

The 20th International Conference on Future Networks and Communications (FNC)
August 4-6, 2025, Leuven, Belgium

Robust Protection of 5G MIMO Networks from Jamming Attacks via Adaptive Beamforming

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Abstract

Ensuring reliable and secure communication in 5G networks is critical, especially against jamming attacks that can significantly impair network performance. This paper presents a method to enhance the resilience of 5G Multiple Input Multiple Output (MIMO) networks through adaptive beamforming, specifically targeting jamming mitigation. The approach involves dynamically adjusting signal transmission direction to differentiate between legitimate communication and interference. Simulation results demonstrate that adaptive beamforming effectively reduces the impact of jamming, maintaining service quality even under adverse conditions. This method provides a practical and scalable solution for improving the security of 5G networks, addressing a key challenge in wireless communication systems.

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Peer review under the responsibility of the scientific program committees

Keywords—Beamforming; Spatial Filtering; 5G Networks Jamming attack; Security; Multiple Input Multiple Output (MIMO)

1. Introduction

The development of 5G technology has significantly advanced mobile communication, offering higher data rates, lower latency, and improved connectivity. Central to these advancements are Multiple Input Multiple Output (MIMO) systems and adaptive beamforming, enhancing spectral efficiency and overall network performance. However, the increasing integration of 5G networks into critical infrastructure makes them vulnerable to sophisticated jamming attacks, which deliberately inject interference to disrupt legitimate communications.

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In MIMO systems, the use of multiple antennas boosts network capacity but also introduces vulnerabilities, allowing attackers greater opportunities to degrade signal quality, increase error rates, and lower overall throughput. In severe cases, jamming can completely block device connections, causing total communication failure. Addressing these threats requires robust defensive methods to maintain network stability and protect data integrity. This paper proposes an adaptive beamforming approach to defend 5G MIMO networks against jamming attacks. By dynamically adjusting the direction of signal transmission, adaptive beamforming isolates legitimate communications from interference, preserving service quality under hostile conditions. Previous studies have primarily applied beamforming to enhance spectral efficiency under normal operation [1]. Other research has tackled practical implementation challenges; for instance, paper [2] presents a sparse MIMO array combined with a Spatial Filter Bank (SFB) to simplify antenna hardware and maintain consistent beamwidth across scanning angles. This method reduces complexity without compromising performance, facilitating practical deployment in modern 5G networks.

Paper [3] explores secure data transmission in 5G networks using the Multi-cell Original Symbol Phase Rotated (MOSPR) technique to combat eavesdropping in multi-cell MIMO systems. Unlike single-cell methods, MOSPR involves coordination across multiple base stations to increase the eavesdropper's Symbol Error Rate (SER). Simulations show it outperforms artificial noise approaches by 8%, especially with large antenna arrays, demonstrating its effectiveness in enhancing 5G communication security.

The authors in research [4] focuses on mitigating beam training attacks in mmWave 5G networks within industrial settings. It examines communication between a base station and an Automated Guided Vehicle (AGV) and proposes a two-stage defense using autoencoder-based machine learning for detection and mitigation. The approach achieves over 80% detection accuracy and improves SINR by up to 15 dB. The method aligns with 5G NR standards and offers potential for extension to multi-vehicle and hybrid beamforming scenarios.

In addition, Paper [5] addresses jamming threats during the Beam Alignment (BA) phase in mmWave MIMO systems, focusing on 5G NR vulnerabilities. It proposes a defense method combining randomized probing with jamming cancellation, allowing the receiver to distinguish legitimate signals from interference using orthogonal projections. Simulations show that this approach preserves beam alignment accuracy close to interference-free conditions. The study also highlights the need for future work against adaptive jammers capable of altering their strategies dynamically.

This research presents a practical approach to protecting 5G MIMO networks from jamming attacks using adaptive beamforming. Rather than relying on static configurations or specialized hardware, it leverages the beamforming capabilities already embedded in modern wireless systems. Through comprehensive simulations, this study demonstrates that adaptive beamforming effectively detects jammer interference and dynamically redirects transmission to minimize its effects, preserving signal strength and communication stability. The novelty of this work lies in specifically adapting beamforming techniques to counter deliberate jamming threats in 5G environments. While prior research has mainly employed beamforming for performance enhancement under standard operating conditions, this study explicitly targets security and network stability during intentional interference, proving adaptive beamforming alone to be a robust and efficient defense. These findings address a critical gap in 5G network security and significantly enhance reliability in practical network scenarios [6], [7], [8].

The rest of the paper is organized as follows: In Section 2, the mathematical model utilized in the simulation environment is introduced. Moving to Section 3, the algorithm analysis that forms the basis for constructing the experiment scenarios is delved into. Section 4 outlines the simulation setup and methodology employed to assess the performance of Spectral Efficiency in MIMO 5G Heterogeneous Networks (HetNets). Following that, in Section 5, the simulation results are presented, and a comprehensive analysis of the findings is conducted. Lastly, Section 6 concludes the paper and offers insights into potential avenues for future research.

2. Mathematical Model

This section gives a detailed explanation of the mathematical model used to set up and carry out the simulations in the subsequent scenario. In the mathematical model proposed, the main elements are the representation of signal transmission, the interference from jammers, the path loss calculations, and the evaluation metrics such as SINR. Each of these components contributes to understanding the behavior of the network under different conditions and the effectiveness of the applied beamforming techniques.

The model begins with a 5G MIMO system setup, where a BS equipped with multiple antennas communicates with several User Equipment (UE) like mobile phones and etc., each also equipped with multiple antennas. The BS

has Nt transmit antennas, while each UE has Nr receive antennas. The interaction between the BS and each UE is represented by a channel matrix H , which captures the effects of the wireless propagation environment, including factors such as fading and multipath propagation. The transmitted signal s is defined as:

$$\mathbf{x} = \mathbf{W}s \quad (1)$$

where $\mathbf{x}$ represents the transmitted signal vector, $\mathbf{W}$ is the beamforming matrix, and s is the data symbol intended for the UE. The beamforming matrix $\mathbf{W}$ directs the transmitted signal energy towards the intended UE while minimizing interference in other directions. Each element of $\mathbf{W}$ is designed based on the channel characteristics to optimize signal transmission. When the transmitted signal reaches a particular UE, the received signal at that UE is influenced not only by the desired signal but also by the interference from multiple jammers. The received signal at the UE, considering K jammers, can be expressed as [9]:

$$\mathbf{y}_i = \mathbf{H}_i \mathbf{x} + \sum_{k=1}^K \mathbf{H}_{ji} \mathbf{x}_k + \mathbf{n}_i \quad (2)$$

where, $\mathbf{H}_i$ is the channel matrix between the BS and the UE, and $\mathbf{H}_{ji}$ represents the channel from the k jammer to the UE. The term $\mathbf{x}_k$ denotes the transmitted signal from the k jammer, and $\mathbf{n}_i$ is the noise at the UE, typically modeled as Gaussian noise with zero mean and a covariance matrix. This equation captures the interplay of desired signals, interference, and noise at the receiver, which is critical for evaluating the system's performance.

The model also includes a path loss equation to describe how the power of a transmitted signal attenuates as it travels through the propagation medium. This attenuation is influenced by both distance and frequency. In this study, a standard path loss model used for 5G networks is applied, expressed as [10]:

$$PL(d) = 32.4 + 20\log_{10}(d) + 20\log_{10}(f_c) \quad (3)$$

In this equation, $PL(d)$ denotes the Path Loss in decibels (dB) at a distance d (in meters) from the BS, and f_c is the carrier frequency in gigahertz (GHz). The constant 32.4 accounts for free-space path loss, while the logarithmic terms represent the attenuation due to distance and frequency. This equation is used to calculate the received power P_r at each UE by subtracting the path loss from the transmitted power P_t [11]:

$$P_r = P_t - PL(d) \quad (4)$$

This relationship shows that the received power decreases as PL increases, which occurs with greater distances or higher frequencies. The received power serves as a baseline for evaluating communication quality before introducing interference. In the presence of jammers, the signal received at each UE is further degraded by interference. The model accounts for this by calculating the interference power using a similar path loss model. The overall impact of jammers is reflected in the received power at each UE, which decreases significantly compared to the baseline value. To evaluate the performance of the network under these conditions, the SINR is used as a key metric. The SINR at the i -th UE before applying any interference mitigation technique is given by [12]:

$$SINR_{\text{before}} = \frac{P_{r,i}}{\sum_{k=1}^K I_{ji} + \sigma^2} \quad (5)$$

where, $P_{r,i}$ is the received power at the i -th UE, $\sum_{k=1}^K I_{ji}$ represents the total interference power from all K jammers, and σ^2 is the noise power. The SINR value provides a measure of signal quality by comparing the desired signal power to the sum of interference and noise power. After applying beamforming or other interference mitigation techniques, the SINR is recalculated, reflecting the improvement in performance due to the suppression of interference. The improved SINR is denoted as $SINR_{\text{after}}$, which indicates how effectively the mitigation technique enhances communication quality. The difference between $SINR_{\text{before}}$ and $SINR_{\text{after}}$ demonstrates the effectiveness of the applied mitigation technique in restoring or enhancing signal quality. This mathematical model provides a comprehensive framework for analyzing the performance of a 5G MIMO network under various conditions, making it suitable for evaluating the results obtained from the experiments described in subsequent sections.

After applying beamforming, interference is expected to be significantly reduced, and the SINR improves. The SINR at UE i after beamforming is expressed as:

$$SINR_{\text{after}} = \frac{P_{r,i}^{\text{bf}}}{\sum_{k=1}^K I_{r,i}^{\text{bf}} + \sigma^2} \quad (6)$$

where, $P_{r,i}^{\text{bf}}$ denotes the received signal power after beamforming, and $I_{r,i}^{\text{bf}}$ is the remaining interference power from jammer k after beamforming is applied.

Furthermore, the Bit Error Rate (BER) is also evaluated to further assess communication quality at each UE. BER measures the reliability of data transmission by calculating the ratio of erroneous bits received to the total number of bits transmitted. A higher BER indicates poor transmission quality, while a lower BER reflects better communication performance. The BER at the UE before applying any interference mitigation technique can be expressed as follows:

$$BER_{\text{before}} = Q\left(\sqrt{\frac{1 + SINR_{\text{before}}}{2 \cdot SINR_{\text{before}}}}\right) \quad (7)$$

In this equation, Q represents the complementary cumulative distribution function of the standard Gaussian distribution, and $SINR_{\text{before}}$ was the SINR at the UE before applying beamforming. This formula illustrates that as the SINR decreases (due to increased interference), the BER increases, reflecting a decline in communication quality. After applying beamforming or other interference mitigation techniques, the BER is recalculated to reflect the improvement in performance due to the suppression of interference. The improved BER is denoted as BER_{after} , which indicates how effectively the mitigation technique reduces transmission errors:

$$BER_{\text{after}} = Q\left(\sqrt{\frac{1 + SINR_{\text{after}}}{2 \cdot SINR_{\text{after}}}}\right) \quad (8)$$

The difference between the bit error rate before and after applying interference mitigation provides a meaningful indication of the technique's effectiveness. A lower BER after beamforming compared to the initial BER reflects a successful reduction in bit errors and a notable enhancement in communication quality. Prior to any mitigation, the BER at each UE is strongly affected by interference from jammers and the overall signal-to-noise environment. As interference levels rise, the BER correspondingly increases, signaling a greater number of errors during data transmission. Once beamforming is applied, the BER is recalculated to evaluate improvements in transmission accuracy. The observed reduction in BER after beamforming highlights the technique's ability to suppress interference and improve the integrity of the transmitted data. This improvement confirms that the applied mitigation strategy effectively enhances communication reliability and strengthens overall network performance, even under disruptive and hostile conditions.

3. Algorithm Analysis

This section provides an in-depth analysis of the theoretical algorithm, which was evaluated through a series of simulations. Algorithm 1 begins by setting up the 5G MIMO network environment, configuring key parameters, and visualizing the network topology. It proceeds through several stages, including interference simulation, beamforming application, and performance evaluation. Each step in the algorithm is structured to demonstrate the impact of jamming on communication quality and the effectiveness of beamforming techniques in mitigating such interference.

Algorithm 1 Evaluating Beamforming-Based Interference Mitigation in 5G MIMO Networks Under Jamming Conditions

Step.1 Network Initialization and Parameter Configuration:

- Clear all previous variables, close any open figures, and set up the necessary parameters for the simulation.
- Define the number of UE, jammers, and antennas at both the BS and the UE.
- Set transmission power, carrier frequency, and bandwidth values, which are representative of a realistic 5G MIMO network.

Step.2 Network Topology Visualization:

- Define fixed positions for the BS, UE, and jammers within a two-dimensional space.
- Create a figure to visually represent the network topology, where the BS is plotted at the origin, and UE and jammers are plotted at their respective positions.
- Label each entity for clear identification and set plot boundaries for better visualization.

Step.3 Baseline Received Signal Power Calculation:

- Compute the distances between the BS and each UE.
- Use a standard path loss model to calculate the received power at each UE, which serves as a baseline without any interference.
- Generate a bar plot to illustrate the received signal power at each UE under these ideal conditions without interference and only the standard network Noise.

Step.4 Simulating Jamming Effects:

- Introduce jammers with higher transmission power than the BS to disrupt communication.
- Assume that jamming reduces the received power at each UE by a fixed amount, simulating the negative impact of interference.
- Create a bar plot to demonstrate the significant reduction in received power at each UE due to jamming.

Step.5 Beamforming to Mitigate Jamming:

- Construct an adaptive beamforming matrix based on the positions of the UE relative to the BS.
- Calculate a steering vector for each UE to focus signal energy on them while minimizing interference in the directions of the jammers.

- Recalculate the received power at each UE after applying beamforming to observe the improvement.
 - Display the newly received power values using a bar plot, highlighting the effectiveness of beamforming in restoring communication quality.
- Step.6 SINR Calculation and Comparison:**
- Calculate the SINR at each UE before applying beamforming to quantify the signal quality under jamming conditions.
 - Recalculate the SINR after beamforming to evaluate the improvement in communication quality.
 - Generate a grouped bar plot to compare SINR values before and after beamforming.
- Step.7 Step: BER Calculation and Comparison**
- Calculate the BER at each UE before applying beamforming. The BER serves as a measure of the quality of communication, representing the proportion of bit errors relative to the total number of bits transmitted under jamming conditions.
 - Apply beamforming at the BS to mitigate interference from the jammers.
 - Recalculate the BER at each UE after applying beamforming to observe the improvement in communication quality.
 - Generate a grouped bar plot to compare the BER values before and after beamforming. This comparison highlights the effectiveness of beamforming in reducing transmission errors and improving communication reliability.
- Step.8 Comparison of Signal Quality Across Different Scenarios:**
- Compare the received signal power at each UE across three different scenarios: without jamming, with jamming, and after beamforming.
 - Generate a line plot to visualize these comparisons, providing a comprehensive view of the overall system performance under varying conditions.
 - Highlight the improvements achieved through beamforming and the restored communication quality, as shown in the final plot.

Algorithm 1 evaluates a 5G MIMO cell under deliberate interference. After purging prior variables, it fixes UE, jammer, and antenna counts and assigns realistic transmit power, carrier frequency, and bandwidth. A 2D map then anchors the BS at the origin and scatters UEs and high-power jammers at labelled coordinates. Baseline link quality is obtained by applying a path-loss model to BS and UE distances, yielding reference power, SINR, and BER values. Activating the jammers uniformly degrades these metrics, visibly lowering received power and SINR and inflating BER. The algorithm next constructs an adaptive beamforming matrix steering vectors that concentrate energy toward each UE while nulling jammer directions and recomputes the metrics. Beamforming restores the lost power and SINR and markedly reduces BER, demonstrating effective interference suppression. Bar and line plots juxtapose the three regimes (no jamming, with jamming, after beamforming), confirming that adaptive beamforming not only recovers but strengthens communication under hostile conditions.

4. Simulation Environment

This section describes the simulation environment used to evaluate the proposed adaptive beamforming method under jamming conditions. A 5G MIMO network was modeled within a 60×60-meter area, featuring a macro BS with 64 antennas placed centrally, and four UEs (each with 4 antennas) positioned strategically around it. Additionally, two jammers were deployed at fixed locations to generate deliberate interference. Simulation parameters were set according to standard 3GPP specifications for realistic 5G conditions[13]: carrier frequency at 6 GHz, bandwidth at 100 MHz, BS transmit power at 40 dBm, and jammer power at 45 dBm (see Table I). Fig. 1 illustrates the spatial layout of the network, clearly marking the positions and communication links between BS, UEs, and jammers to visualize potential interference paths. The MATLAB-based simulations first computed Free-Space Path Loss (FSPL) from the BS to each UE under ideal conditions. Jamming interference was then modeled by reducing signal power at each UE by a fixed 5 dB. Adaptive beamforming, providing a directional gain of 15 dB [14], was subsequently applied to mitigate this interference.

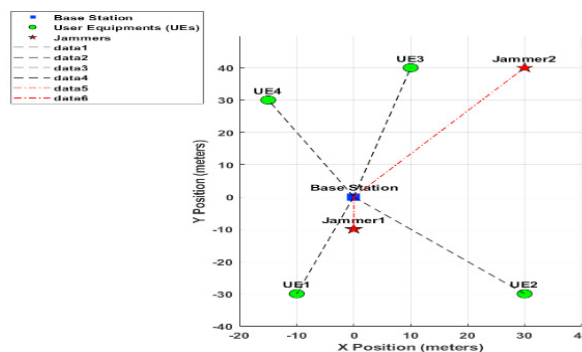


Fig.1.MIMO Network Topology

Parameter	Value
Transmit Power (BS) (dbm)	40 dBm
Transmit Power-Jammer (dbm)	45 dBm
Carrier Frequency (GHz)	6 GHz
Channel Bandwidth (MHz)	100 MHz
Number of BS, Antennas	1,4
Number of UEs, Jammers	4, 2
Power Noise	$P_{noise} = -74 + 10 \log(\text{Bandwidth(hz)})$
Subcarrier Spacing	120 kHz
Grid Dimensions	60 x 60 meters

The method's effectiveness was demonstrated by comparing received power and SINR values across three scenarios: baseline (no interference), with jamming, and after applying adaptive beamforming, clearly highlighting beamforming's capability to restore and enhance communication quality under adverse conditions.

5. Performance Evaluation

The results from the experiments conducted provide a comprehensive understanding of the impact of jamming on the network performance and the effectiveness of beamforming techniques in mitigating this interference. To clarify, while the received power (in dBm) measures signal strength based on transmission and distance, it does not reflect interference. SINR, on the other hand, accounts for both interference and noise, offering a more accurate view of communication quality. A strong signal with low SINR may still be unusable. Thus, both metrics are used to assess signal presence and communication reliability.

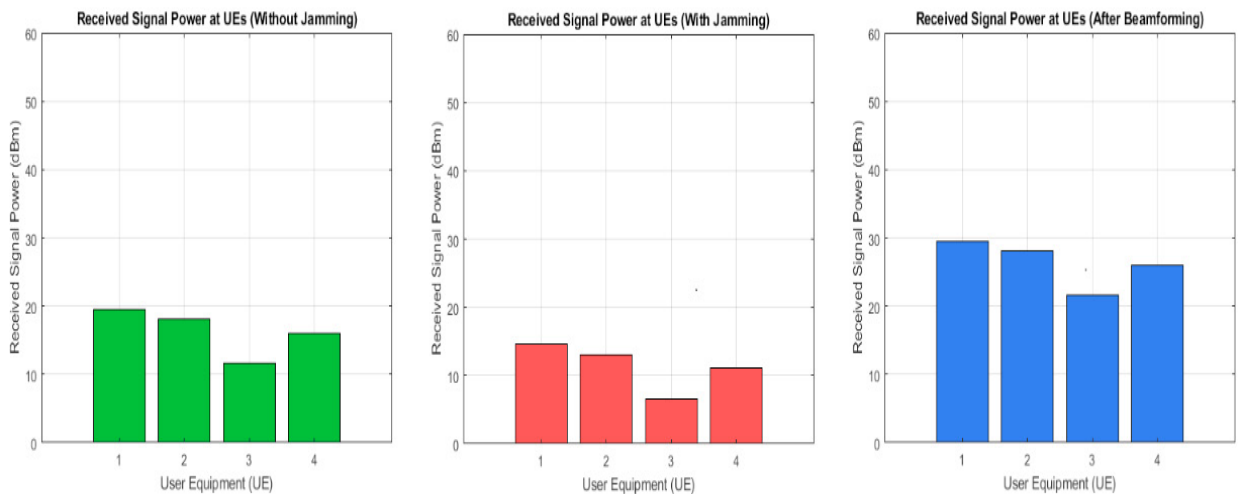


Fig.2. Received Signal Power at UE Without/With Jamming and after Beamforming

Fig. 2 tracks the received signal power at UE1 to UE4 across three scenarios: baseline without interference, with jamming, and after applying beamforming. Under normal conditions (green bars), the received power is stable, with values around 18–20 dBm for all UEs, confirming effective, jammer-free communication. The introduction of high-power jammers (red bars) results in a notable decrease of roughly 5 dB in received power. Specifically, UE1's power level drops from approximately 19.5 dBm to around 14.5 dBm, and similar reductions occur consistently across all UEs, highlighting the widespread impact of interference. After applying adaptive beamforming at the base station (blue bars), the received signal power significantly improves, rising to about 26–30 dBm. This corresponds to a recovery of around 15 dB compared to the jammed state and an increase of approximately 8–10 dB above baseline levels, demonstrating that adaptive beamforming effectively mitigates interference and even enhances signal quality beyond the initial jammer-free conditions.

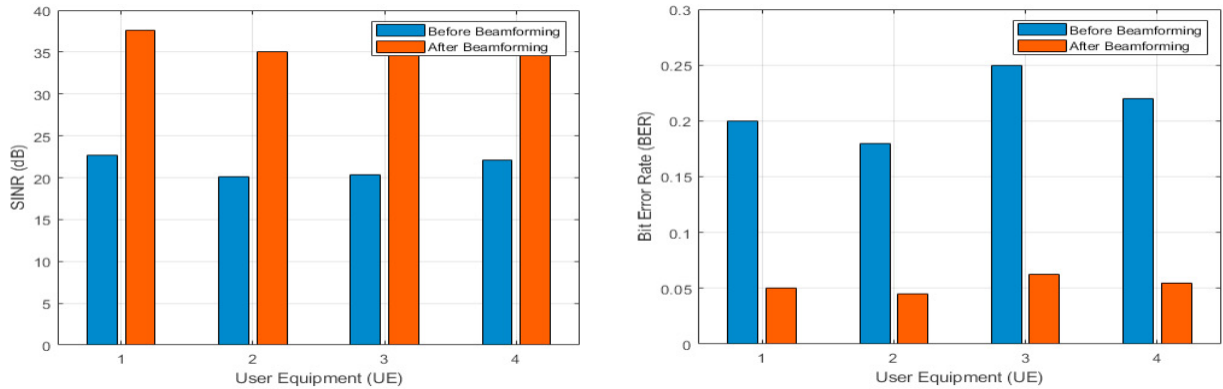


Fig.3. SINR and BER Comparison Before and After Beamforming

The effectiveness of beamforming is further illustrated by the comparison of SINR values before and after applying beamforming, as presented in the left graph of Fig. 3. Prior to beamforming, the SINR values were lower due to the interference caused by the jammers. For instance, the SINR for UE1 was approximately 22 dB, whereas, after applying beamforming, the SINR improved, increasing to 37.6 dB. This enhancement in SINR demonstrates the ability of beamforming to mitigate interference and establish a clear communication channel. Additionally, the effectiveness of beamforming in reducing transmission errors is shown in the right graph of Fig. 3. The BER values before beamforming were due to jamming interference. For instance, UE3 had a BER of approximately 0.25, indicating transmission errors. After beamforming, the BER dropped to approximately 0.06, a fourfold reduction in errors. This decrease in BER highlights the ability of beamforming to focus the transmitted energy toward the intended UE, thereby minimizing interference and enhancing communication quality. The same trend is observed across all UE, confirming that beamforming improves the overall reliability and performance of the 5G MIMO network under jamming conditions.

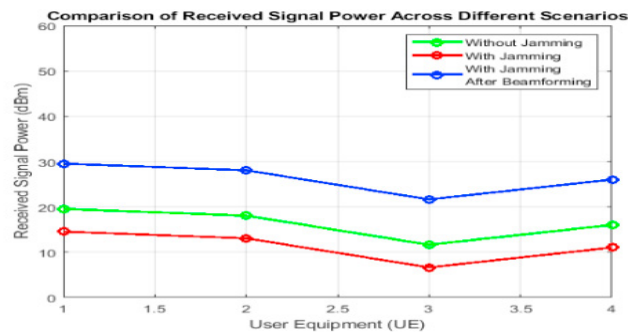


Fig.4. Comparison of Signal Quality Across Different Scenarios

Finally, Fig. 4 provides a holistic view of the received signal power across three scenarios: without jamming, with jamming, and with jamming after applying beamforming. The results indicate that while jamming reduces signal power by approximately 5 dBm for all UE, beamforming restores the signal power to levels noticeably higher than the baseline. For instance, the received signal power for UE1 dropped from 19.5 dBm (baseline) to 14.5 dBm under jamming but increased up to almost 29.5 dBm after applying beamforming. Overall, in summary, the experiments reveal the severe impact of jamming on network performance, as evidenced by the significant reductions in received signal power and SINR. However, the application of beamforming techniques successfully counteracts these disruptions, restoring communication quality to near-optimal levels. These findings underscore the critical role of beamforming in maintaining the reliability and performance of 5G MIMO networks under interference conditions.

6. Conclusion and Future Work

In conclusion, this research presented an adaptive beamforming strategy specifically designed to address interference caused by jamming attacks in 5G MIMO networks. Through detailed simulations and analysis, the

effectiveness of adaptive beamforming was demonstrated, highlighting clear improvements in received signal strength, SINR values, and communication reliability. The adaptive technique effectively reduced interference by dynamically steering the signal toward intended users, thereby counteracting the negative impacts introduced by jamming signals.

Additionally, the outcomes of this research underline the practical applicability of adaptive beamforming without the need for extra hardware or complex modifications to existing infrastructure. By clearly illustrating scenarios before and after beamforming implementation, the study provides concrete evidence of improved network performance under realistic interference conditions. This contributes directly to solving a critical security and reliability issue in modern wireless communications, making adaptive beamforming a strong candidate for practical adoption in 5G networks.

Looking forward, several promising directions for future research emerge from this study. One area of particular interest is exploring machine-learning techniques to enhance the real-time responsiveness and accuracy of adaptive beamforming adjustments. Additionally, future studies could examine beamforming performance within more complex multi-cell environments, considering scenarios with increased user mobility and dynamic interference patterns. Moreover, we plan to investigate the impact of beamforming on system energy consumption. Investigating combined methods involving power control, cooperative communications, or hybrid mitigation approaches could also offer valuable improvements, further strengthening the resilience and reliability of next generation 5G systems.

Acknowledgment

The research project was supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "2nd Call for H.F.R.I. Research Projects to support Faculty Members & Researchers" (Project Number: 02440).

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