IOSUD - Universitatea Politehnica Timişoa
Şcoala Doctorală de Studii Inginereşti

Enhancement of 5G Systems using Massive MIMO and Beamforming technologies

PhD Thesis – Summary

for obtaining the scientific title of doctor at
Universitatea Politehnica Timișoara
in doctoral domain of Electronics, Telecommunications, and Information Technology engineering

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month 07. year 2026

This thesis addresses the growing gap between the bandwidth demands of modern wireless applications — ultra-high-definition streaming, cloud computing, AR/VR, and IoT — and the capacity limits of traditional sub-6 GHz communication systems. It argues that the millimeter-wave (mmWave) spectrum, with its substantially larger available bandwidth, is essential for supporting multi-gigabit 5G data rates, but that exploiting it requires advanced antenna technologies and signal processing to counteract mmWave's inherent propagation weaknesses: higher free-space path loss, poor penetration, and high sensitivity to physical obstructions.

The main objective of this PhD thesis is to analyze and improve the performance of 5G systems using Massive MIMO and beamforming technologies, while also investigating operational aspects relevant to network design and deployment. The research focuses on the relationship between antenna configurations, channel conditions, beamforming techniques, system capacity, inter-cell interference, and data traffic behavior at the transport layer.

The thesis is structured in four main research directions. The first direction presents the analysis of the fundamental 5G technologies, with an emphasis on MIMO, Massive MIMO, and Beamforming. The second direction focuses on experimental and simulation-based evaluation of 5G systems, including comparisons between Open-Loop MIMO and Closed-Loop MIMO solutions. The third direction is on the Beamforming techniques, Beam Management, and Synchronization Signal Block (SSB) analysis. The fourth direction is optimization in 5G networks, providing interference management, link budget, and congestion control at the transport layer.

1. INTRODUCTION

The thesis opens by tracing the evolution of 5G networks against the backdrop of relentless traffic growth. It identifies the specific service categories placing pressure on wireless infrastructure and explains why sub-6 GHz spectrum alone can no longer meet demand. This motivates the shift toward mmWave spectrum as the core enabler of multi-gigabit throughput. With the increasing demand for modern wireless communications, the mobile networks have been improved to enhance Quality of Service (QoS) and manage the radio resources efficiently [1].

MIMO (Multiple-Input Multiple-Output) is an important technology widely used in current wireless systems. MIMO uses multiple antennas at both the transmitter and receiver sides to enhance spectrum utilization, reliability, and data rates.

Massive MIMO was one of the more sophisticated solutions. This was created in response to the growing number of connected users. Massive MIMO, a key technology of 5G and future wireless networks, uses many antennas at the base station to significantly increase network capacity, coverage, and spectral efficiency. Moreover, the beamforming technique, which directs the radio signals to the user equipment (UE) instead of broadcasting the energy in all directions, can also further improve the system performance. This leads to better signal quality, less interference, and higher overall network efficiency. Beam management is responsible for controlling and keeping communication beams to provide effective coverage to users in different locations and mobility situations. Due to the constantly changing network conditions and user behavior, beam management strategies should be dynamically adapted to ensure a stable and reliable connection [2].

Optimization is a major contributor to the overall performance of 5G networks, ensuring the efficient utilization of available radio and network resources. Key optimization events include link budget analysis to estimate signal propagation properties and coverage performance, interference management to minimize performance degradation due to adjacent cells and simultaneous transmissions, as well as transport layer congestion control mechanisms to guarantee stable data flows under different traffic conditions. Other important optimization techniques are radio resource management, power allocation, load balancing, and scheduling algorithms. The combination of both techniques enables 5G networks to achieve high throughput, low latency, high spectral efficiency, and reliable service delivery in both dense urban environments and large-scale deployment scenarios. mmWave offers abundant bandwidth, but its propagation characteristics — high path loss, weak penetration, obstruction sensitivity — mean that raw spectrum alone is not enough. Spectral efficiency and network capacity must be improved through smarter antenna and signal-processing techniques, setting up Beamforming and Massive MIMO as the technologies under investigation [3].

2. KEY TECHNOLOGIES FOR 5G AND BEYOND

This chapter lays the theoretical groundwork. Multiple-Input Multiple-Output is a widely adopted technology to increase the spectral efficiency and the overall system capacity. MIMO systems use multiple antennas at the transmitter and receiver to transmit multiple data streams at the same time, thereby increasing data rates without the need for additional spectrum. MIMO beamforming is a popular research topic for spectrum reuse and quality preservation.

In practice, three MIMO configurations are worth differentiating. Today, most Wi-Fi routers and LTE user equipment are configured as 2×2 systems, with two transmitting antennas and two receiving antennas. The 4x4 configuration offers significant increases in spectral efficiency and is becoming more common in 5G deployments, where hardware costs still constrain the number of antennas a device can support.

Massive MIMO is a different technology with tens to hundreds of antennas aggregated at the base station. The fundamental principle is common to all three configurations. The antenna array generates a matrix of independent channels in space that can operate simultaneously within the same frequency band. Instead of sending power in one direction, power is shared among the array, improving efficiency and avoiding the risk of overloading a single path. This is basically spatial multiplexing in a simple case of just two users. Two separate data streams, both sent at the same time, and one user does not take away bandwidth from the other [4].

Beamforming is defined as a signal-processing technique that steers electromagnetic wave transmission or reception toward specific spatial directions by adjusting the amplitude and phase of signals across multiple antenna elements. Rather than radiating uniformly, it concentrates power toward the intended user, improving signal strength while suppressing interference toward other users and neighboring cells.

Beamforming and MIMO go together because a multitude of antennas are needed to perform beamforming. The number of antennas present in the network can greatly influence the quality of the beam used by the Base Transceiver Station (BTS) to communicate with User Equipment. More antennas mean a tighter beam, which means less power is needed to send data, and less interference with nearby radio signals. Beamforming also improves radio-resource utilization by enabling multiple users to be served simultaneously through spatial separation [5]. Beamforming techniques can be categorized based on various criteria such as weight vector application, signal bandwidth, channel estimation, or signal domain. Table 1 provides a brief description of different types of beamforming [6].

Table 1: An outlook on beamforming techniques [5].

Criterion	**Beamforming types**	
Weight vector	Fixed Beamforming	Adaptive Beamforming
Location	Transmit Beamforming	Receive Beamforming
Signal Bandwidth	Narrowband Beamforming	Wideband Beamforming
Channel Estimation	Implicit Beamforming	Explicit Beamforming
Signal Domain	Frequency/Transform Domain Beamforming	Space-time Beamforming
		Analog / Digital

The Grid of Beams (GoB) method is a common beam management scheme in 5G systems. Instead of computing the optimum beamforming weights at each time instance based on the instantaneous channel conditions, the angular coverage area is divided into a fixed set of directional beams that cover the entire service area. Each beam is generated using a pre-determined beamforming vector from a codebook, with each vector corresponding to a specific steering direction. The User Equipment, when working inside the network, tests the quality of the available beams and reports the associated performance metrics like Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), and Signal-to-Interference-plus-Noise Ratio (SINR). The network uses these measurements to select the beam with the best communications conditions and updates this selection continuously to adapt to the mobility of users and variations of the radio environment [7].

Network slicing is a critical component of the next generation of wireless systems. Network slicing allows the creation of multiple virtual networks on a common physical infrastructure, each of which is customized to meet the requirements of a particular application. So, resource allocation strategies should be more flexible to satisfy the different and sometimes even conflicting

requirements of these services. Energy-aware scheduling methodologies that can dynamically balance throughput, latency, and power efficiency, considering the network conditions, are expected to be incorporated in future resource allocation frameworks. These new concepts enable the evolution from 5G to 6G and promote intelligent, adaptive, sustainable, and high-performance networks.

This chapter summarizes the main principles, architecture, and practical implementations of MIMO and beamforming technologies. These technologies are essential in 5G networks and will remain important in future 6G systems, where higher data rates, better spectral efficiency, wider coverage, and improved reliability are required [8].

3. Experimental Measurements in 5G MIMO Systems

This chapter examines how Massive MIMO and beamforming jointly drive throughput and spectral efficiency gains in 5G communication systems. Simulation results combined with practical experiments show that scaling up the antenna array—from smaller 4×4 configurations to large-scale 64×64 arrays—yields substantial improvements in both data rates and network reliability. A comparative study of Open-Loop (OL) and Closed-Loop (CL) MIMO transmission techniques is presented. The impact of antenna scaling on overall network performance was investigated across three MIMO configurations—4×4, 16×16, and 64×64. Among these, the 64×64 MIMO configuration demonstrates the greatest spatial diversity. Leveraging multiple antennas allows the system to better exploit multipath propagation, resulting in improved link reliability and higher data rates. Compared to the 4×4 and 16×16 systems, the 64×64 configuration delivers superior capacity and performance in congested wireless environments where numerous users contend for limited radio resources.

These findings reinforce the benefits of large-scale MIMO, particularly for applications demanding high capacity, reliability, and spectral efficiency. However, several practical implementation challenges must be considered, including channel estimation errors, hardware constraints, increased signal-processing complexity, and higher deployment costs. As a result, while high-dimensional MIMO systems such as 64×64 offer substantial performance gains, these benefits may be constrained in real-world deployments unless such technical challenges are adequately addressed [9].

Beamforming performance can be assessed using the Massive MIMO Channel System. The simulator's primary goal is to improve signal precision and reliability by replicating the localization and monitoring of user equipment. By mirroring UE location, tracking, power fluctuations, and other characteristics within a MIMO testing environment, this equipment aims to boost throughput in both uplink and downlink directions while simultaneously enhancing signal quality and robustness. The Air Interface MIMO simulator supports up to 64 channels and 16 streams, with Radio Units' (RUs) outputs connected to the device's inputs, and the device's outputs linked to the UEs. The device functions as a comprehensive matrix system for amplitude and phase channel control, enabling the positioning and allocation of user equipment to specific beams and thereby creating a flexible testing environment. Because uplink and downlink signals are handled independently, the setup provides a realistic simulation of an Over-the-Air (OTA) test.

Pairing theoretical evaluation with practical testing on the Massive MIMO Channel System (MCS) device is used to validate theoretical throughput results under realistic operating conditions. The findings reveal a strong synergy between beamforming and MIMO: by focusing signal energy on specific users, beamforming reduces interference and boosts overall spectral efficiency.

Practical measurements were carried out using MCS equipment, which functions as a conducting far-field chamber, to determine throughput performance in a 5G system and to tune beam directions for optimal throughput. Two distinct scenarios were evaluated:
Scenario 1: Single-Cell Throughput Validation for 1×UE.
Scenario 2: Simultaneous Multi-User Traffic Validation for 4×UEs.

In Scenario 1, the emphasis is on achieving a measured throughput as close as possible to the theoretical maximum for a single UE within a single-cell environment. The configuration under test targets a 5G DL throughput of 726 Mbps. The tested design has a 40 MHz channel bandwidth and a carrier frequency of 3.6 GHz. It employs Time Division Duplex as the deployment method for efficient frequency use and 256QAM modulation

Hardware setup is presented in Figure 1. The MCS is connected to a radio unit operating in 8×4 Closed Loop MIMO mode, with the equipment serving as an extension to the conventional radio module by linking the Radio Units to the UEs. UE placement on a given beam is achieved by configuring static beam-scanning parameters in the MCS menu, namely element vertical spacing, horizontal/vertical beam MCS coordinates, and beam angle.

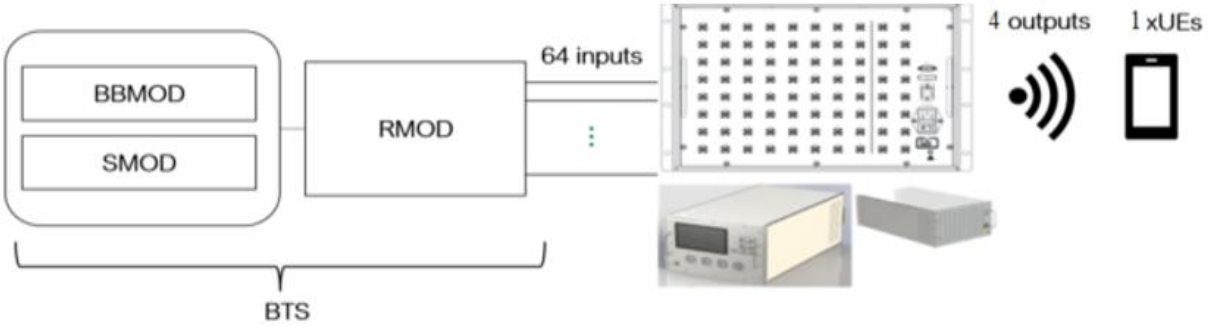


Figure 1: Testing environment- Scenario 1 [10].

Practical measurements achieved 695 Mbps, demonstrating that the MCS can successfully recreate optimal radio conditions and reach performance levels close to theoretical targets. The objective was to reach a theoretical throughput of 726 Mbps, and the measured value came in at approximately 695 Mbps. Testing was conducted in a single-cell scenario. In addition, the Air Interface MIMO simulator allows beam orientations to be monitored and configured, enabling precise adjustments that help achieve optimal radio conditions and drive real-time throughput as close to theoretical limits as feasible.

Scenario 2 examines the impact of increasing the number of antennas, using simultaneous Multi-User Traffic Validation with 4xUEs. A 32T32R antenna configuration is employed, using 16 outputs from the simulator to serve all four mobiles simultaneously. The equipment was directly connected to the antennas of a specific Massive MIMO Radio Module. With a capacity of 64 channels and 16 streams, the equipment is integrated with a conventional radio module by connecting the radio units' output ports to the MCS inputs; the equipment's outputs are then connected to the UE terminals. To prevent interference, the UEs are distributed across different horizontal coordinates while sharing the same vertical axis. Figure 2 shows the testing environment used for Scenario 2.

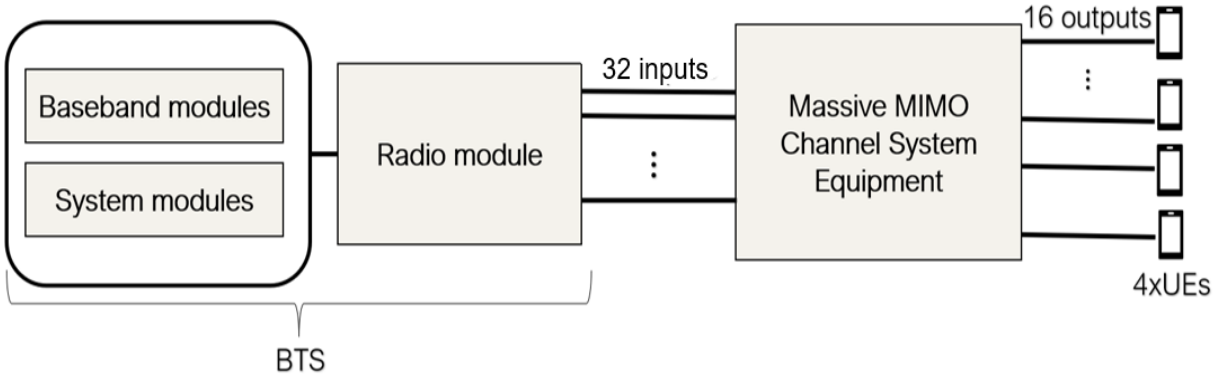


Figure 2: Testing environment using MCS equipment- Scenario 2 [11].

The system achieved a total cell traffic of 4.077 Gbps, with mobile devices paired to enable simultaneous data transmission and reception. The use of 16 antennas allowed traffic to be allocated separately to each UE—for instance, UE1 reached 1.32 Gbps while UE4 reached 0.865 Gbps—confirming that Massive MIMO can deliver high-speed individual traffic to multiple concurrent users within the same cell. Scenario 2 illustrates the benefits achievable through simultaneous testing with a 16DL8UL strategy, demonstrating that four UEs can operate within a single 5G cell, each experiencing a distinct level of traffic.

In conclusion, this chapter serves as a comprehensive validation of the significance of Massive MIMO and Beamforming in the development of 5G technology. Progressing from antenna-scaling simulations to multi-user throughput testing in an experimental setting, the findings confirm that large-scale antenna arrays combined with beamforming are essential to meeting 5G's demands—ensuring the network retains sufficient capacity for emerging services while preserving connection reliability.

4. BEAMFORMING TECHNIQUES: BEAM MANAGEMENT AND SSBS ANALYSIS

Beamforming is an advanced signal processing technique to create antenna radiation patterns to steer the signals towards specific terminals while reducing interference, increasing the received signal power at each user, and reducing interference from other users to improve the total capacity. It improves system performance by increasing energy efficiency, security, mmWave, SNR, spatial filtering, multi-user capability, and directional transmission, which is achieved by applying the computed weights to the individual antenna elements, generally by digital signal processing (DSP) algorithms, which estimate the Direction of Arrival. This method is essential for frequencies above 6 GHz and is also applicable to the sub-6 GHz bands.

Beam management and the role of synchronization signal blocks in different deployment scenarios are covered in this chapter. It shows how the higher spectral efficiency, signal performance, coverage, and capacity of beamforming are essential to enable 5G services such as eMBB, URLLC, and mMTC [5].

Beam Management (BM) plays an essential role in the operation of 5G NR technology. The Layer 1 and Layer 2 processes are responsible for setting up and maintaining optimum beam-pair links between the gNodeB and the User Equipment. Beam management in 5G NR networks, especially in millimeter-wave deployments, requires a significant amount of signaling overhead from beam measurements, feedback, and coordination. This UL beam reporting accounts for about

15% of this overhead, which is increased with denser deployment of the antenna array and the larger size of the beam codebook. Beam management consists of five operations upon Initial beam establishment (IBE): beam sweeping, measurement, determination, reporting, and recovery, as shown in Figure 3.

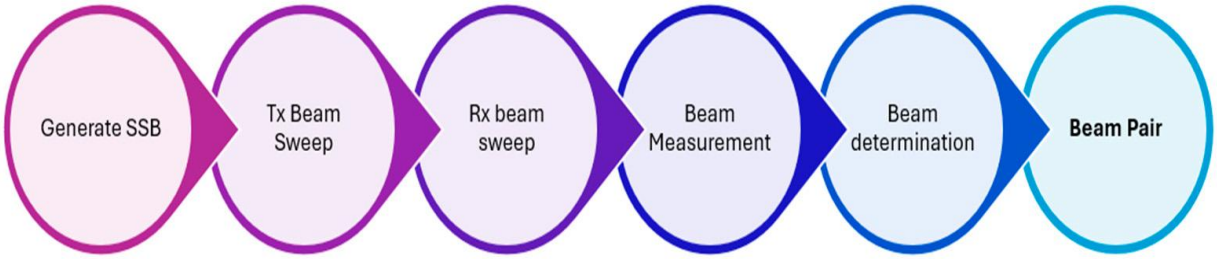


Figure 3: Architecture of the Beam management process [5].

The spectrogram analysis of synchronization signal blocks in both FR1 and FR2 environments shows that 5G's flexible time-frequency structure allows a larger number of transmitted SSBs, combined with higher subcarrier spacing, to achieve greater spectrum utilization and denser temporal SSB distribution—enabling faster beam sweeping and more effective synchronization. The simulation results show a direct proportional relationship between beam directivity and signal strength: narrower beams improve RSRP and spatial selectivity, while wider beams ensure easier access and coverage acquisition. An optimal balance between beam directivity, beamforming gain, and synchronization overhead is therefore needed for the best system performance. Moreover, SSBs improve spatial coverage and beam selection but increase signaling overhead [12].

Overall, optimizing SSBs, beam sweeping, and beam selection helps streamline the access procedure by reducing access delay, improving cell discovery, and increasing reliability in dense urban areas.

5. Optimization in 5G Network Operations

This chapter focuses on two critical aspects of 5G network optimization: interference and link budget analysis, and Transport Layer congestion control mechanisms based on specific traffic models. To support performance assessment through simulation, key parameters are defined to distinguish uplink and downlink requirements in both single-cell and multi-cell scenarios. The five main performance parameters considered are: physical resource blocks, user throughput, cell throughput, cell-edge user throughput, and latency.

The interference margin in a 5G network design is a scientifically estimated safety margin in the link budgeting process. The analysis of the link budget shows that the interference margin is an important parameter in the evaluation of the link budget, since it decreases the co-channel interference considerably. The methodology calculates the geometrical distribution factor under the assumption that all base stations transmit with the same power. The simulations carried out with a massive MIMO system with 64 transmitting antennas and 1xUE at 3.6 GHz demonstrated

the significant effect of the interference margin on the resulting SINR, highlighting the importance of this in creating a reliable and efficient 5G infrastructure [13].

The Transmission Control Protocol (TCP) is essential for ensuring reliable end-to-end data delivery, engineered to support data rates of up to 400 Gbps. The analysis of TCP performance in 5G environments explores how various congestion management techniques affect network behavior, particularly under high-speed, high-density traffic conditions. Transport-layer congestion performance in 5G networks is assessed through File Transfer Protocol (FTP) traffic, comparing FTP with and without the TCP slow-start mechanism using performance indicators such as user and cell throughput, Round-Trip Time (RTT), latency, and PRB utilization across two distinct scenarios [14].

Congestion control in 5G networks can be done on different layers of the protocol stack. Network-layer solutions are used to manage traffic, but traditional congestion control is performed at the transport layer using TCP to ensure reliable end-to-end data delivery. Heterogeneous services, wide connectivity, and highly dynamic traffic patterns can quickly lead to congestion scenarios. This is especially true of the need for effective congestion control at the transport layer.

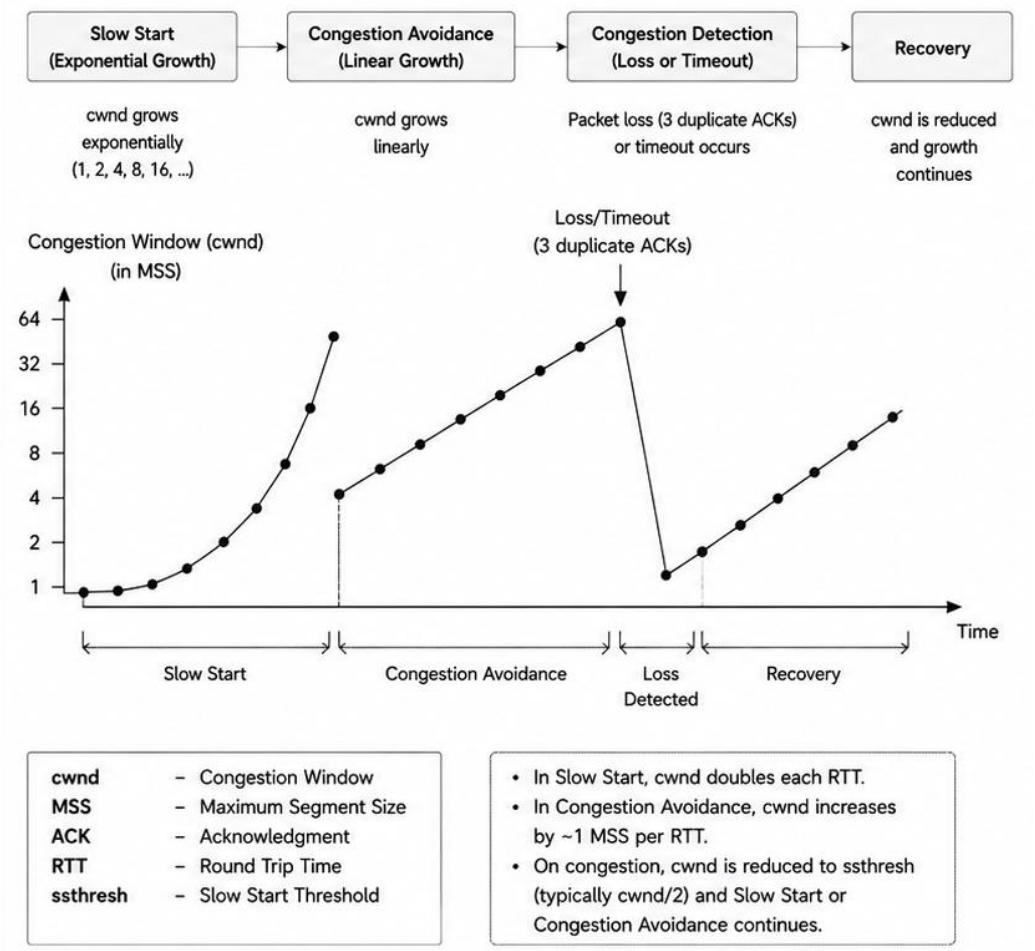


Figure 4: Congestion window.

The results of the simulation clarify the performance of TCP over 5G networks, in the case of congestion in uplink and downlink transmissions. In this study, the performance metrics considered are cell throughput, cell user throughput, latency, PRB utilization, and uplink data volume. The results show that a typical cell edge user can support 5 Mbps throughput in the uplink scenario with 23-30% PRB utilization depending on certain system parameters.

Transmission delay is low up to 85-95% PRB utilization and increases drastically thereafter. This is where the TCP slow start algorithm comes into play. This greatly reduces latency. This is because the data is split into smaller chunks that can be sent faster than larger 500 kB packets that would require multiple slots. The downlink data volume is kept between 80% and 90% of the PRB utilization with maximum throughputs of 1.2 Gbps in a single cell scenario and 800 Mbps in a multi-cell scenario. The maximum latency was 45ms for the single cell and 55ms for the multicell scenario for cell-edge users. The cell edge throughput was 20 Mbps [15].

6. Conclusions and Contributions

This thesis investigates the application of Massive MIMO, Beamforming, and Beam Management techniques for the improvement of the efficiency of 5G systems by theoretical analysis, simulations, measurements of parameters, network planning, and transport layer optimization.

The first contribution is a theoretical study of the Massive MIMO system and Beamforming technique, analyzing how different antenna configurations, propagation conditions, and transmission technologies affect capacity, efficiency, and throughput. This analysis combines analytical modeling with simulations demonstrating the benefits of increasing antenna count and employing spatial multiplexing to boost capacity without compromising spectral efficiency.

The second contribution verifies Massive MIMO performance experimentally using the Massive MIMO Channel System. Rather than relying solely on analytical comparisons and predictions, this study validates its theoretical findings through real-world experimentation, showing that throughput values close to theoretical targets are indeed achievable under suitable channel conditions.

The third contribution addresses beamforming and beam management techniques in 5G NR systems. It provides a comprehensive discussion of analog, digital, and hybrid beamforming technologies, alongside an analysis of beam sweeping, measurement, determination, reporting, and recovery—explaining their importance for maintaining reliable connections in highly directional networks. The study also examines Synchronization Signal Blocks (SSBs) and their role in initial access and beam selection, leading to a fourth contribution: the evaluation of SSB-based synchronization through spectrogram analysis, covering deployment scenarios in Frequency Ranges 1 and 2 and the impact of subcarrier spacing, frequency range, and the number of transmitted SSBs.

A further contribution is the development of an interference-margin estimation technique for downlink link-budget calculations in 5G. This technique incorporates geometry distribution

estimation, signal-to-interference ratio estimation, and neighboring-cell load estimation, revealing a strong correlation between network loading and the required interference margin. The thesis also contributes an analysis of transport layer congestion control mechanisms and their behavior in wireless environments, examining how core TCP mechanisms—slow start, congestion avoidance, fast retransmission, and fast recovery—operate while accounting for the added challenge that packet losses in wireless networks may stem from channel conditions rather than congestion.

Finally, the thesis discusses its findings in relation to technologies anticipated to influence the future development of Beyond-5G and 6G systems, such as AI-based network optimization, cloud-native RANs, network slicing, energy-efficient communications, reconfigurable intelligent surfaces, and massive cell-free MIMO. These contributions improve the theoretical understanding and practical guidance to Massive MIMO communications, Beamforming and Beam management, radio network planning, and transport layer optimization, providing a basis for the design of future high-capacity wireless communication systems.

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