates the concepts of SPSK and ABPM. The data rate and overall system performance are enhanced with APSK. The performance of APSK is comparable to that of a spatial multiplexing system, but it has a gain of 3.5 dB and uses fewer RF chains than a strategy based on SM. A precoder approach based on LR is the last scheme in this thesis. In order to enhance the system's performance, this new LR pre-coder is used with the generalized pre-coding aided spatial modulation (GPSM) scheme. It demonstrates a gain of more than 1 dB over the conventional GPSM. Furthermore, a less difficult suboptimal detector technique is suggested to get similar performance as the ML detector. When combined with the LR pre-coding method, it allows for substantially reduced detection complexity while maintaining the GPSM scheme's performance.

### 2.1 Transmission Techniques for MIMO

By using multiple antennas, MIMO systems allow numerous data streams to be sent concurrently across a wireless channel. MIMO increases data speed, energy efficiency, interference reduction, and reliability. Originally used in the early 2000s, transmit diversity is especially useful in the downlink system as it increases dependability by employing a large number of transmitters. Spatial multiplexing and transmitting diversity (STC) are two of the most widely used transmission methods.

### 2.2 Beamforming

It is possible to modify the direction of the beam pattern and enhance coverage for specific users by using several antennas to broadcast beamforming, which balances the phase and amplitude of each antenna signal. The beamforming gain of the array, which is achieved when every antenna in the array contributes to the guided signal, makes this feasible. With beamforming, the direction of arrival (DoA), or the direction from which the signal will come, may be determined at the receiving end. It may be used to suppress some interfering signals by choosing a beam pattern null in the direction of the undesirable signal.

### 2.3 Transmit Diversity

The most popular transmit diversity approach is STC; the receiver has to know the channel in order to decode the signal. By concurrently delivering several copies of the same data via distinct fading pathways, STC aims to improve connection dependability. Because it is unlikely that numerous signals would fade concurrently, this reduces the chance that a signal will fade completely. Space time block codes (STBCs) are the most studied type of space-time code despite the fact that there are numerous varieties due to their ease of implementation.

### 2.4 Spatial Multiplexing

Separating the informational sequence into streams that will get different treatment is the main objective of the spatial multiplexing process. Thus, spatial multiplexing boosts the spectral efficiency by delivering many independent streams via various antennas. Three separate encoding scenarios comprise the encoding techniques of these methods:

- Horizontal
- Vertical
- Diagonal

### 2.5 Precoding

One major problem in the detection process is the separation of data streams based on MIMO demands. When generating the broadcast signals for MIMO systems using the pre-coding or pre-equalizer approach, the CSI has to be present at the transmitter. The CSI is obtained for a fixed channel (non-mobile) or a fairly constant channel over a reasonable amount of time.

When CSI is available at the transmitter side, pre-equalization at the transmitter can be utilized to partially separate the broadcast symbols.

## 3. THE ADVANCEMENT OF WIRELESS TECHNOLOGIES

The evolution of wireless technologies has been rapid and transformative, revolutionizing communication, connectivity, and numerous industries.

### 3.1 Initial generation (1g) [2]:

- The first wireless technology, known as 1G, was created in the 1980s and was mostly used for analog phone services.
- Initially introduced in the early 1980s, the earliest commercial 1G networks had limited capacity and coverage.
- Examples include the Total Access Communication System (TACS) in Europe and the

Advanced Mobile Phone System (AMPS) in the United States.

**3.2 Generation Two (2G) [3]:**

- When 2G first appeared in the late 1980s and early 1990s, communication switched from analog to digital.
- Data services like SMS (Short Message Service) and digital voice compression were launched by it.
- Global System for Mobile Communications (GSM), Code Division Multiple Access (CDMA), and Time Division Multiple Access (TDMA) are important standards.

**3.3 Generation Three (3G) [4]:**

- With the advent of 3G technology in the early 2000s, data speed was greatly increased, allowing for the use of applications like mobile internet access and video calling.
- There was a lot of prominence for standards like CDMA2000 and Universal Mobile Telecommunication Systems (UMTS).
- The foundation for mobile broadband was established by 3G networks.

**3.4 Generation Four (4G) [5]:**

- 4G Long-Term Evolution (LTE) brought about a significant improvement in latency reduction, capacity, and data rates.
- It made it possible to broadcast HD video and play online games and run other programs that need a lot of bandwidth.
- More improvements were brought about by LTE-Advanced and LTE-Advanced Pro, including carrier aggregation and increased spectrum efficiency.

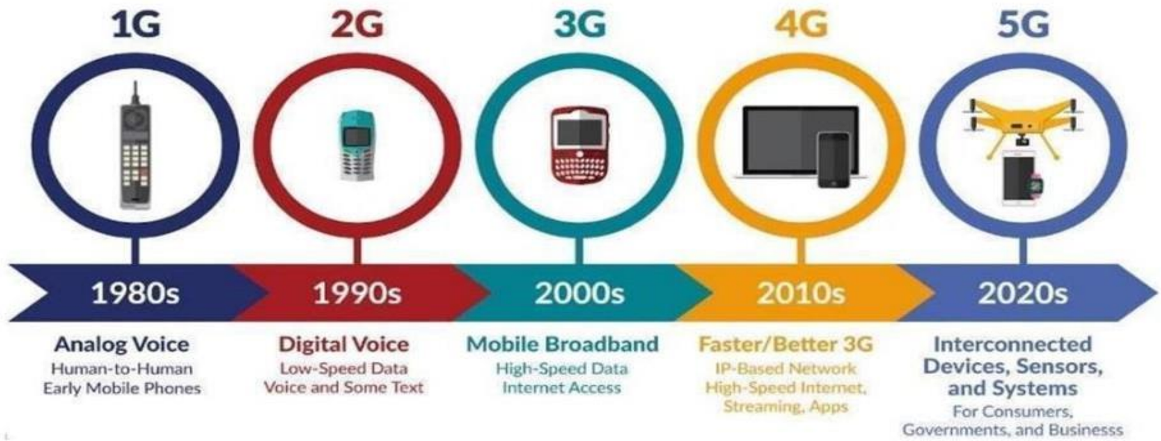


***Figure 1. Evolution of mobile networks in time***

## 4. 5G CORE ARCHITECTURE

The 5G core network architecture, upon which the new 5G standard is built, enables 5G to meet the increased throughput requirements. Cloud-aligned Service-Based Architecture [6] (SBA), which encompasses all 5G services and interactions, including session management, authentication, security, and traffic aggregation from end devices, is being used by 3GPP in the new 5G core. With virtualized software functionalities provided via the MEC [8] infrastructure, which is essential to 5G architectural ideas, NFV [7] is emphasized in the 5G core. The essential elements of a 5G core network are shown in the following 5G network topology diagram:

This is how it works:

**4.1 User Equipment (UE):** User Equipment [9], such as 5G smartphones or 5% cellular devices, connects to the 5G core and then to Data Networks (DN), such as the internet, via the 5G New Radio Access Network.

**4.2 Radio Access Network (RAN):** The User Equipment and the Core Network are connected wirelessly by means of the Radio Access Network [10]. Base stations, antennas, and other devices that offer wireless coverage in a certain region are part of the RAN. Three frequency bands are intended for use by the 5G RAN: Low, Mid, and High.

**4.3 User Plane Function (UPF):** Between the User Equipment (UE) and the external networks, the User Plane Function carries IP data flow (user plane).

**4.4 Network Exposure Function (NEF):** Another essential part of the 5G core network is the Network Exposure Function [11], which builds a bridge between the 5G core network and external applications, allowing network operators to safely expose network functions and interfaces at a granular level. Additionally, the NEF gives Application Functions a way to safely send data to the 3GPP network [12].

**4.5 Network Repository Function (NRF):** The NRF, which acts as a single repository for all NF instances, is a crucial component needed to achieve the new service-based architecture in the 5G core network. It oversees managing the NF profile lifetime, which includes deregistering profiles that are no longer in use, updating outdated profiles, and registering new ones. A standards-based API for 5G NF registration and discovery is provided by the NRF. From a technical standpoint, NRF works by keeping track of information about every Network Function instance, including the capabilities, services, and capacities that they provide. A newly created NF instance registers with the NRF and provides all the required information when it is instantiated. The target NF's instance details may therefore be obtained by any NF requesting information from the NRF to interact with another NF. Based on the requested service and capacity, the NRF provides the most appropriate NF instance information in response to this question.

**4.6 Policy Control Function (PCF):** Particularly in the context of 5G and upcoming innovations, the PCF is crucial to the architecture of mobile networks. It serves as the principal component responsible for putting policies into place pertaining to user access control, quality of service [13] (QoS), and resource distribution on the network. Its main job is to monitor and optimize network resource distribution, ensuring that service providers may deliver a range of services that meet requirements and criteria.

**4.7 Unified Data Management (UDM):** To make data assets simpler to access, analyze, and use inside an organization, UDM refers to the process of integrating and centralizing data from several sources. To combine data from many sources, including databases, apps, file systems, and cloud services, into a single, cohesive data ecosystem, it entails utilizing technologies, procedures, and approaches.

**4.8 Authentication Function Server:** A key element of network security systems, particularly in settings where access control is necessary, is an authentication server [14]. Verifying the identification of people or devices trying to join to a network or access certain resources is its main purpose.

**4.9 Access and Management Mobility Function:** To provide consumers with seamless mobility and safe and effective access to 5G networks, the AMF [15] is essential. Delivering high-performance mobile services and enabling a broad range of use cases in 5G networks, such as enhanced Mobile Broadband (eMBB), massive Machine Type Communication (mMTC), and Ultra-Reliable Low-Latency Communication (URLLC), are made possible by its features.

**4.10 Session Management Function:** In order to keep user sessions safely and effectively within a website or software program and to give users a smooth, safe experience, session management is essential.

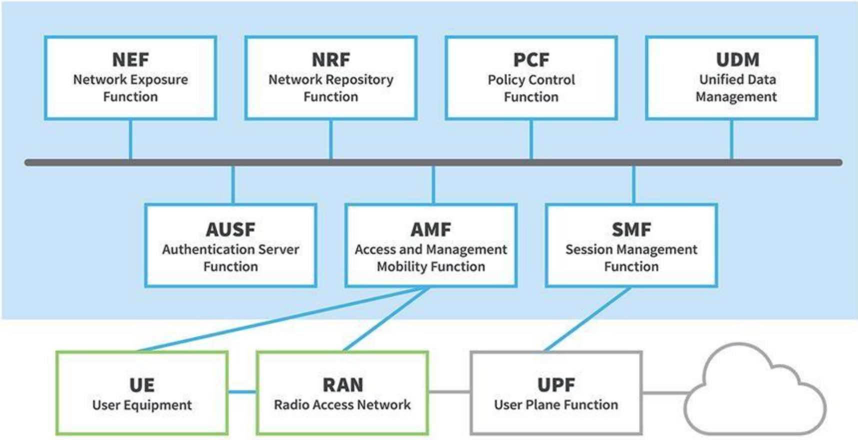


*Figure 2. Core Architecture*

## 5. MULTIPLE ACCESS TECHNIQUES

Conventional analog modulation systems, like FM and AM, can limit the amount of data carried inside each channel when linking users that share the same radio spectrum. Only one discussion may be held on each channel at once, necessitating the participation of two users—one broadcasting and one receiving.

**5.1 TDMA:** Time Division Multiple Access is referred to as TDMA [18]. TDMA separates the primary RF channel into time slots as opposed to several sub-channels. The same RF frequency [19] is used by each slot, yet distinct conversations can be carried out. For instance, if the primary channel is split up into four time slots, each one will broadcast data and information for one-fourth of the initial period. This kind of voice reduction is made possible by digital technology. There are practical distance restrictions, though. The number of blocks that an individual RF channel may carry before base station slot overlap occurs is determined by these restrictions. Because TDMA allocates specific periods for transmission and receiving, it also makes telephone-style talks easier.

With TDMA, each user uses a distinct time slot to transmit in turn in a sequential manner. Because of how quickly this change occurs, all users believe they are utilizing the same RF channel at the same time. TDMA increases the data capacity of the channel by allocating a different bandwidth chunk to each other, allowing for numerous conversations to occur simultaneously. A variation known as North American TDMA is used in North America. TDMA is a feature of almost all 2G cellular networks, including:

- Mobile Phone Service with Digital Advancement [20]
- Global System for Mobile Communication (GSM)
- Personal Digital Cellular (PDC)
- Network Enhanced Digitally Integrated [21]

**5.2 FDMA:** Frequency Division Multiple Access is the acronym for this technology [22]. It creates several smaller sub-channels from the available radio frequency (RF) channel. As an illustration, a 13 kHz narrowband FM channel that was previously utilized for a single discussion can be divided into two 6.5 kHz sun-channels that can each support a different conversation. This technique is not new and works with analog and digital radios. By utilizing one channel for signal transmission and another for reception, it also permits telephone-style talks. Call interference is a significant drawback of this technology when more sun-channels are added within the primary channel. This problem occurs because it is challenging to filter out one targeted sub-channel while rejecting the others at the receiver's end due to the smaller spacing between channels. As a result,splitting a 13 kHz narrowband channel frequency continuously into two or more sub-channels is not feasible.

**5.3 CDMA:** The acronym for Code Division Multiple Access is CDMA [23]. In contrast to previous techniques, CDMA gives each channel a distinct code rather than segmenting the primary RF channel into many time slots or sub-channels. CDMA transmits individual slots concurrently, as contrast to TDMA, and utilizes the same frequency for transmission in every slot, unlike FDMA. Imagine a situation where four code slots are created via CDMA to carry independent talks on the primary RF channel. This is feasible as information from a transmitter with the same coding can only be reconstructed by the receiver. The drawback to this approach is that it allows the receiver to interpret messages with various codes on the same frequency as noise. when a result, when the user base grows, noise levels rise and impact system coverage as a whole.

## 6. 5G's IMPACT ON INDUSTRIES

Massive potential will arise across a range of businesses with the introduction of 5G. The way 5G will affect the Internet of Things is one of its fascinating features.


*Figure 3. 5G use case scenarios*

### 6.1 Agricultural Industry

Human life depends on agriculture. Despite technological advancements and their effects on many other industries, agriculture is falling behind and remains heavily reliant on physical labor. Conventional agricultural methods have little effect and waste natural resources needlessly. Innovation in the farming industry will be necessary to increase the efficacy of farming methods.

Legacy methods will be replaced by the introduction of 5G technology and the pace of digital transformation across sectors.

Food demand is growing daily, yet there are fewer natural resources available. Reduced agricultural yields are simply a result of rising global temperatures, changing climate patterns, and increased weed and insect infestation. Furthermore, since relatively little of the food produced reaches customers, food waste is a serious issue.

### 6.2 Autonomous Vehicles

Autonomous vehicles were merely a thing of science fiction a few years ago. Nonetheless, a lot of automakers have already begun to include auto drive features in their vehicles today. The development and smooth operation of self-driving automobiles will be greatly impacted by 5G. A vast quantity of data must be sent simultaneously between cars and several other devices in order for autonomous driving to function. With 5G networks, it will be feasible since latency will be drastically reduced and vehicle response times will be 10-100 times faster than with present networks.

### 6.3 Health Industry

The internet already plays a huge role in the health business. Healthcare systems throughout the world are under tremendous strain to manage the little resources that are now available due to the world's population growth. With the aid of clever robots, 5G will enable qualified medical professionals to work remotely and deliver necessary basic care. Additionally, it will make it possible for individuals to use resources effectively and autonomously from wherever they are.

The field of surgery is where 5G is also being used. With the necessary latency, throughput, and dependability amongst wireless robots, a surgeon operating from a distance of hundreds of kilometers may still do surgery with the same level of tactile sensation, using robotic probes in place of the surgeon's hands.

### 6.4 Industrial Automation

The primary benefit of 5G in industrial automation is the complete replacement of all wired equipment with cheaper, more effective wireless technology. Numerous synchronized robots systems are now in use in supply chain applications and manufacturing.

The high quality of service needed for smart factories will be made possible by the arrival of 5G, which has fast throughput, low latency, and exceptional dependability. Furthermore, functional safety between humans, machines, and the environment will eventually be maintained by 5G.

### 6.5 AR and VR

Many industries may make advantage of AR and VR technologies. The applications of AR and VR will grow much further with the introduction of 5G. one of the important manufacturing industries. This sector has been greatly impacted by the capacity to display the physical components that are difficult to perceive with the unaided eye or that are dangerous to touch. Furthermore, it is possible to construct a virtual prototype in advance rather than squandering numerous hours and dollars on actual prototypes.

## 7. RESEARCH METHODLOGY

MIMO, is a technology that uses numerous antennas at the transmitter and reception ends; this is also known as spatial diversity [24]. Systems that used spatial diversity before the 1990s usually switched between two antennas. Transmitter diversity refers to the use of numerous antennas at the transmitter; receiver diversity refers to the use of multiple antennas at the receiver. Wireless network dependability and channel capacity are successfully increased by this method. In the beginning, point-to-point MIMO configurations with two antennas each were common. But shortly, multi-user MIMO—which allowed many base station antennas to interact with a single antenna receiver—became popular. This change allowed for the use of less costly antennas at the single-antenna terminals while reducing system costs because expensive antennas were only required at the base stations. This technology has the ability to improve both capacity and dependability while also having the capability to reduce mistake rates. By sending many copies of our message via different channels, we lessen the chance that any one signal will be impacted at the same time. These many copies are received, processed, and the original message is recovered upon reception, improving communication performance and stability and reducing error rates. Due to these benefits, MIMO technology has been incorporated into LTE, 802.11 (WiFi) [25], and 802.16 (WiMAX) [26], among other communication protocols. Both spatial diversity and spatial multiplexing are used in MIMO communication [27]. Spatial diversity entails sending the same data along several routes, where it is received at several antennas and analyzed. Spatial multiplexing, on the other hand, increases speed at the possible expense of dependability by breaking the data into smaller segments and sending them via several pathways. Two techniques called spatial multiplexing and spatial diversity are used in MIMO communication. Transmitting the same data over a variety of pathways, followed by several antennas receiving it and processing it to increase dependability, is known as spatial diversity. On the other hand, spatial multiplexing increases speed at the expense of dependability by breaking up the data into smaller pieces and transmitting each segment via a separate path.

Several transmitter and receiver antennas linked by a fading channel are used in a MIMO configuration to transfer data. Assume we have M antennas for the broadcaster and N antennas for the reception. We make matrices with t rows for the transmitter and r rows for the receiver for both the transmitter and receiver antennas.

The basic equation for MIMO system is given by Y=H.X+W [28]

Where, Y= Nx1 Receiver matrix

H= NxM Channel matrix

X= Mx1 Transition matrix & W= Noise

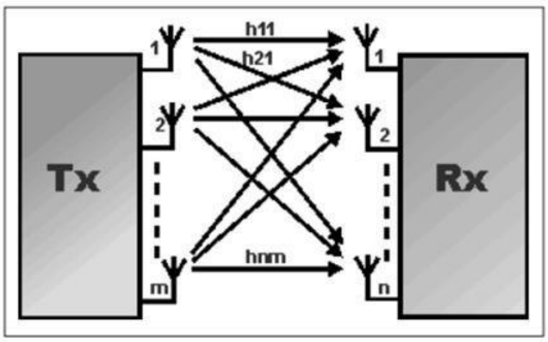


***Figure 4. MIMO system***

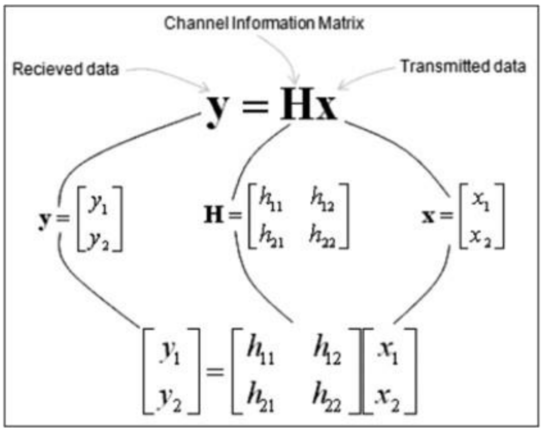


***Figure 5. MIMO Matrix Representation***

Future technological developments will strive to optimize gains and simplify signal processing by using methods such as MIMO or large-scale antenna systems (LSAS). MIMO systems have the potential to use 100 or more antennas, while conventional MIMO systems usually use less than ten. However, because to restrictions on getting channel status information, not every antenna is active at the same time. Conventional TDMA, FDMA, and OFDM multiplexing methods are combined in MIMO. It is expected that next MIMO versions would run at very low power, maybe milliwatts. Among the difficulties include minimizing the advantages from multiuser multiplexing, correcting inaccuracies in channel status data, and reducing interference. Of special concern is the rising power consumption at base stations. It is assumed that base stations have more antennas than users, providing more degrees of freedom for efficient transmission and interference avoidance. The efficiency of MIMO is an additional advantage. According to predictions, a single-antenna user in a MIMO system can achieve performance similar to a Single-Input-Single-Output [30] (SISO) system by reducing transmit power relative to the number of base station antennas, either with perfect Channel State Information [29] (CSI) or proportional to the square root of the number of base station antennas with imperfect CSI. Given the growing worries about excessive energy usage in wireless networks, this greater energy efficiency is essential. Moreover, a MIMO system's operating range may be greater than a SISO system's if there was enough power at the base station.

It is possible to build MIMO technology with reasonably priced, low-power components. It is possible to replace conventional high-power amplifiers with more reasonably priced models that produce milliwatts of output. It is also possible to do away with large, cumbersome equipment, including the coaxial cables that link mobile switching centers and base stations. The averaging out of noise, fading, and defects through the combining of signals from several antennas is the fundamental idea of MIMO functioning. Even with more than 100 antennas, not all of them are in use at the same time, giving MIMO systems a lot of flexibility. As a result, these systems have very little latency as compared to traditional configurations. MIMO configurations reduce latency, which is frequently brought on by fading from the signal traveling via several pathways to the receiver. This is because there are many antennas and degrees of freedom. However, there are other restrictions to take into account, such pilot contamination and channel reciprocity, which might result from interference from nearby cells and call for mitigation techniques.

## 7. CONCLUSION

The impending release of fifth-generation wireless communication technologies, which promise previously unheard-of speed, capacity, and dependability, is poised to completely change connection. The key components and developments of 5G technology are covered in detail in this article. After providing a brief historical overview, the article delves into the fundamental concepts that underpin 5G networks, including MIMO and millimeter wave spectrum usage. Moreover, 5G networks include much higher capacity, which allows a considerable increase in the number of connected devices per unit area. The Internet of Things (IoT) will grow as a result of this improved connection, bringing in the era of smart homes, intelligent transportation systems, and smart cities.

## REFERENCES

1.Popovski P, Trillingsgaard KF, Simeone O, Durisi G. 5G Wireless Network Slicing for eMBB, URLLC, and mMTC: A Communication-Theoretic View. IEEE Access [Internet]. 2018; 6: 55765–79. Available from: https://doi.org/10.1109/access.2018.2872781

2.Palanisamy S, Thangaraju B, Khalaf OI, Alotaibi Y, Alghamdi S, Alassery F. A Novel Approach of Design and Analysis of a Hexagonal Fractal Antenna Array (HFAA) for Next-Generation Wireless Communication. Energies [Internet]. 2021; 14: 6204. Available from: https://doi.org/10.3390/en14196204

3.Palanisamy S, Thangaraju B, Khalaf OI, Alotaibi Y, Alghamdi S, Alassery F. A Novel Approach of Design and Analysis of a Hexagonal Fractal Antenna Array (HFAA) for Next-Generation Wireless Communication. Energies [Internet]. 2021; 14: 6204. Available from: https://doi.org/10.3390/en14196204

4.Palanisamy S, Thangaraju B, Khalaf OI, Alotaibi Y, Alghamdi S, Alassery F. A Novel Approach of Design and Analysis of a Hexagonal Fractal Antenna Array (HFAA) for Next-Generation Wireless Communication. Energies [Internet]. 2021; 14: 6204. Available from: https://doi.org/10.3390/en14196204.

5.Palanisamy S, Thangaraju B, Khalaf OI, Alotaibi Y, Alghamdi S, Alassery F. A Novel Approach of Design and Analysis of a Hexagonal Fractal Antenna Array (HFAA) for Next-Generation Wireless Communication. Energies [Internet]. 2021; 14: 6204. Available from: https://doi.org/10.3390/en14196204

6. Li B, Fei Z, Zhang Y, Guizani M. Secure UAV Communication Networks over 5G. IEEE Wireless Communications [Internet]. 2019; 26: 114–20. Available from: https://doi.org/10.1109/mwc.2019.1800458

7. https://www.sdxcentral.com/5g/definitions/top-5g-business-case/5g-nfv/

8. article | What is multi-access edge computing? [Internet]. Available from: https://www.redhat.com/en/topics/edge-computing/what-is-multi-access-edge-computing

9. Bikram Kumar (2019). Online Distributed User Association for Heterogeneous Radio Access Network.

10.https://www.ericsson.com/en/ran#:~:text=A%205G%20Radio%20Access%20Network,deliver%20the%20best%20network%20performance.

11. Lee WCY. Overview of cellular CDMA. IEEE Transactions on Vehicular Technology [Internet]. 1991; 40: 291–302. Available from: https://doi.org/10.1109/25.289410

12.https://www.3gpp.org/technologies/5g-system-overview#:~:text=3GPP%20defines%20not%20only%20the,vendor%20and%20inter%2Doperator%20context.

13. Aljiznawi RA, Alkhazaali NH, Jabbar SQ, Kadhim DJ. Quality of Service (QoS) for 5G

Networks. International Journal of Future Computer and Communication [Internet]. 2017; 6: 27–30. Available from: https://doi.org/10.18178/ijfcc.2017.6.1.483

14. Xiaoting Huang (2021). Authentication Mechanisms in the 5G System.

15. Maraj Uddin Ahmed Siddiqui (2022). Mobility Management Issues and Solutions in 5G-and-Beyond Networks: A Comprehensive Review

16. Haesik Kim (2020). Ultra-Reliable and Low Latency Communication Systems

17. Eryk Dutkiewicz (2017). Massive Machine-Type Communications

18. Agiwal M, Roy A, Saxena N. Next Generation 5G Wireless Networks: A Comprehensive Survey. IEEE Communications Surveys and Tutorials/IEEE Communications Surveys and Tutorials [Internet]. 2016; 18: 1617–55. Available from: https://doi.org/10.1109/comst.2016.2532458

19. https://www.rfglobalsolutions.co.uk/what-is-radio-frequency-rf/

20. https://www.tutorialspoint.com/digital-advanced-mobile-phone-system

21. https://www.techopedia.com/definition/7670/integrated-digital-enhanced-network-iden

22. Noune M, Nix A. Frequency-domain precoding for single carrier frequency-division multiple access. IEEE Communications Magazine [Internet]. 2009; 47: 68–74. Available from: https://doi.org/10.1109/mcom.2009.5116802

23. Yang N, Wang L, Geraci G, Elkashlan M, Yuan J, Di Renzo M. Safeguarding 5G wireless communication networks using physical layer security. IEEE Communications Magazine [Internet]. 2015; 53: 20–7. Available from: https://doi.org/10.1109/mcom.2015.7081071

24. Diggavi SN, Al-Dhahir N, Stamoulis A, Calderbank AR. Great Expectations: The Value of Spatial Diversity in Wireless Networks. Proceedings of the IEEE [Internet]. 2004; 92: 219–70. Available from: https://doi.org/10.1109/jproc.2003.821914

25. https://www.4gon.co.uk/solutions/introduction_to_802_11_wifi.php

26. Behnam Kamali (2018). The IEEE 802.16 Standards and the WiMAX Technology

27. Spencer QH, Swindlehurst AL, Haardt M. Zero-Forcing Methods for Downlink Spatial Multiplexing in Multiuser MIMO Channels. IEEE Transactions on Signal Processing [Internet]. 2004; 52: 461–71. Available from: https://doi.org/10.1109/tsp.2003.821107

28. Webster E. MIMO (multiple input, multiple output) [Internet]. Mobile Computing. 2021. Available from: https://www.techtarget.com/searchmobilecomputing/definition/MIMO

29. Mo J, Heath RW. Capacity Analysis of One-Bit Quantized MIMO Systems With Transmitter Channel State Information. IEEE Transactions on Signal Processing [Internet]. 2015; 63: 5498–512. Available from: https://doi.org/10.1109/tsp.2015.2455527

30. Carroll R, Lindorff D. An adaptive observer for single-input single-output linear systems. IEEE Transactions on Automatic Control [Internet]. 1973; 18: 428–35. Available from: https://doi.org/10.1109/tac.1973.1100367