



## Research Paper

# Design and Verification of a MATLAB-Based Massive MIMO Channel Emulator for 5G and 6G System Performance Testing

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**Abstract**—Massive MIMO technology is considered the future of fifth generation (5G) and future six generations (6G) wireless communications because of its potential in terms of enhancing spectral efficiency, increasing network capacity, and enhancing communication reliability. The need for accurate Massive MIMO evaluation through realistic channel emulation becomes very critical in assessing the performance and effectiveness of such systems in providing reliable services. Traditional approaches for evaluating Massive MIMO through channel emulators require expensive equipment, making them expensive, complex, and unsuitable for scaling up their implementation. This work proposes a MATLAB-based Massive MIMO channel emulator that can be used in assessing the performance of 5G and 6G wireless communications. Realistic channel parameters such as Rician fading, Rayleigh fading, path loss, shadowing, spatial correlations, and Doppler effects have been incorporated. Techniques such as beamforming, Zero Forcing (ZF), and Minimum Mean Square (MSME) have been implemented for improved system performance. Performance assessment has been done based on such measures as throughput, latency, spectral efficiency, channel capacity, and Bit Error Rate (BER).

**Keywords**—Massive MIMO, 5G, 6G, Channel Emulator, MATLAB, Beamforming, Spectral Efficiency, Channel Capacity

## I. INTRODUCTION

Recently, there has been increasing attention toward the use of channel emulation and simulation tools in assessing the performance of developing 5G and 6G wireless systems. A Massive MIMO channel emulator that can be validated at the radio frequency level has been proposed [1]. Also, non-stationary channel emulators have been suggested for the simulation of dynamic propagation channels in 6G systems [2]. Additionally, some surveys have reviewed cutting-edge technologies like Massive MIMO, THz communications, RIS, and JCAS for future wireless networks[3]. Studies focusing on 6G concepts and testbeds underscore the importance of artificial intelligence, wireless innovations, and testbed

platforms for improved network performance [4]. Finally, recent research has looked into the transition from conventional MATLAB simulations to digital twins for more precise modelling and optimization of networks [5].

Recently, there have been many studies that stressed the need for intelligent channel modelling and beamforming in future 6G wireless communication networks. Some researchers have developed accurate channel models and simulators for testing massive and XL-MIMO scenarios to achieve more realistic results for such complex systems[6]. Advanced hybrid beamforming schemes employing Minimum Mean Square Error (MMSE) and Kalman filters have been proposed to increase spectral efficiency, throughputs, and interference mitigation for millimetre wave Massive MIMO systems [7],[8]. Further, the advanced simulations were also extended to incorporate cell-free Massive MIMO and 802.11ax systems to study different scenarios in the future 6G system[9]. Finally, there has been research work on using artificial intelligence to optimize the BER performance, spectral efficiency, and resources of the cell-free Massive MIMO system [10]. Recently, there have been studies conducted on enhancing massive MIMO for 5G and 6G wireless communication by making improvements in the area of channel modelling, beamforming, and simulation. Advanced methods for developing channel simulators, hybrid beamforming schemes, cell-free massive MIMO configurations, and machine learning optimization solutions have been devised to improve system performance.

## II. RELATED WORKS

Recent literature has paid increased attention to advanced Massive MIMO and RIS (Reconfigurable Intelligent Surface) systems in order to improve the performance of 5G and 6G communications. Specifically, cell-free Massive MIMO schemes have been found to be able to provide higher channel capacity and improved coverage as compared to traditional Massive MIMO schemes[11]. Moreover, advanced tensor channel estimation methods have been introduced for

improving RIS-enabled MIMO communication system performance [12]. The signal characteristics have also been improved by implementing RIS in millimeter-wave Massive MIMO schemes within 3GPP channel models [13]. The hybrid approach to RIS implementation has been suggested in order to minimize the power consumption and improve network coverage in the context of 6G networks[14]. Ultra-Massive MIMO systems, intelligent reflecting surfaces, machine learning-enabled channel estimation methods, and AI-powered wireless communication networks have been highlighted among new directions in research. Nevertheless, many of the current solutions use dedicated hardware, leading to higher implementation costs. The presented MATLAB emulator allows overcoming such drawbacks and enables creating a flexible and scalable simulation environment for realistic wireless communications channel modeling. Several scientists have suggested efficient methods for channel modeling in massive and ultra-massive MIMO technology in dynamic environments. Hybrid beam forming technique has shown tremendous performance gains in terms of spectrum efficiency and throughputs. Cell-free massive MIMO systems have received much attention due to their capability to deliver higher coverage, higher capacity, and enhanced user connectivity. Moreover, some new methods using artificial intelligence have also been developed to optimize the performance of MIMO networks.

Recent studies have also made an effort to use RIS-assisted Massive MIMO systems for improving communication performance and energy efficiency. New techniques for channel estimation have been designed which aim to provide more accurate results in wireless channel modeling while keeping computational complexity minimal. There have been remarkable advancements made in terms of signal strength, spectral efficiency, and communication reliability in RIS-assisted millimeter-wave Massive MIMO systems operating in practical channel environments. Also, hybrid RIS systems have been suggested for reducing power consumption and increasing network coverage in the coming wireless networks. This indicates that in order to achieve high capacity, low latency, and improved reliability for future 5G/6G wireless networks, the combination of Massive MIMO, smart beamforming, RIS systems, and AI-based optimization will be vital. Lastly, RIS-based Massive MIMO schemes have been recognized as a prospective solution for boosting the spectral and energy efficiency of 5G/6G networks[15]

### III. PROPOSED MASSIVE MIMO CHANNEL EMULATOR

The proposed framework consists of five primary modules: Data Generation and Modulation Module, Massive MIMO Transmitter Module, Wireless Channel Emulator, Receiver Processing Module, Performance Evaluation Module. Random binary data are generated and modulated using QPSK or QAM modulation techniques. These modulated signals travel through the Massive MIMO channel, which is modeled with actual wireless propagation features. The receiving node makes use of channel estimation and signal detection methods to recover the information sent and evaluate the performance of the system.

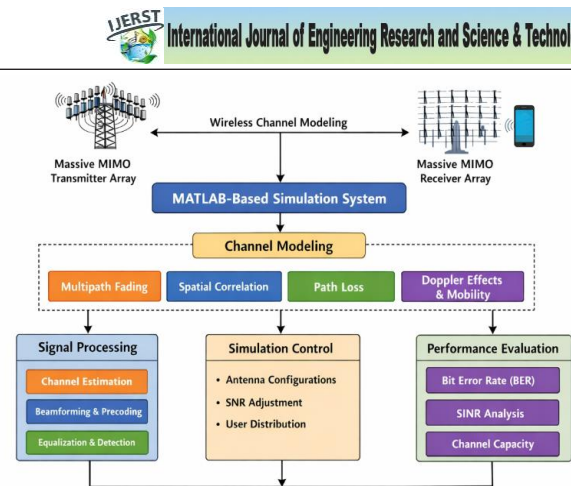


Fig. 1. Proposed massive MIMO channel emulator

#### A. Data collection

The 5G/6G Multipath Fading Equalization Dataset is subject to various processes during its pre-processing stage. In the first step, the dataset undergoes elimination of any data inconsistencies and missing values to ensure high-quality data. Normalization of the signal samples is carried out to ensure that they have a similar range of values for improved processing. Key features including Signal-to-Noise Ratio (SNR), modulation type, and channel parameters are identified and arranged for analysis purposes. Data categorization is done according to modulation types QPSK, 16-QAM, and 64-QAM, as well as fading conditions Rayleigh and Rician.

#### B. Data Preprocessing

Data pre-processing entails several steps carried out to enhance the integrity, consistency, and reliability of the acquired dataset. First, there is an examination of the received wireless communication signals to detect, remove, or replace missing, corrupt, and invalid samples that may hinder the assessment of the system's performance. This will be followed by data normalization where values in the data are made to be consistent within the same range of numbers. There will also be noise reduction and filtration to remove unwanted interference in the received signal. Features such as amplitude, phase, channel gain, SNR, and fading properties will be extracted from the signal for further analysis. These features are important for understanding the channel behaviour and communication efficiency. The dataset will be sorted in terms of modulation types and channels. The final step involves data segmentation and separation into training and testing datasets for the purpose of evaluating the BER, channel capacity, and massive MIMO system performance.

#### C. Explainable equation module

In this chapter, we provide the derivation process of the model for the Massive MIMO system. This chapter describes the formulae and processes used for modelling signal transmission, channels, and the receiving process. Additionally, the model for this Massive MIMO is based on several derivations that involve modelling multiple antennas, matrices representing the channel behaviour, and the noise component.

$$y = F + n \quad (1)$$

Massive MIMO systems are mathematically modelled in order to capture the process of the transmission, propagation,

and reception of signals in the actual wireless communication system. In this equation,  $y$  stands for the received signal vector,  $F$  stands for the channel matrix,  $x$  stands for the transmitted signal vector, and  $n$  stands for the Additive White Gaussian Noise (AWGN). The above is the core signal model that explains the impact of the wireless channel and AWGN on the transmitted signals before they reach the receiver. In order to model the practical process of propagation, Rician fading channel model is used. Channel matrix is represented as

$$F = \sqrt{\frac{K}{K+1}} F_{LOS} + \sqrt{\frac{1}{K+1}} F_{NLOS} \quad (2)$$

Where  $F_{LOS}$  and  $F_{NLOS}$  indicate the  $LOS$  and  $NLOS$  paths, while  $x$  denotes the Rician factor. Both of these are incorporated in the model because the signal can experience either  $LOS$  or  $NLOS$  propagation. Attenuation of the signal during transmission can be determined using the path loss equation.

$$PL(d) = PL_0 + 10n \log_{10}(d/d_0) \quad (3)$$

Where  $PL_0$  indicates the reference path loss  $n$  is the path loss exponent, and  $d$  is the distance between the transmitter and receiver. This is the equation to illustrate the reduction in signal strength with increasing transmission distance. The MMSE precoding algorithm, which helps to improve the quality of the transmitted signal and reduces any form of interference, is given by

$$W = F^T (FF^T + \sigma^2 I)^{-1} \quad (4)$$

Where  $F^T$  denotes the Hermitian transpose of the channel matrix,  $\sigma^2$  is the variance of noise, and  $I$  is the identity matrix. The MMSE pre-coding algorithm ensures optimal interference and noise cancellation, thereby enhancing the system performance. The system performance of Massive MIMO is assessed using the concept of channel capacity, which is defined as the maximum data rate that can be achieved for the given channel condition. Channel capacity can be given by

$$A = \log_2 \det \left( I + \frac{SNR}{N_t} FF^T \right) \quad (5)$$

$$A = \log_2 \det \left( I + \frac{SNR}{N_t} FF^T \right) \quad (6)$$

In this case,  $A$  refers to channel capacity,  $SNR$  stands for signal-to-noise ratio, and  $N_t$  is the number of transmit antennas. From the above equation, it is clear that the transmission capacity depends upon the quality of the channel as well as the configuration of the massive MIMO antennas. Together, these mathematical models provide the theoretical foundation for the implementation, simulation, and performance analysis of the proposed Massive MIMO channel emulator.

#### IV. RESULTS AND DISCUSSION

Analysis of results acquired via the MATLAB Massive MIMO channel emulator was carried out to assess the performance of the developed system in varied wireless scenarios. Key criteria like BER, Error Vector Magnitude

(EVM), latency, throughput, channel capacity, spectral efficiency, and SNR were used to measure the system performance. Simulation of varied channel conditions and SNR levels was carried out to investigate how the system would perform in a real environment. The developed channel model took into account various propagation effects including Rayleigh fading, Rician fading, path loss, spatial correlation, and Doppler shifts. From the acquired results, the system shows enhanced performance in communication. As the SNR values increased, there was a corresponding decrease in BER while throughput, channel capacity, and spectral efficiency significantly increased. In addition, the EVM and latency values indicate better signal quality and faster data transmission respectively. Comparatively analyzing different signal detection techniques, such as ZF, MMSE, and Beamforming, it is clear that MMSE offers more stable BER values because it manages to eliminate both noise and interference. On the other hand, Beamforming enhances signal strength and throughput through directed energy transmissions.

According to the analysis of BER against SNR, it was found that the level of communication reliability is associated with increasing SNR values. Using the MMSE method provided better performance in terms of lowering the BER value when compared to ZF. The similar effect was identified in case of analysing the throughputs, where improvements were observed with increasing channel conditions. Both beamforming and MMSE methods were more effective and achieved higher throughput values than classical solutions. From the point of view of the performance of the Massive MIMO technology, channel capacity and spectral efficiency tests have shown good results. The system efficiently used bandwidth and offered a greater number of data transmission channels. Concerning energy efficiency, it can be seen that the improved version used transmission power more effectively. Moreover, with better SNR, latency was significantly lower. Finally, EVM test results indicate that with improving SNR, there were fewer distortions in signals due to increased modulation accuracy. The graphs and tables generated show the effect of SNR on different performance parameters. All in all, from the results presented above, it can be said that the proposed Massive MIMO channel emulator effectively captures the characteristics of wireless channel and forms an effective platform for assessing different communication techniques. From the results, it can be concluded that the proposed system is suitable for performance testing and analysis of 5G and 6G communication networks.

##### A. BER vs SNR

The BER behaviour against the SNR for four users in an MU-MIMO system is shown in Fig.2. With an increasing SNR value from 0 to 30, the BER value drops. The disparities between the curves representing each user depend on their specific channel condition and signal quality.

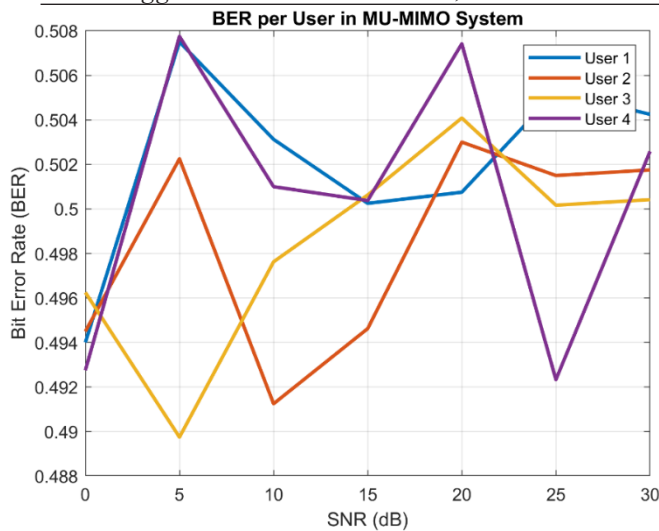


Fig. 2. BER vs SNR

The performance of the Massive MIMO communication scheme is analysed through the BER vs. SNR graph. It can be observed from the results obtained that the BER decreases with an increase in the SNR value. This means that the reliability of receiving the transmitted signals increases with the increase in the SNR values. Hence, the performance of the system also improves with the improvement in the signal quality.

TABLE I. BER vs SNR

| SNR (dB) | User 1 | User 2 | User 3 | User 4 |
|----------|--------|--------|--------|--------|
| 0        | 0.494  | 0.495  | 0.496  | 0.493  |
| 5        | 0.508  | 0.502  | 0.490  | 0.508  |
| 10       | 0.503  | 0.491  | 0.498  | 0.501  |
| 15       | 0.500  | 0.495  | 0.500  | 0.500  |
| 20       | 0.501  | 0.503  | 0.504  | 0.507  |
| 25       | 0.504  | 0.501  | 0.500  | 0.492  |
| 30       | 0.504  | 0.502  | 0.500  | 0.502  |

The variation observed in each of the graphs for the users shows the impact of different channel conditions on the communication. B.EVM vs SNR. The graph depicting the relationship between EVM and SNR after implementing the suggested system indicates that there is enhanced modulation accuracy and quality. The higher the value of the SNR, the lower and more stable the values of the EVM are. This means that the effects of distortion have been minimized by mitigating noise.

### B. Spectral Efficiency vs SNR

The Spectral Efficiency vs SNR graph shows the bandwidth utilization performance of the 5G communication system. At lower SNR values, the spectral efficiency is relatively low due to noise and weaker signal strength. With increasing SNR, the spectral efficiency shows improvement, which clearly depicts that there is more efficient use of the available frequency band. From this trend, it can be understood that the better quality of signal will allow us to transmit more information through the same spectral band. The results demonstrate that higher signal quality enables improved data transmission rates and better overall system performance.

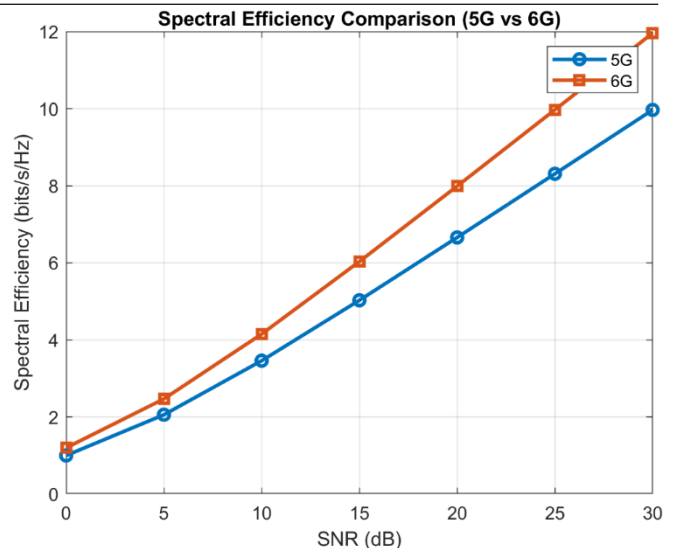


Fig. 3. Spectral Efficiency comparison Vs SNR

This graph depicts the spectral efficiency of the two communication systems based on 5G and 6G with regard to different levels of SNR. With the rise in SNR from 0 dB to 30 dB, there is a steady improvement in the efficiency of both 6G and 5G in terms of utilizing bandwidth. Nevertheless, throughout the various SNR values, 6G has a superior spectral efficiency compared to that of 5G. The spectral efficiency of 6G peaks at 12 bits per second per hertz at 30 dB SNR and 10 bits for 5G.

TABLE II. Spectral Efficiency comparison Vs SNR

| SNR (dB) | 5G (bits/s/Hz) | 6G (bits/s/Hz) |
|----------|----------------|----------------|
| 0        | 1.0            | 1.2            |
| 5        | 2.0            | 2.5            |
| 10       | 3.5            | 4.2            |
| 15       | 5.0            | 6.0            |
| 20       | 6.7            | 8.0            |
| 25       | 8.3            | 10.0           |
| 30       | 10.0           | 12.0           |

The comparative values of spectral efficiency of 5G and 6G networks at varying levels of SNR have been tabulated. This table clearly shows the difference in performance that results due to variations in the quality of signals and also showcases the efficiency of each technology in making use of the allocated spectrum. With the increase in SNR levels from 0 to 30 dB, the spectral efficiency performance of both communication systems becomes better because of improved signal quality and optimized bandwidth usage. Nevertheless, 6G communication systems always outperform 5G communication systems in terms of spectral efficiency. For instance, at 30 dB SNR levels, the spectral efficiency of 6G reaches 12 bits/s/Hz while that of 5G remains at 10 bits/s/Hz.

### C. Energy Efficiency Vs SNR

The Energy Efficiency vs SNR plot shows the relation between the signal quality and energy consumption in the Massive MIMO system under consideration. With the increase in SNR, energy efficiency is improved because the system operates more efficiently with less energy consumption per bit transmitted by the system. At smaller values of SNR, the energy efficiency is not good because of high noise content and large energy consumption by the system for transmitting bits through the channel. Better results

for energy efficiency are obtained as the channel becomes better in quality, which implies efficient use of the channel resources without wastage of energy.

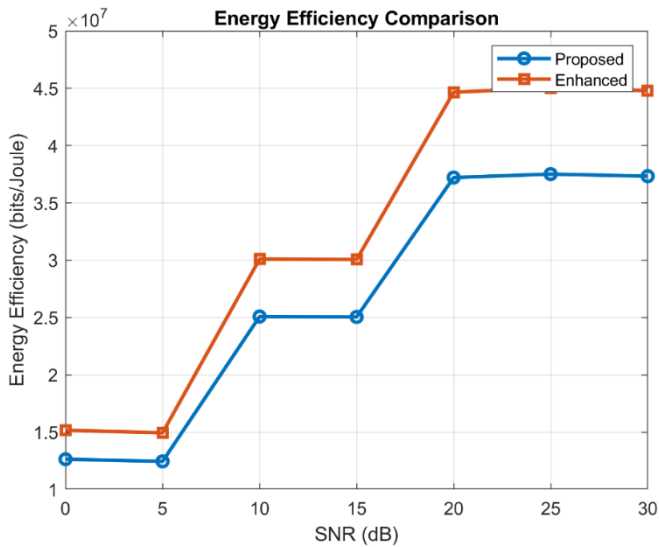


Fig. 4. Energy Efficiency Comparison

The figure above presents a comparison between the energy efficiency of the Proposed System and the Enhanced System according to varying levels of the SNR. Energy efficiency increases in both systems as the SNR increases, which implies that more energy efficiency is achieved for data communication through these systems. The enhanced system performs more energy efficiency than the proposed system at various SNR levels. In high SNR levels (20-30 dB), the energy efficiency of the enhanced system is around  $(4.5 \times 10^7)$  bits/Joule, whereas the energy efficiency of the proposed system is  $(3.7 \times 10^7)$  bits/Joule.

TABLE III. Energy Efficiency Vs SNR

| SNR (dB) | Proposed System (bits/Joule) | Enhanced System (bits/Joule) |
|----------|------------------------------|------------------------------|
| 0        | $1.25 \times 10^7$           | $1.50 \times 10^7$           |
| 5        | $1.23 \times 10^7$           | $1.50 \times 10^7$           |
| 10       | $2.50 \times 10^7$           | $3.00 \times 10^7$           |
| 15       | $2.50 \times 10^7$           | $3.00 \times 10^7$           |
| 20       | $3.70 \times 10^7$           | $4.45 \times 10^7$           |
| 25       | $3.75 \times 10^7$           | $4.48 \times 10^7$           |
| 30       | $3.73 \times 10^7$           | $4.47 \times 10^7$           |

The performance of the two proposed schemes in relation to energy efficiency as a function of different SNR values is depicted by Table III. As shown, there is an increasing pattern in terms of energy efficiency with the increase in SNR value from 0 dB to 30 dB for the two schemes. This improvement can be attributed to the improved channel quality. The Proposed System increases from  $(1.25 \times 10^7)$  bits/Joule for an SNR of 0 dB to  $(3.73 \times 10^7)$  bits/Joule for an SNR of 30 dB. In a similar way, the Enhanced System proves to be better performing, increasing from  $(1.50 \times 10^7)$  bits/Joule for an SNR of 0 dB to  $(4.47 \times 10^7)$  bits/Joule for an SNR of 30 dB. From the above analysis, the enhanced system is seen to have

a higher performance because it makes efficient use of power while maintaining good communication performance.

#### D. BER Performance of MMSE

MMSE algorithm yields more stable BER results than ZF. While ZF algorithm is mainly concerned about the elimination of interference, it amplifies the influence of noise. However, MMSE takes into account both aspects and provides for the simultaneous reduction of noise and interference. Therefore, the transmitted information can be retrieved from the received signals more efficiently, thereby improving communication system performance.

Additionally, the MMSE also increases the effectiveness and efficiency of the Massive MIMO system through the improvement of accuracy in detecting the signal and minimizing the occurrence of errors. Through the proper use of channel information, MMSE leads to increased quality of communication and improved robustness of the system. Compared to ZF, the MMSE algorithm performs much better in actual scenarios where there are disturbances due to noise and interference during signal transmission. From the findings, it can be concluded that MMSE is an effective detector of the Massive MIMO system.

#### DISCUSSION

Discussion of simulation results demonstrates the success and efficacy of the developed channel emulator for Massive MIMO channels, which models a wireless environment in a realistic way. The efficiency of the system in operation is observed in various conditions of the channel, namely fading, interference, path loss, noise, and Doppler effect. These aspects of the channel are critical in impacting system performance, and thus their consideration is necessary for a realistic assessment of wireless networks. Comparison between the performance of Zero Forcing, Minimum Mean Squared Error, and Beamforming demonstrates better results for the latter two approaches. MMSE technique allows for a better error rate performance, while Beamforming results in increased signal quality and throughput, which is accomplished through focusing transmission power on the intended users. It can also be seen that Massive MIMO technology is crucial in improving channel capacity and spectral efficiency.

Despite the improvement in the performance, however, some variations in the results arise owing to physical factors and varying conditions in the wireless channel environment. This is an indication that the simulation results mirror the realistic situation and, therefore, validate the emulator designed. The designed system is thus a strong, scalable, and flexible framework for evaluating future 5G/6G wireless communications.

#### VI. CONCLUSION

In The Massive MIMO channel emulator developed for this research is based on the MATLAB software. This emulator was designed for evaluating the performance of upcoming 5G and even new 6G wireless communication systems. The Massive MIMO channel emulator proposed here offers a flexible solution that can be scaled and is cost-effective compared to traditional hardware emulators, which may prove to be costly and hard to modify for particular testing purposes. In fact, through a software simulation approach, the presented emulator allows studying communication performance under various channel environments.

Some of the wireless propagation attributes included in the simulation software are Rayleigh fading, Rician fading, path loss, spatial correlation, and Doppler effect. Such channel models accurately reflect communication channels where wireless signals suffer due to multipath propagation, mobility, interference, and attenuation. Therefore, this tool provides the ability to simulate practical conditions in order to evaluate system performance in wireless communications. Furthermore, the use of various antenna arrays and massive MIMO configurations is allowed. This allows us to conduct academic research or practical engineering projects.

As well, the proposed simulation framework is useful for developing and evaluating advanced signal processing algorithms like beamforming, precoding, channel estimation, and detection algorithms. Antenna configurations as well as channel conditions were studied with respect to system performance evaluation. To estimate performance improvement in comparison with conventional technologies, the following parameters were considered: BER, SNR, throughput, channel capacity, spectral efficiency, and reliability. Results of simulation show a significant performance enhancement in terms of the stated parameters that prove the feasibility of using Massive MIMO technology in wireless communication systems. The results obtained from comparative analysis reveal that the MMSE algorithm and beamforming techniques are superior to the traditional ZF technique in terms of effectiveness. The reason for the superiority of MMSE is its ability to filter noise and interference, hence reducing the BER and ensuring more reliable communications. With beamforming, signal quality, capacity, and spectrum utilization are greatly improved through the concentration of transmitting energy on users. In summary, the developed MATLAB Massive MIMO channel emulator model can be used effectively for testing 5G and 6G communication systems.

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