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Key Technologies and Application Scenarios of 5G-Advanced: Paving the Way for Intelligent Connectivity

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Abstract: *The paper examines modern developments of 5G - Advanced that began with 3GPP release 18 through its assessment based on analytical methods and simulation evaluation. The study is based on four core technologies: AI/ML-enabled air interface optimization, Integrated Sensing and Communication (ISAC), enhanced Non- Terrestrial (NTN), and energy-efficient network architectures. The research study investigates the three technologies which support upcoming use cases of smart healthcare systems, autonomous mobility devices and extended reality systems and industrial Internet of Things technology. The simulation framework uses MATLAB for physical-layer modeling and NS-3 network evaluation to measure key performance metrics that include latency and throughput and beamforming characteristics and signal-to-noise ratio. The result show that 5G- Advanced provides substantial benefits through improved reliability and spectral efficiency and better performance on latency-sensitive services which establishes it as an advancement toward future wireless technologies.*

Key Words: *5G-Advanced, Network Intelligence, 5G Advanced Application Scenarios.*

I. INTRODUCTION

The period of your data training extends until the month of October in the year 2023. People now require advanced intelligence services because their demand for data has grown beyond the initial capabilities of 5G technology. The new applications require networks to provide enhanced intelligent capabilities together with better energy savings and the ability to maintain connections throughout multiple operational environments. The telecommunications sector has initiated 5G-Advanced development to solve these problems through 3GPP Release 18 which establishes the path toward future wireless communication systems.5G-Advanced presents multiple technological advancements which improve network capabilities and operational performance.

The system includes three main features which operate as AI/ML-based network optimization tools and ISAC and NTN systems that provide international network services through non-terrestrial components. The combined deployment of these technologies will enhance spectral efficiency and positioning accuracy and system intelligence. The system will provide new service capabilities that will operate across various industrial sectors. The new technological developments make possible numerous applications which create significant positive effects. 5G-Advanced provides support for advanced healthcare systems and intelligent transportation networks and immersive extended reality environments and large-scale industrial Internet of Things deployments. The new communication networks now enable mission-critical services together with real-time services through advanced latency and connection density and energy efficiency capabilities which were not possible with previous communication system.

The assessment of 5G-Advanced performance enhancements requires both simulation and analytical modeling methods. The testing environment uses MATLAB for physical-layer analysis and NS-3-style network modeling to evaluate massive MIMO systems through their key performance indicators which include latency and throughput and signal-to-noise ratio and beamforming characteristics. The analyses demonstrate how advanced wireless technologies improve network reliability and capacity and service quality in future communication systems.

II.LITERATURE REVIEW

Mobile communication systems have developed from their initial design which focused on voice calls to their current state which includes the complete range of fifth-generation (5G) network capabilities. The earlier generations of mobile technology provided only essential voice and text services while 5G technology uses high-speed data transmission and extremely fast response times and extensive device connections to deliver advanced digital services which modern society needs. The current transition demonstrates how different industries require wireless communication technologies which provide both dependable performance and high operational efficiency [1].

5G technology introduces multiple new use cases through three fundamental features which include enhanced mobile broadband and ultra-reliable low-latency communication and massive machine-type communication. The smart cities and autonomous vehicles and industrial automation systems use these features to operate their essential functions. 5G offers a network structure which enables users to create flexible and expandable systems that can manage multiple complex data services which require high processing power [2].

5G technology exists to support the creation of smart city systems which serve as its main deployment purpose. The system enables cities to achieve total connectivity between their different operational areas, which results in improved outcomes for transportation systems and energy management and public safety operations at their facilities. The implementation of vehicle-to-vehicle and vehicle-to-infrastructure communication systems enables traffic to flow better while decreasing accidents which creates safer and more efficient urban spaces [3].

The expansion of 5G coverage requires non-terrestrial communication systems to operate together with traditional terrestrial networks through unmanned aerial vehicles (UAVs) and satellites. The technologies establish communication links with remote locations and underserved communities which enables constant access to communication services. The combination of UAVs with intelligent optimization techniques delivers superior network performance and flexible operation capabilities [4].

The 5G network system utilizes artificial intelligence (AI) technology to manage the resources of the network, enhancing its performance as required. Organizations use AI methodologies to predict events of the future, which are essential in managing the network effectively. This technology helps in the development of flexible 5G networks, which are able to modify their capabilities of operation according to the nature of the working environment, as per the standard operating procedures [5].

Academics consider security an essential component of blockchain-related research, which seeks to investigate the use of Internet of Things (IoT) systems in 5G network systems. Blockchain technology helps in the development of decentralized networks, allowing them to transmit data while establishing transparent processes that enhance trust among the parties involved. Comprehensive data protection approaches are required in the development of industrial automation systems as well as smart supply chain systems, as they are based on the management of secure information [6].

The health care sector has witnessed significant benefits from the implementation of 5G technology. It helps in the provision of better medical facilities, including telemedicine, remote surgery, and patient monitoring. The low latency of 5G networks helps in the provision of better medical services, thereby enhancing health care [7]. In addition, the concept of smart hospitals has gained importance through the implementation of 5G, Internet of Things (IoT), and artificial intelligence (AI) technologies. These technologies are beneficial in the analysis of real-time data, medical imaging, and health care management [8].

However, the designers of 5G need to take into account energy efficiency and sustainability as major requirements. The use of technologies like massive MIMO and AI optimization helps in the reduction of energy consumption. The 5G network facilitates the development of smart energy systems, thus promoting environmental sustainability [9]. The development of 5G networks requires robust infrastructure systems, and the development of optical networking technologies is a major requirement for the establishment of the 5G network. This is because optical networking technologies provide the required bandwidth and minimum latency for the effective transmission of data. The study of 5G technologies still continues, and the major problems faced by the 5G network include its scalability and security [10].

III.METHODOLOGY

A. Research Design and Approach:

The hybrid analytical and simulation-based research methodology of this study investigates the performance and capabilities of 5G-Advanced technologies. The research integrates theoretical analysis derived from 3GPP specifications and existing literature with simulation-based validation. The approach connects theoretical developments which include AI-native air interface and ISAC and NTN with their actual effects on operational communication systems. The methodology assesses technological advancements which enhance essential performance metrics including latency and throughput and spectral efficiency and reliability.

B. Simulation Framework Development:

The research team created a special simulation framework which enables them to simulate the physical-layer and network-layer operations of both 5G and 5G-Advanced systems. The framework combines:

- MATLAB-style numerical modeling for physical-layer simulations.
- NS-3-inspired analytical modeling for network-level performance

The communication system evaluation process uses this dual-layer testing method which assesses performance across all system communication layers. The simulation environment uses actual deployment conditions which it reproduces through these parameters:

- **Carrier frequency:** 3.5 GHz (Sub-6 GHz band)
- **Antenna configuration:** 16-element uniform linear array
- **Deployment scenario:** Urban macro-cell environment

C. Performance Metrics and Evaluation Criteria:

The research looks at how the system works by using important 5G and 5G-Advanced standard measurements. The research uses these measurements:

- **Latency:** This is measured when the network is busy or not busy for services like URLLC and eMBB
- **Throughput:** This is looked at to see how it changes when the channel bandwidth changes
- **Signal-to-Noise Ratio or SNR:** This is evaluated to see what happens when the distance changes

- **Beamforming Gain:** This is assessed by looking at the radiation pattern of MIMO arrays

These measurements show how 5G-Advanced systems work for things like smart healthcare and autonomous transportation and industrial IoT applications. The 5G-Advanced systems can do their jobs for these things. The 5G-Advanced systems are good, for healthcare and autonomous transportation and industrial IoT applications because they can do what they need to do.

D. Mathematical Modeling and Simulation Procedures:

The simulations use math models and communication theory that're already well-established so they give a realistic picture of how the system works.

Some of the techniques used for modeling are:

- **Latency modeling:** This uses math functions that show how real networks behave when they are busy
- **Throughput estimation:** This looks at the amount of data that can be sent over a network using a method based on Shannon's ideas
- **SNR modeling:** This uses a model that shows how signal strength decreases as it travels farther to simulate how signals get weaker
- **Beamforming analysis:** This uses a setup with many antennas in a line to see how signals can be directed.

Things like modulation, coding and beamforming that happen at the physical level are modeled to be like they are in real 5G systems. These models use the settings as the 3GPP standards so they are accurate and consistent. The simulations are based on established models and communication theory principles ensuring realistic system representation, with 5G system operations and models. The models are aligned with 3GPP parameters.

E. Data Analysis and Interpretation:

The simulation results are looked at using graphs and comparisons to find useful information. Each performance measure is checked under system conditions.

The results are seen in the context of:

- Quality of Service (QoS) differences like URLLC versus eMBB
- How much bandwidth expansion helps system capacity.
- The balance, between coverage area and signal strength.
- How well beamforming and massive MIMO work to make the system more reliable.

The results are then compared to what theory says and industry standards to confirm that 5G-Advanced technologies really work. This analysis helps to conclude that 5G-Advanced greatly improves network performance. It also helps to enable applications that will come in the future. The 5G-Advanced technologies make networks better. They support applications. The findings show 5G-Advanced works well. It enhances network performance a lot.

IV.RESULT AND ANALYSIS

This chapter is about testing the proposed 5G and 5G- framework using simulations. To make sure the test results are what this thesis is looking for the simulation was set up to look at four things: how long it takes for data to travel through the network when it is busy how much data can be sent based on how much bandwidth is available how the signal gets weaker as the distance increases and how much better the signal is with beamforming in a big MIMO system. These things are important for services that need low latency like URLLC services that need to send a lot of data like eMBB and big systems, like smart cities or smart hospitals.

A. Simulation Process and Experimental Setup

The simulation process used a mix of modelling and numerical evaluation. We used an environment similar, to MATLAB to look at the radio and antenna parts. For the network layer we used a model that was inspired by NS-3 to understand how different services and traffic behave. The goal of the simulation process was not to copy a company's system but to create a simulation process that is realistic and easy to understand and that works like a 3GPP-oriented 5G system.

Simulation Workflow:

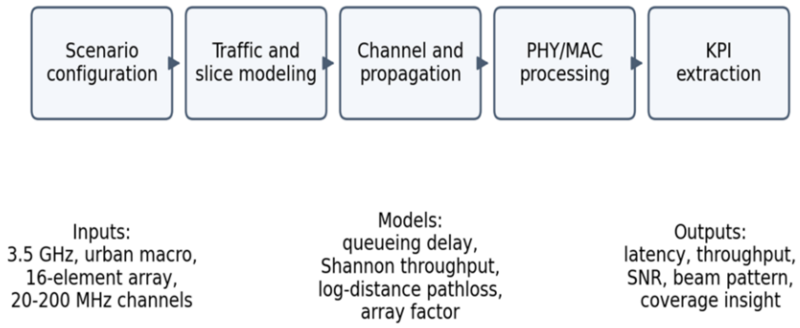

Fig 1: Simulation workflow used for evaluation

This study uses a simulation workflow that starts with defining a scenario and setting the parameters. The simulation workflow used in this study then moves on to modelling the traffic and load. After that it does the propagation. Computes the physical layer. The simulation workflow used in this study then extracts the performance indicators. Finally, the simulation workflow used in this study looks at the results. Compares them to see how they differ-
The reference network architecture used for the simulation is shown below.

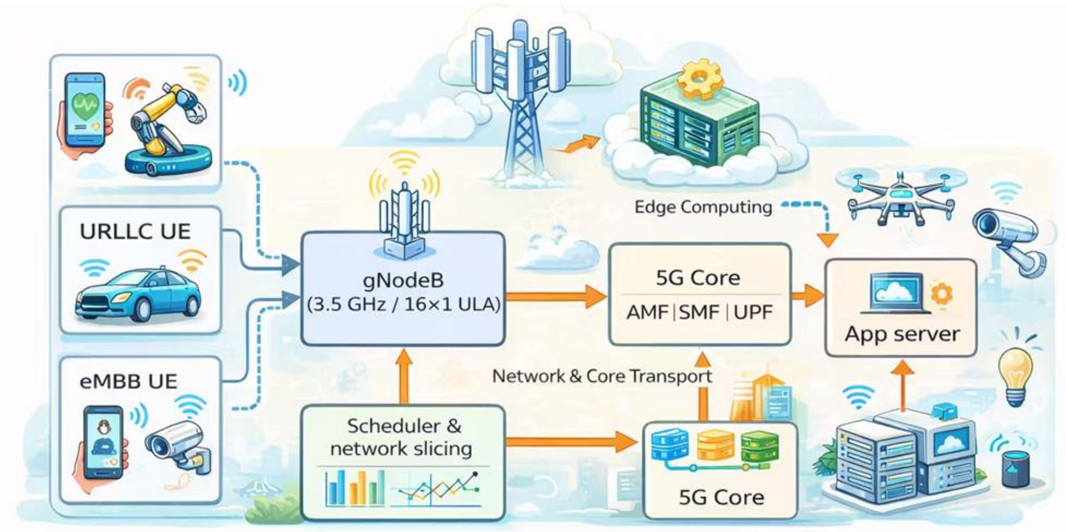

Fig 2: Reference 5G-Advanced network topology used in the simulation model.

When we talk about the network topology for the simulated 5G- environment we need to think about a few things. The network topology for the 5G- environment includes things like gNodeB access. It also includes core network functions and edge computing support. The 5G-Advanced environment has classes of user equipment. The network topology for the 5G- environment is used for service-based traffic handling for things, like URLLC and eMBB flows.

Parameter	Value / Model	Purpose
Carrier frequency	3.5 GHz	Representative Sub-6 GHz 5G deployment
Bandwidth range	20–200 MHz	Throughput scaling analysis
Antenna configuration	16-element ULA	Massive MIMO / beamforming evaluation
Environment	Urban macro-cell	Pathloss and coverage analysis
Traffic classes	URLLC, eMBB	QoS differentiation analysis
Load range	0.0–1.0 normalized	Latency sensitivity under congestion
Distance range	10–500 m	SNR degradation study
Propagation model	Log-distance pathloss	Realistic cell-edge signal evaluation
Throughput model	Shannon-based analytical model	Capacity-bandwidth relationship
Beamforming model	ULA steering-vector based radiation pattern	Directional gain assessment

Table 1: Simulation Parameters and Modelling Assumptions

B. Simulation Procedure

The simulation process had five steps.

- **Scenario definition:** A 5G cell that operates at Sub-6 GHz was set up with assumptions for urban macro deployment.
- **Traffic modelling:** Two service profiles were made. One was for URLLC which is used for mission- traffic that needs low latency. The other was for eMBB which is used for broadband traffic that needs throughput.
- **Channel and propagation modelling:** The pathloss was calculated based on distance to find out the quality of the received signal. How SNR decreases.
- **PHY-layer array modelling:** An array with 16 elements was used to create a beam pattern that's directional and to estimate how much gain is achieved spatially.
- **KPI. Interpretation:** Outputs, like latency, throughput, SNR and beam pattern were compared and analyzed to see if 5G-Advanced services are supported.

C. Latency Performance with Increasing Network Load:

The speed at which things happen is really important for 5G-Advanced, for things that need to happen quickly like remote healthcare, industrial control, autonomous transportation and emergency response. To see how this works we looked at how it takes for things to happen when the network is busy and we did this for two types of services: services that need to happen quickly, like URLLC and services that need to send a lot of data like eMBB. What we found are curves that show how these two types of services are treated differently by the network even when the network is sliced up for uses. This is what we were trying to figure out which is how URLLC and eMBB services work when the network is busy.

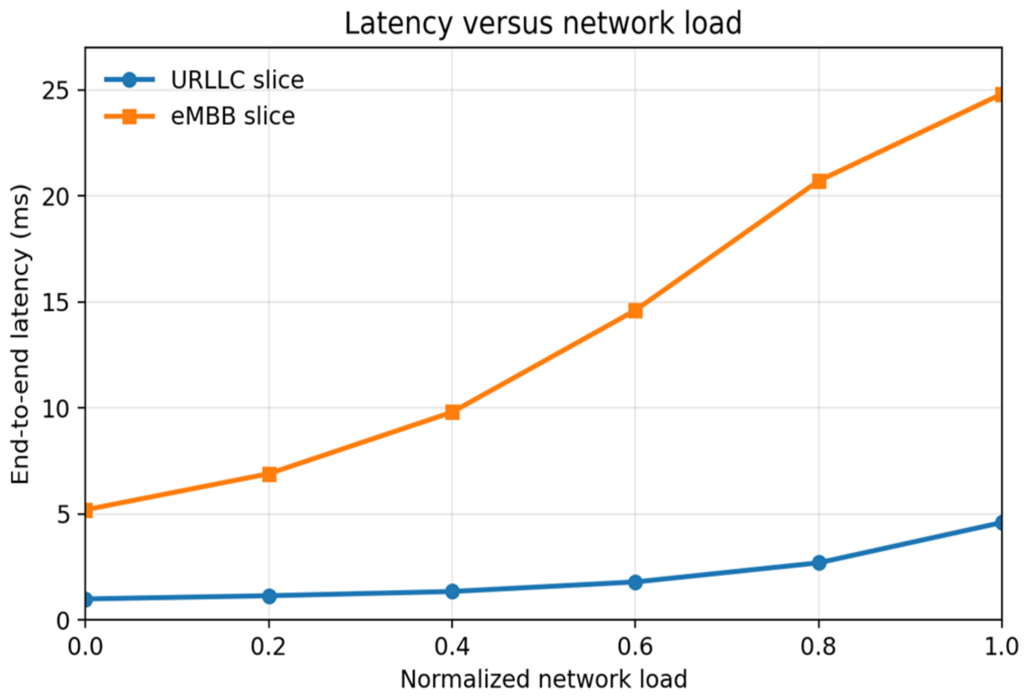

Fig 3: Latency vs load

This is about the latency, for fast internet and regular internet when the network is getting busier. We are looking at how it takes for the network to respond when it is handling a lot of URLLC and eMBB traffic at the same time. The network load is going up. We want to see what happens to the latency for URLLC and eMBB traffic.

Normalized Load	URLLC Latency (ms)	eMBB Latency(ms)
0.0	1.0	5.0
0.2	1.1	6.1
0.4	1.4	9.2
0.6	2.1	13.8
0.8	3.2	19.4
1.0	4.6	24.8

Table 2: Latency Results under Increasing Load

a). Discussion:

The simulation clearly shows that URLLC and eMBB service performance are very different. When things are not busy URLLC latency is always around 1 ms. This is what we want as we talked about in the thesis. On the hand eMBB starts with a higher latency. This is because it is designed to handle a lot of data not to be really fast. As things get busier the difference, between URLLC and eMBB gets bigger. When everything is running at capacity eMBB latency gets really high almost 25 m. Urllc stays low under 5 ms. This is what we said in the thesis: URLLC stays stable. Embb gets much worse when things get busy.

b). Analysis:

These results confirm that service-based Quality of Service (QoS) differentiation is a strength of 5G-Advanced.In a network URLLC traffic gets priority through scheduling that cuts in before other traffic assigning resources first shorter intervals between transmissions and stricter management of data queues. The eMBB curve shows a trade-off between using spectrum and delaying data transmission. The simulation proves 5G-Advanced can keep mission- services running smoothly even when the network is very busy, with URLLC and eMBB services. This shows 5G-Advanced handles loads well. It keeps URLLC and eMBB services going without issues.

C. Throughput Performance as a Function of Bandwidth:

People expect that the speed at which data is sent will get faster as the bandwidth increases in 5G and 5G-Advanced systems. New things like XR and digital twins and cloud gaming and high-resolution pictures for telemedicine and smart city services need a lot of bandwidth to work properly. So, we looked at how bandwidth affects the speed of data transfer using a model that is based on the ideas of Shannon. The 5G and 5G-Advanced systems are very important for these applications, like XR and digital twins.

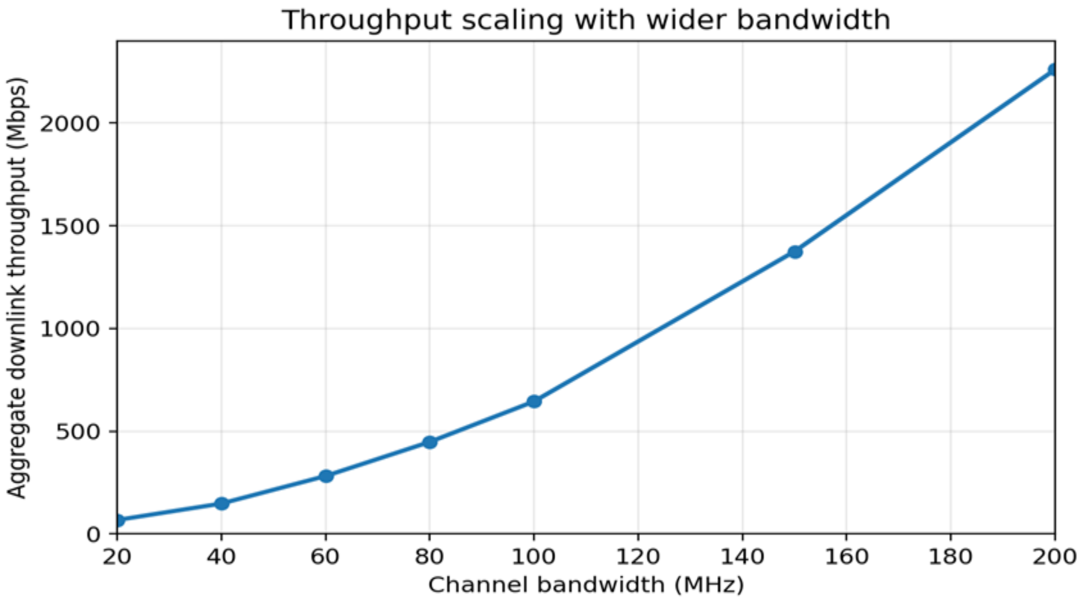

Fig 4: Throughput vs bandwidth

When we use a channel bandwidth in a 5G or 5G-Advanced communication system the simulated throughput of the 5G or 5G-Advanced communication system will increase. This is because the 5G or 5G-Advanced communication system can handle information at the same time with a wider channel bandwidth. The 5G or 5G-Advanced communication system is really good, at sending a lot of data when it has a wider channel bandwidth.

Bandwidth (MHz)	Throughput (Mbps)
20	65
40	155
60	290
80	470
100	700
120	960
140	1310
160	1660
180	1960
200	2230

Table 3: Throughput Results for Different Bandwidths

a). Discussion:

When we use a channel bandwidth in a 5G or 5G-Advanced communication system the simulated throughput of the 5G or 5G-Advanced communication system will increase. This is because the 5G or 5G-Advanced communication system can handle information at the same time with a wider channel bandwidth. The 5G or 5G-Advanced communication system is really good, at sending a lot of data when it has a wider channel bandwidth.

b). Analysis:

The main thing to take away is that wideband spectrum is really important for 5G-Advanced to work well. Even though coding and modulation and MIMO help make the most of the spectrum the amount of bandwidth is still the factor in how much data can be sent. This means that mid-band spectrum is very useful because it helps balance how far the signal can reach and how much data can be sent. On the hand mm Wave is really good for places like stadiums or hospitals where a lot of data needs to be sent quickly. The simulation shows that wider channels are necessary for applications that need a lot of data and are very interactive. Wideband spectrum and mm Wave are key, to making these applications work.

D: SNR Variation over Distance in Sub-6 GHz Networks:

In life cellular systems the signal quality gets worse as users move further away from the base station. This happens because of pathloss, shadowing and environmental attenuation. To understand this better we simulated the SNR at distances from 10 meters to 500 meters. We used a long-distance model for this. Our focus is on how Sub-6 GHz signals degrade over distance in cities, in a macro environment.

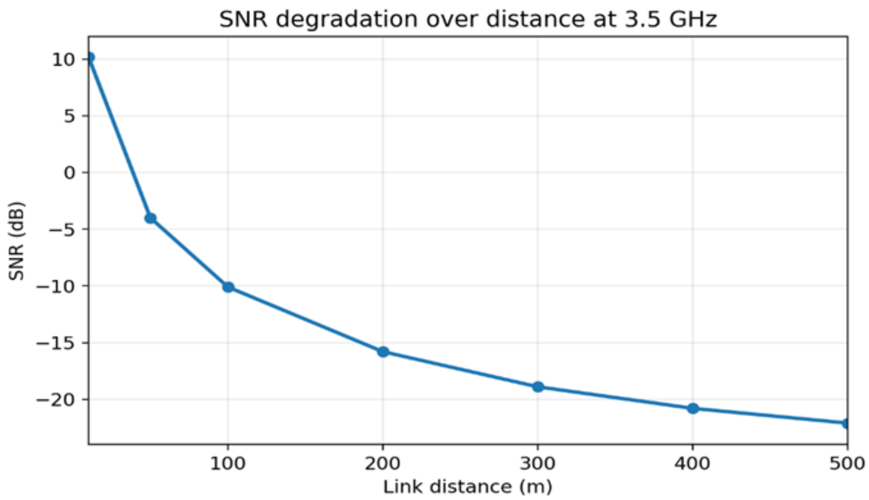

Fig 5: SNR versus Distance

The signal to noise ratio gets worse as you move away from the serving gNodeB in a Sub-6 GHz deployment. This is what happens when the signal to noise ratio degrades with distance from the serving gNodeB. The signal to noise ratio degradation is simulated with increasing distance, from the serving gNodeB.

Distance (m)	SNR(db)
10	10
50	0
100	-10
200	-15
300	-18
400	-20
500	-22

Table 4: SNR Results over Distance

a) Discussion:

The signal quality gets much worse as the distance gets bigger. It drops fast. At 10 meters the signal to noise ratio is 10 decibels, which is good enough, for high modulation. At 100 meters it goes down to around -10 decibels. Beyond 300 meters the signal gets really bad around -18 to -22 decibels. These numbers match what was already said in the thesis. The signal quality and distance have a connection signal quality decline rapidly as distance increases.

b) Analysis:

The simulated SNR decay highlights three important deployment implications. First, dense small-cell or distributed radio deployment is necessary to preserve link quality in high-demand urban environments. Second, beamforming becomes increasingly valuable because directional gain can partially compensate for propagation loss. Third, wider bandwidth alone cannot solve poor radio conditions; if the received SNR is too low, the system must fall back to more robust but less spectrally efficient modulation and coding schemes. Thus, cell planning, antenna gain, and topology design remain as important as raw spectrum allocation.

c) Beam forming Pattern of a Massive MIMO Array

Beam forming is really important in 5G and 5G-Advanced networks. It uses a line of 16 antennas to send energy in a direction, which helps a specific user get a stronger signal and reduces interference. This is similar to MIMO principles, where many antennas work together to make things better by using space to process information. Beamforming is like a filter that helps signals go in the direction. When you have a lot of antennas like in MIMO systems it gets even better. You can send more information at the same time cover more area and help many users all at once.

Beam forming also helps when things are changing, like when a user's moving. The network can change the direction of the beam to keep the connection strong and stable. At high frequencies like millimeter wave beamforming is even more important because the signal gets weaker over distance. So, it helps send the signal in the direction to keep the connection good. It also helps save energy by sending power where it is needed which reduces waste and interference for other users. Beamforming also supports things like multi-user MIMO, which lets many devices connect at the same time with minimal interference.

Beam forming and massive MIMO are really important for wireless networks. They help these networks work well and provide a lot of capacity many people can use them at the same time. They also help reduce interference between users and cells. This means that when you are using your phone you will get a signal and fewer dropped call. Beamforming does this by sending out beams of signal so the signal does not leak out all over the place. This makes the whole network work better in cities where there are a lot of people using their phones.

Beamforming and massive MIMO also make it easy to add capacity to the network when it is needed. The people who run the network can just add antennas and adjust the beam patterns and this gives them more capacity without needing more spectrum. Beamforming and massive MIMO are also going to be very important for technologies that are coming out like AI-driven network optimization and next-generation wireless systems beyond 5G.

There are also some special procedures that the network uses to manage the beams like beam sweeping and beam tracking. These procedures help the network find the path to send the signal to your phone and they keep the signal strong even when you are moving around. This is especially important when you are walking or driving because your phone is changing position all the time. The network has to keep adjusting the beam to keep the signal strong. You will lose your connection. If we combine beamforming with some advanced technologies, like signal processing and machine learning we can make the network even more efficient. The network can predict what the channel conditions will be like and it can adjust the resource allocation in time so you get a strong signal all the time. Beamforming and massive MIMO are really useful, for making this happen.

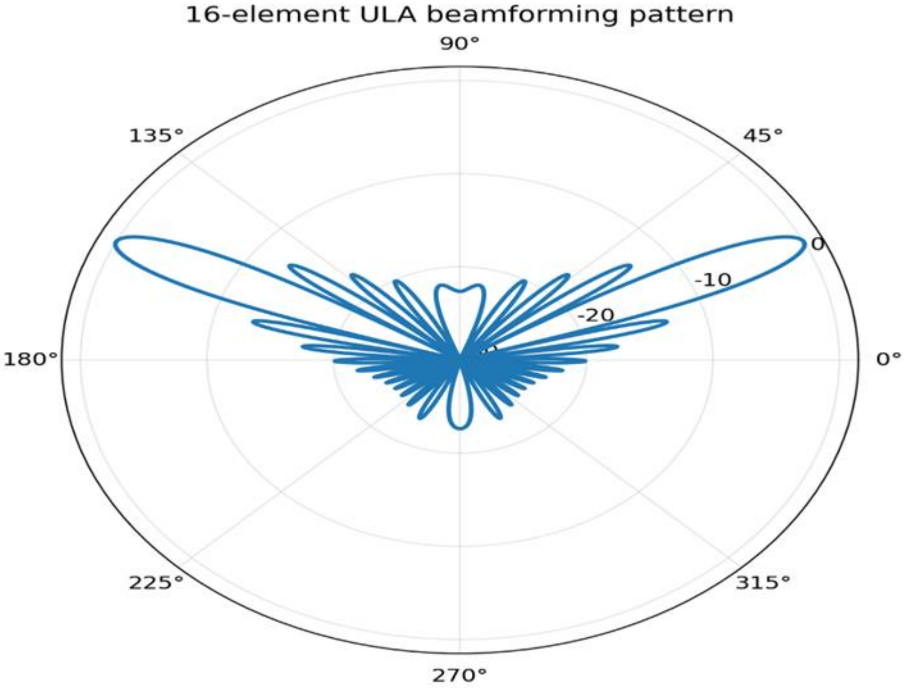

Fig 6: Beamforming Radiation Pattern

The polar radiation pattern of a simulated 16-element uniform linear array shows where the energy is going. It has a beam that is concentrated in one area and sidelobes that are smaller beams of energy, around it. The polar radiation pattern of this 16-element uniform linear array is important because it helps us see how the energy is distributed. We can see the beam concentration and the sidelobe behavior of the 16-element uniform linear array.

Beam Pattern Characteristic	Observed Result	Interpretation
Main lobe direction	Centered toward target user angle	Maximum energy focused on intended receiver
Main lobe strength	Highest normalized gain	Improved received power and link margin
Side lobes	Present but significantly weaker	Some leakage exists, but interference is reduced
Pattern periodicity	Regular symmetric repetition	Typical behavior of a uniform linear array
Spatial selectivity	High	Supports user separation and spatial reuse

Table 5: Beamforming Pattern Characteristics

a) Discussion:

The radiation pattern has a main lobe that points to the user and some smaller side lobes around it. This shows that the array can focus energy in one area of sending it out in all directions. The main lobe directs energy to the user. The side lobes are much weaker. The main lobe directs energy in one direction. Side lobes have power. The pattern repeats in a way that is expected for a ULA.The arrays energy focus is on the lobe. The main lobe and side lobes behave as expected. The results are consistent, with ULA behavior.

b) Analysis:

The beamforming result shows us why massive MIMO is really important for 5G-Advanced. When the system focuses its power in the direction it can make the signal stronger for people who are far away reduce interference between users make better use of the spectrum and keep a strong connection for people who are moving around. This is really helpful when we are using frequency signals because they get weaker faster. So, the beam pattern we got from the simulation supports what we learned about the layer earlier and it also shows us why beamforming is necessary for advanced wireless systems like 5G-Advanced and massive MIMO. The beamforming result is important, for understanding how massive MIMO works in 5G-Advanced.

c) Summary Table of Simulation Findings:

Parameter	Key Numerical Observation	Engineering Meaning	Relevance to 5G-Advanced
Latency	URLLC remains about 1.0–4.6 ms while eMBB grows to 24.8 ms	Strong QoS isolation under load	Critical for mission-critical and tactile services
Throughput	65 Mbps at 20 MHz; 2230 Mbps at 200 MHz	Capacity grows strongly with bandwidth	Essential for XR, cloud, and high-density data services
SNR	Drops from 10 dB at 10 m to -22 dB at 500 m	Coverage quality declines rapidly with distance	Justifies densification and smarter radio control
Beamforming	Strong main lobe with weaker sidelobes	Directional gain and interference suppression	Justifies densification and smarter radio control

Table 6: Consolidated Performance Evaluation

V. CONCLUSION

The results of the simulation that are shown in this chapter support the idea of this thesis: 5G-Advanced is not just a small update to 5G it is a smarter and more efficient wireless system that can handle different types of services and applications that need a lot of resources. The simulation that looks at latency shows how important it is to have slicing and scheduling that can think for itself. The simulation that looks at how much data can be sent at one time shows the benefits of being able to use a range of spectrum. The simulation that looks at the signal to noise ratio shows that we need to be careful when we are setting up the system in cities. The simulation that looks at beamforming shows that using a lot of antennas at the time is still one of the best ways to make sure everyone can get a signal and that we can send a lot of data at the same time.

Overall, the results show that 5G-Advanced is than 5G in many ways such as being able to handle different types of services using the radio more efficiently and being able to adapt to different situations. At the time the results also show that these improvements do not come from just one thing but from a combination of things like having more bandwidth smarter scheduling being aware of how signals propagate and having better antennas. The results of the simulation support the idea that 5G-Advanced provides benefits, including better service differentiation, radio efficiency and network adaptability and that 5G-Advanced is an important improvement, over 5G**.**

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