Sapienza: International Journal of Interdisciplinary Studies | V. 5 | N. 1 | 2024 | e-ISSN: 2675-9780 https://doi.org/10.51798/sijis.v5i1.721

Publisher: Sapienza Grupo Editorial
R. Santa Cruz, 2187, Vila Mariana
São Paulo, Brazil
editor@sapienzaeditorial.com

Sapienza
International Journal of Interdisciplinary Studies
ISSN: 2675-9780

OPEN ACCESS

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Comparison of bit error rate (BER) in multipath phenomena Rayleigh and Rician using QPSK modulation in Multiple Input Multiple Output (MIMO) systems

Comparación de la tasa de Error Binario, en Fenómenos Multitrayecto Rayleigh y Rician, utilizando modulación QPSK, en sistemas Múltiple Entrada Múltiple Salida (MIMO)

Comparação da taxa de erros binários, em fenômenos multipercursos Rayleigh e Rician, utilizando modulação QPSK, em sistemas Multiple Input Multiple Output (MIMO)

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ARTICLE HISTORY

Received: 19-11-2023
Revised Version: 11-01-2024
Accepted: 18-01-2024
Published: 21-01-2024

Manuscript type: Article

ARTICLE INFORMATIONS

Science-Metrix Classification (Domain):
Applied Sciences
Main topic:
Wireless communication system optimization
Main practical implications:
Optimizing communication reliability and efficiency by selecting optimal MIMO configurations under specific fading conditions, enhancing overall system performance
Originality/value:
This research introduces operational advancements by showcasing the 4x4 MIMO configuration's superior performance with the Rician channel, paving the way for improved wireless communication system design and deployment.

ABSTRACT

In wireless communications there are Rician and Rayleigh multipath phenomena, which can cause destructive interference caused by a strong dominant component. The objective of the study is to analyze how these multipath phenomena affect the Bit Error Rate (BER), using phase shift keying (QPSK), as well as 5G Multiple Input Multiple Output (MIMO) technology to reduce or not the effect of fading to improve the BER. For the present study, the quantitative method is used to measure BER by comparative simulations of Rician and Rayleigh phenomena using different MIMO antenna configuration schemes using Matlab software. When comparing the multipath Rician and Rayleigh phenomena with QPSK modulation, it was determined that the most efficient channel is the Rician channel, since the BER is lower, performing a 4x4 MIMO antenna configuration. However, this efficiency may change if another type of modulation is used, which implies reducing the bit rate causing a reduction in bandwidth.

Keywords: BER, MIMO, Multipath, Rayleigh, Rician.

RESUMO

Nas comunicações sem fio, há fenômenos de Rician e Rayleigh multipath, que podem causar interferência destrutiva, causada por um forte componente dominante. O objetivo do estudo é analisar como esses fenômenos de multicaminho afetam a taxa de erro de bits (BER), usando o QPSK (phase shift keying), bem como a tecnologia MIMO (Multiple Input Multiple Output) 5G para reduzir ou não o efeito do desvanecimento para melhorar a BER. Para o presente estudo, o método quantitativo é usado para medir a BER por meio de simulações comparativas dos fenômenos Rician e Rayleigh usando diferentes esquemas de configuração de antena MIMO usando o software Matlab. Ao comparar os fenômenos de Rician e Rayleigh com modulação QPSK, foi determinado que o canal mais eficiente é o canal Rician, pois a BER é menor, usando uma configuração de antena MIMO 4x4. No entanto, essa eficiência pode mudar se for usado outro tipo de modulação, o que implica a redução da taxa de bits, levando a uma redução da largura de banda.

Palavras-chave: Palavras-chave: BER, MIMO, Multipath/ Múltiplos Caminhos, Rayleigh, Rician.

RESUMEN

En las comunicaciones inalámbricas existen los fenómenos multitrayecto Rician y Rayleigh, los cuales pueden provocar interferencia destructiva, causada por una fuerte componente dominante. El objetivo del estudio es analizar como estos fenómenos multitrayecto afectan a la Tasa de Error Binario (BER), utilizando la modulación por desplazamiento de fases (QPSK), así también como la tecnología Múltiple Entrada Múltiple Salida (MIMO) de 5G a reducir o no el efecto del desvanecimiento para mejorar el BER. Para el presente estudio se utiliza el método cuantitativo para medir el BER mediante simulaciones comparativas de los fenómenos Rician y Rayleigh, utilizando distintitos esquemas de configuraciones de antenas MIMO mediante el software Matlab. Al realizar la comparación de los fenómenos multi trayecto Rician y Rayleigh con modulación QPSK se pudo determinar que el canal más eficiente es el canal Rician, ya que el BER es menor, realizando una configuración de antenas MIMO 4x4. Sin embargo, esta eficiencia puede cambiar si se utiliza otro tipo de modulación, lo que implica reducir la tasa de transmisión de bits provocando una reducción de ancho de banda.

Palabras clave: BER, MIMO, Multitrayecto, Rayleigh, Rician.

INTRODUCTION

Cellular communications have been undergoing a number of changes, which began with the need to transmit audio between two separate geographic points. However, it has been seen that cellular communications have gone through an important evolution, not only with the need to transmit voice but also data, voice and video through its different generations: 1G, 2G 3G, 4G and in the most recent 5G. The latter, 5G communications have as its main objective to transmit the largest amount of information, over long distances and in the shortest possible time, standing out for its high quality and low costs. For this type of transmission, 5G relies on MIMO technology. This involves placing a large number of antennas on the transmitter and/or receiver side, which allows significantly high spectral efficiency and reliability, at least from a theoretical point of view (Hama and Ochiai 2019). According to Sah and Chugh (2021), a channel with MIMO technology allows to have higher reliability for continuous communication configuration, improving the performance of the communication system coverage through relay cooperation, necessary to meet the increasing user demand.

Wireless communications are characterized by fading effects. Large-scale fading represents attenuation in average signal power or path loss due to motion over large areas. Small-scale fading refers to the dramatic changes in signal amplitude and phase that can be experienced as a result of small changes in the spatial separation between a receiver and transmitter (Chandran, Raju, and Reddy 2018). Within these phenomena are Rician and Rayleigh fading.

Different authors have conducted investigations to measure the signal-to-noise (SN) interference ratio and closed-form bit error rate (BER) expressions of the detector, where the error rate performance and outage probabilities of the MMSE detector are also examined based on the high SNR approximation. Based on the Gamma distribution approximation of MMSE receiver output (Hama and Ochiai 2019) by applying the Rician and Rayleig multipath phenomena, using MIMO technology individually, where different types of modulations are included. For example, (Li et al. 2020) determines that using Rician if the parameter K representing the Line of Sight (LOS) power ratio is smaller the BER also decreases.

Among the modulations used for the analysis of these phenomena, authors use the following modulations: BPSK (Binary shift phase modulation), QPSK (Quad-phase phase shift keying) and QAM (quadrature amplitude modulation). The PSK phase shift keying technique is a process that transmits information or data by modulating the phase of a reference signal which is also called a carrier wave. The function of the demodulator is to determine the phase of the received signal and assign it back to the symbol that represents the phase shift keying technique is a process that transmits information or data by modulating the phase of a reference signal that is also called a carrier wave. The function of the demodulator is to determine the phase of the received signal and assign it back to the symbol it represents (P, M.G, and M 2016). The BPSK modulation scheme represents the change of data, or modulating two different phases of a reference signal (carrier), each of these phases are separated by 180° (Chandran et al. 2018). QPSK can be used to double the data rate compared to a standard BPSK system while maintaining the same signal bandwidth, or to maintain the data rate of BPSK but halving the necessary bandwidth requirement (P et al. 2016). Quadrature amplitude modulation (QAM) is a modulation technique that uses two amplitude-modulated radio frequency carriers that are 90° out of phase. Information transfer is achieved using a mixture of phase and amplitude shift to improve transmission efficiency (Chandran et al. 2018).

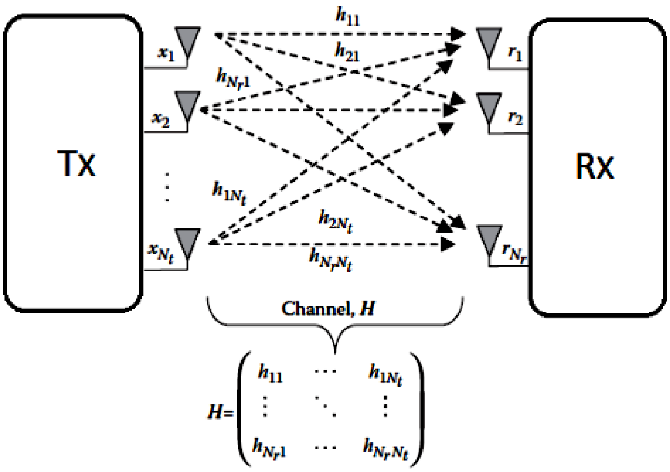
The BER performance of BPSK, QPSK and 16-QAM in OFDM e.g. (Kaur et al. 2018) manifests that the comparison of BER probability performance of three different modulation schemes BPSK, QPSK and 16-QAM the BER probability performance in RS-encoded (Rician Shadowed) OFDM communication system is improved by using BPSK modulation scheme, but (P et al. 2016) indicates that the BER of QPSK is exactly the same as the BER of BPSK and deciding differently is a common chaos when considering or describing QPSK. However, when higher bandwidths are required QSPK is better according to Jangir et al. (2020) especially when using MIMO schemes such as the one studied by Jangir et al. (2020) which performs the study using Long Term Evolution (LTE) technology by means of a 2x2 MIMO scheme. Finally, Pushpalatha et al. (2022) indicates that the BER response using a BPSK modulation against the power transmitted through the Rician channel is better, compared to the Rayleigh fading channel therefore, in this work we intend to perform an accurate comparison to perform a more approximate measurement of BER using QPSK modulation with different MIMO configurations.

MATERIALS AND METHODS

The research applies a quantitative methodology to evaluate the BER by applying different simulated scenarios.

The data are analyzed with the help of mathematical models, MATLAB and Simulink software, using the multipath Rician and Rayleigh phenomena, in the characterization of the Rayleigh channel the amplitude of the signal voltage at reception is taken into account, as well as the received power, for the case of the Rician probability parameters such as the peak amplitude of the dominant signal is taken into account, as well as the power of the components if line of sight (NLOS). The MIMO configuration used is Nt×Nr single user, where Nr is the number of receiving antennas and Nt the number of transmitting antennas as shown in Figure 1.

Figure 1 Block diagram of the MIMO system model.



Source: authors based on GuptaP et al. (2016)

Where:

X: vector of transmitted signal

R: received signal vector

H: channel matrix

N: transmitting antenna number

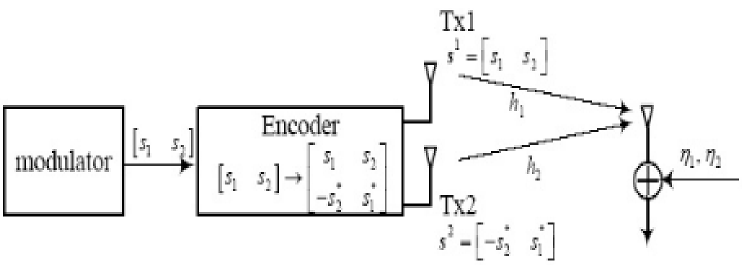
M receiving antenna number

General Model

To perform the simulation, a Bernoulli Binary distribution was used, using a QPSK modulator and then connecting an Alamouti STBC 2x1 System (2 transmitting antennas and 1 receiving antenna) as shown in Figure 2. First, the transmitter collects two constellation symbols, where the set of signal constellations consists of $M = 2^m$. If S_1 y S_2 are the selected symbols, the transmitter sends $S_1$from antenna one and $-S_2^*$ antenna one at a time. Then, at instant two, it transmits S_2 y S_1^* from antennas one and two, respectively. Thus, the transmitted code word is described in equation 1 (Wen, Gong, & Ho, 2010):

$$S = \begin{pmatrix} S_1 & S_2 \\ -S_2^* & -S_1^* \end{pmatrix} \quad 1)$$

Figure 2 Alamounti Code Block Diagram



Source: (Wen, Gong, and Ho 2010)

Finally, the decoder receives the signals r_1 y r_2 sometimes 1 or sometimes 2 respectively as shown in equation 2:

$$\begin{cases} r_1 = h_1 s_1 - h_2 s_2^* + \eta_1 \\ r_2 = h_1 s_2 - h_2 s_1^* + \eta_2 \end{cases} \qquad 2)$$

where η1, η2 are Gaussian noise with zero mean.

Then, the MIMO scheme described above is connected to the multipath phenomena with Rayleigh channel, with a circularly symmetric complex Gaussian complex random variable having the following form:

$$h - h_{re} + jh_{im} \qquad 3)$$

The real and imaginary parts are independent, zero-mean, identically distributed Gaussian random variables with mean 0 and variance σ^2. The probability density function of the magnitude h of the complex Gaussian random variable has been defined as seen in Equation 4 (Ajose, Bakare, and Imoize 2017):

$$P(h) = \frac{h}{\sigma^2} e^{-\frac{h^2}{2\sigma^2}} \qquad 4)$$

The received signal in a Rayleigh fading channel is of the form,

$$y = hx + n \qquad 5)$$

The Rician fading model is similar to the Rayleigh model, except that in Rician there is a strong dominant component. This dominant component can be with LOS, this model has two Gaussian components of random variables, represented by two means (m1 and m2) and variance σ^2(Becker et al. 2015).

A complex Gaussian random variable is defined, as shown in equation 6.

$$Z = X + jY \qquad 6)$$

Now, the envelope of the complex random variable is given by equation 7.

$$R = \sqrt{X^2 + Y^2} \qquad 7)$$

Since, the two variables X and Y have different "means", a non-centrality parameter (indicating the non-central mean) is defined, as shown in equation 8.

$$s = \sqrt{m_1^2 + m_2^2} \qquad 8)$$

The non-centrality parameter (the imbalance in the means) is caused by the presence of a dominant path, in a Rician fading environment. Because of this, the Rician K-factor represents the ratio of LOS power (or dominant multipath component) and NLOS power (or remaining multipath components), this is defined in such a scenario (Becker et al. 2015) as shown in Equation 9.

$$K = \frac{Potencia\ de\ componentes\ LOS}{Potencias\ de\ componentes\ NLOS} \qquad 9)$$

The envelope (R) follows the Rician distribution, whose PDF is given by:

$$f_r = \frac{r}{\sigma^2} e^{\left(-\frac{r^2+s^2}{2\sigma^2}\right)} I_0\left(\frac{rs}{\sigma^2}\right) \qquad 10)$$

Following the schematic the output is connected to Additive white Gaussian noise model (AWGN). The AWGN is commonly used to transmit signal as the signals travel from the channel and simulate the channel background noise.

According to Ajose et al. (2017) the mathematical expression in the received signal that passed through the AWGN channel is given as seen in equation 11.

$$r(t) = s(t) + n(t) \tag{11}$$

Where s(t) is the transmitted signal and n(t) is the background noise.

Similarly, the probability density function for an AWGN is defined as:

$$p(r) = \frac{r}{\sigma\sqrt{2\pi}} e^{\left(\frac{-(x-\mu)^2}{2\sigma^2}\right)} \tag{12}$$

Where μ is the mean and σ is the standard deviation.

As a final part of the scheme, the Alamunti decoder, a QPSK decoder, a display to visualize the BER data and the BER plot generator that works with the Matlab tool bertool are connected. Another parameter to be studied is the gradient of the BER change and the signal to noise ratio according to equation 13, this will allow to evaluate the performance of the transmission system according to the scenarios proposed in section 2.2, which will be correlated with the Pearson's quadratic correlation factor R_y^2 given by equation 14, which will be obtained by analyzing the Doppler frequency of the simulated scenario with the theoretical Doppler frequency in wireless transmission systems with MIMO.

$$\frac{\Delta BER}{\Delta dB(S/_N)} = \frac{1}{N-1}\sum_{i=2}^{N} \frac{BER_i - BER_{i-1}}{(S/_N)_i - (S/_N)_{i-1}} \tag{13}$$

The R_y^2 will yield a metric or indicator of the transmission tuning band, the value of which tends to one will R_y^2 value that tends to one will allow to determine which is the most efficient system.

$$R_y^2 = 1 - \frac{\sum_{i=0}^{N}\left(\widehat{Y}_i - Y_i\right)}{\sum_{i=0}^{N}(Y_i)^2} \tag{14}$$

Where $\widehat{Y}_i$ is the magnitude of the transmission Doppler survey

Where Y_i is the ideal magnitude of the Doppler study

Equation 14 will not consider the suppression of the average value of the samples to quantify all the components of the spectral study. Next, the possible scenarios to be tested in the investigation are presented.

Simulation Scenario 1

Parameter	Value
Probability of 0	0.5
Modulation Scheme	QPSK
Alamounti Encoder	2 transmitting antennas
Multipath phenomenon	Rayleigh
Maximum Doppler Shift	40 Hz
MIMO scheme	2 transmitting antennas, 2 receiving antennas
Channel AWG	watts input power 2 bits per symbol, guard duration 1.6 ms

Simulation Scenario 2

Parameter	Value
Probability of 0	0.5
Modulation Scheme	QPSK
Alamounti Encoder	3 transmitting antennas
Multipath phenomenon	Rayleigh
Maximum Doppler Shift	40 Hz
MIMO scheme	3 transmitting antennas, 3 receiving antennas
Channel AWG	watts input power 2 bits per symbol, guard duration 1.6 ms

Simulation Scenarios3

Parameter	Value
Probability of 0	0.5
Modulation Scheme	QPSK
Alamounti Encoder	4 transmitting antennas
Multipath phenomenon	Rayleigh
Maximum Doppler Shift	40 Hz
MIMO scheme	4 transmitting antennas, 4 receiving antennas
Channel AWG	watts input power 2 bits per symbol, guard duration 1.6 ms

Simulation Scenario 4

Parameter	Value
Probability of 0	0.5
Modulation Scheme	QPSK
Codificacodor Alamounti	2 transmitting antennas
Multipath phenomenon	Rician factor k=20
Maximum Doppler Shift	40 Hz
MIMO scheme	2 transmitting antennas, 2 receiving antennas
Channel AWG	watts input power 2 bits per symbol, guard duration 1.6 ms

Simulation Scenario 5

Parameter	Value
Probability of 0	0.5
Modulation Scheme	QPSK
Alamounti Encoder	3 transmitting antennas
Multipath phenomenon	Rician factor k=20
Maximum Doppler Shift	40 Hz
MIMO scheme	3 transmitting antennas, 3 receiving antennas
Channel AWG	watts input power 2 bits per symbol, guard duration 1.6 ms

Simulation Scenario 6

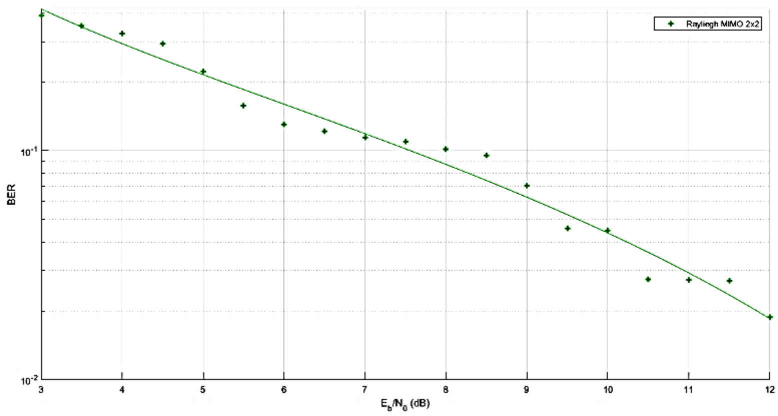
Parameter	Value
Probability of 0	0.5
Modulation Scheme	QPSK
Alamounti Encoder	4 transmitting antennas
Multipath phenomenon	Rician factor k=20
Maximum Doppler Shift	40 Hz
MIMO scheme	4 transmitting antennas, 4 receiving antennas
Channel AWG	watts input power 2 bits per symbol, guard duration 1.6 ms

RESULTS AND DISCUSSION

Figures 3, 4 and 5 show the BER value with respect to the Signal to Noise Ratio (SNR or Eb/No), in decibels (db) of the configurations according to scenarios 1, 2 and 3 above, based on the Raylingh configuration and the different MIMO schemes.

Specifically, Figure 3 shows the result of the simulation of the Rayleigh phenomenon with a 2x2 MIMO scheme, where the BER with 12 dB of energy per bit / spectral density of noise power ratio) reached the value of 0.019.

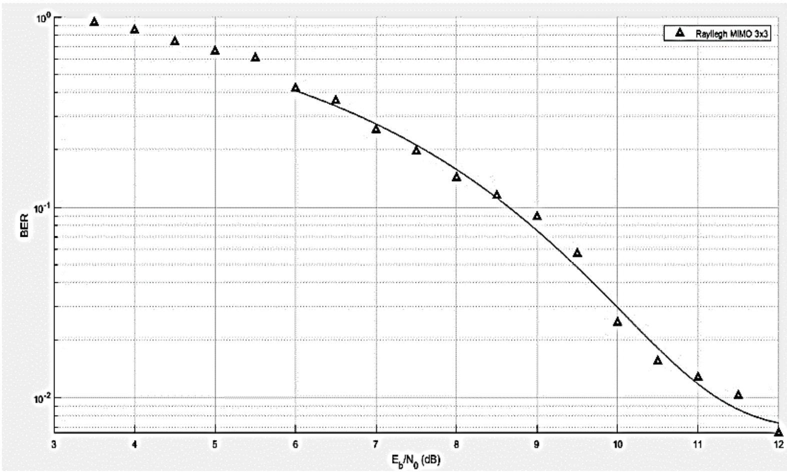
Figure 3 Simulation Scenario1



Source: authors based on the research data (2023)

Figure 4 shows the simulation of the Rayleigh phenomenon with a 3x3 MIMO scheme, where the BER with a 12 dB energy per bit / spectral density ratio reached a value of 0.0019.

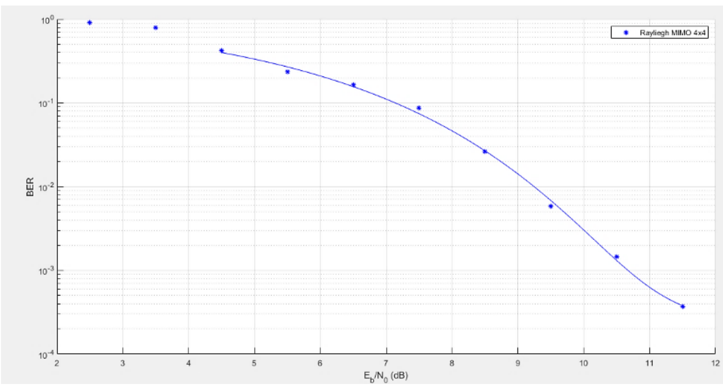
Figure 4 Simulation Scenario 2



Source: authors based on the research data (2023)

Figure 5 shows the simulation of the Rayleigh phenomenon with a 4x4 MIMO scheme, where the BER with a 12 dB energy per bit / spectral density ratio reached a value of 0.004.

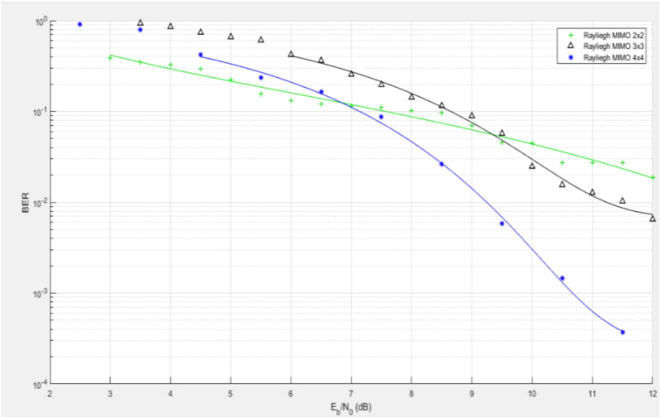
Figure 5 Simulation Scenario 3



Source: authors based on the research data (2023)

Finally, Figure 6 shows a comparison of scenarios 1, 2 and 3, in which it can be seen that the lowest BER is obtained with a 4x4 MIMO antenna configuration, the latter being the most efficient configuration.

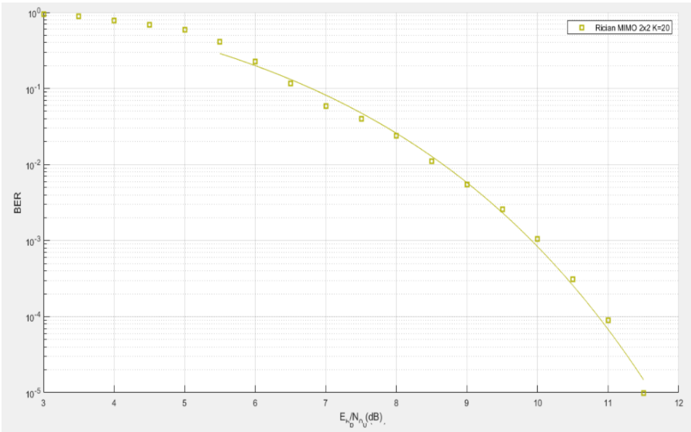
Figure 6 Comparison of the Rayleigh Phenomenon



Source: authors based on the research data (2023)

Figures 7, 8 and 9 show the simulation of scenarios 4, 5 and 6 applying the Rician multipath phenomenon. Specifically, Figure 7 shows the simulation of the Rician phenomenon with a 2x2 MIMO scheme, where the BER with 11.5 dB energy per bit / spectral density ratio reached a value of 0.00001.

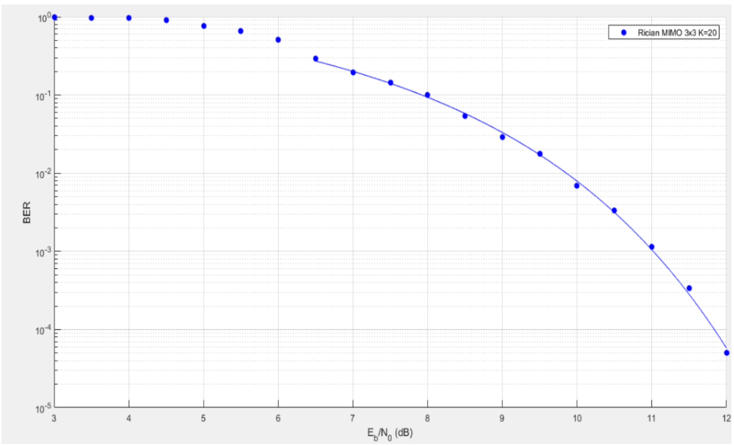
Figure 7 Simulation Scenario 4



Source: authors based on the research data (2023)

Figure 8 shows the simulation of the Rayleigh phenomenon with a 3x3 MIMO scheme, where the BER with 12 dB, energy per bit / spectral density ratio reached a value of 0.00004.

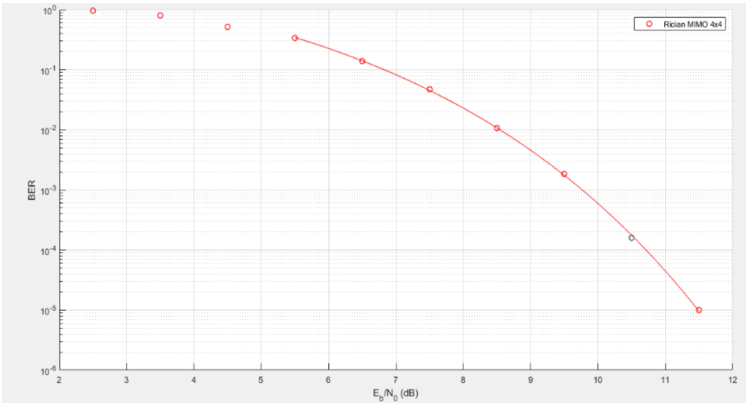
Figure 8 Simulation Scenario 5



Source: authors based on the research data (2023)

Figure 9 shows the simulation of the Rayleigh phenomenon with a 4x4 MIMO scheme, where the BER with 11.5 dB of energy per bit / spectral density ratio reached a value of 0.00001.

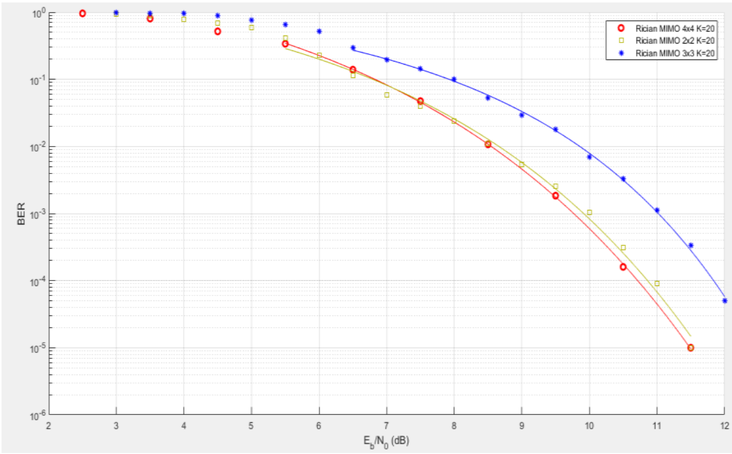
Figure 9 Simulation Scenario 6



Source: authors based on the research data (2023)

The next point is the comparison of the Rician multipath phenomenon applying the three MIMO schemes as shown in Figure 10, in this particular case the most deficient scheme is the 3x3 configuration, however, the most efficient is still the 4x4 MIMO scheme but without much difference in BER with respect to the configuration with Rician and 4x4 MIMO.

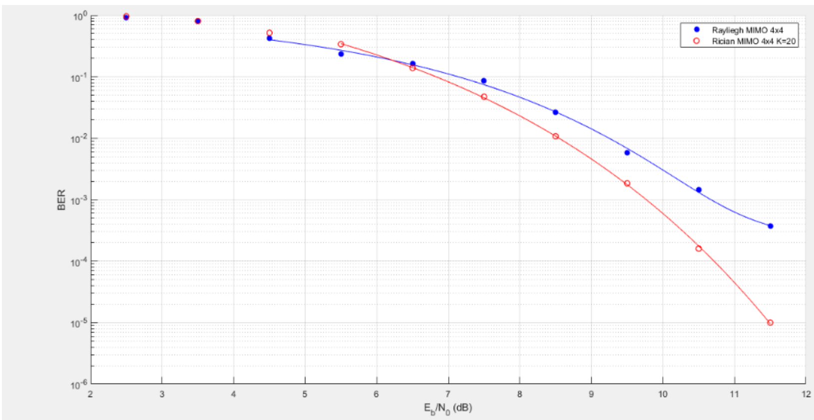
Figure 10 Comparison of the Rician Model



Source: authors based on the research data (2023)

Finally, we compare the two models with the most efficient configurations, being the configuration with Rician fading with a value of K=20 and MIMO 4x4, being approximately 10% more efficient with respect to the VER as shown in Figure 11.

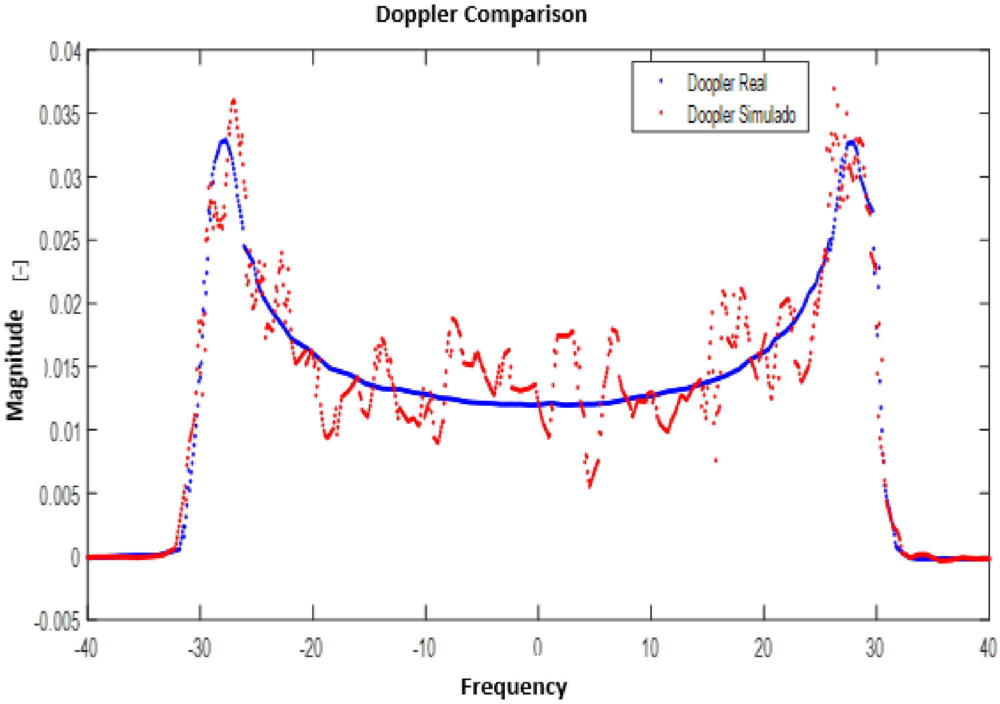
Figure 11 De Rician and Rayleigh comparison with 4x4 MIMO



Source: authors based on the research data (2023)

Figure 11 shows that the higher the signal to noise ratio (Eb/No) the BER decreases and therefore the rate of change or gradient of change is higher. According to the evaluation criteria for each of the scenarios, the Doppler frequency graphs are obtained, as shown below, as well as the value of R_y^2.

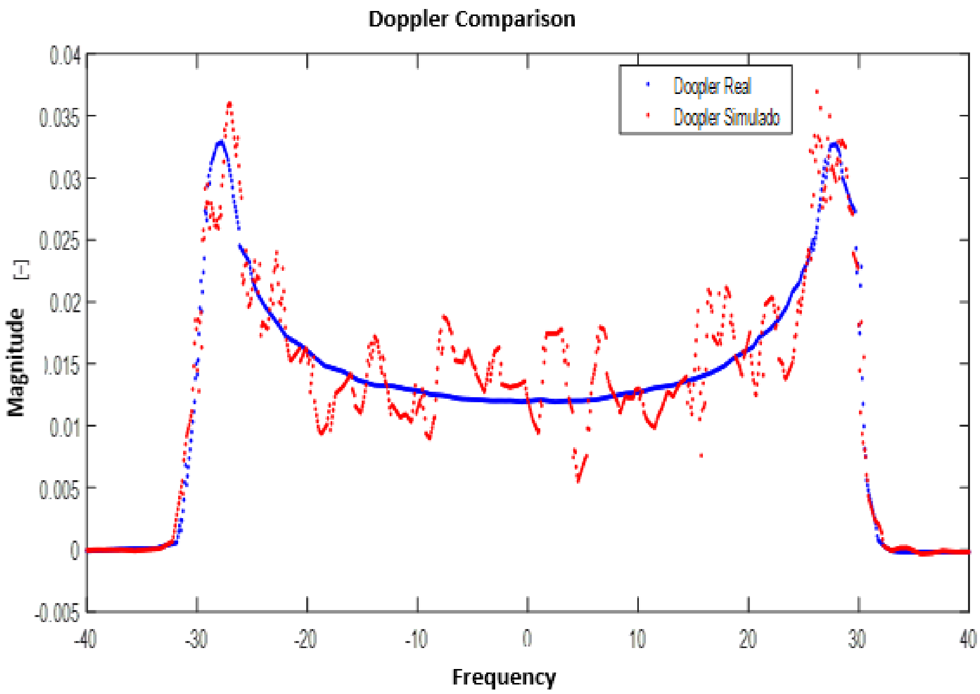
Figure 12 Doppler Comparison with Rician Phenomenon MIMO 2x2



Source: authors based on the research data (2023)

Note: Figure 12 shows a value of $R_y^2 = 0.968268494304479$

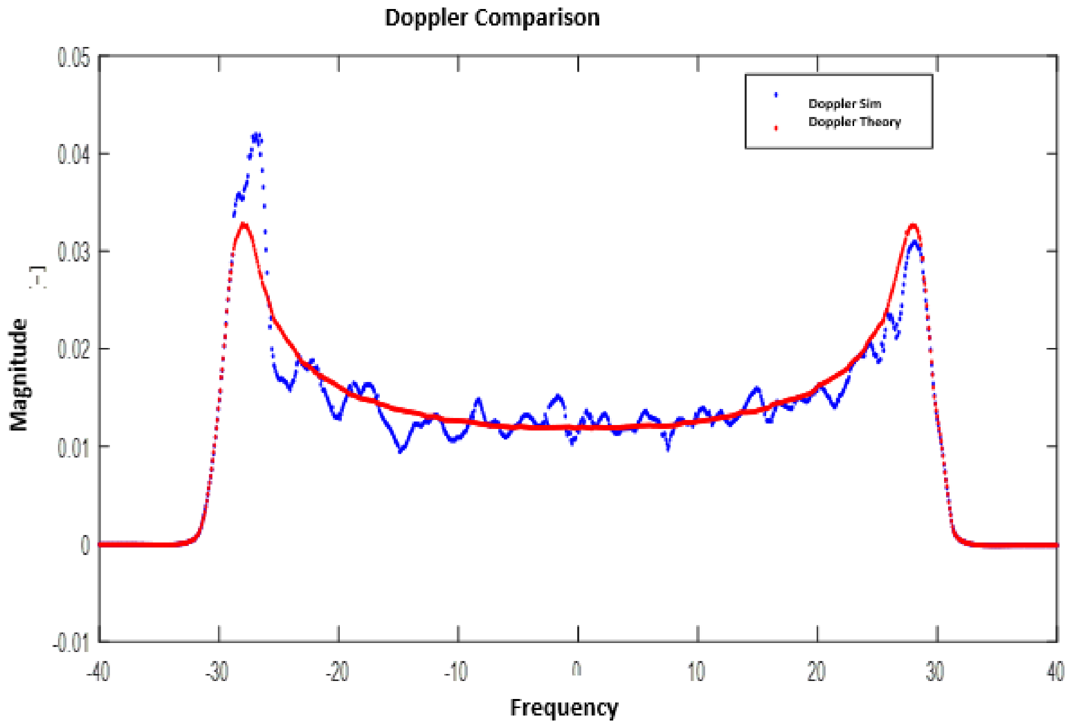
Figure 13 Doppler comparison with Rayleigh MIMO 2x2 Rayleigh Phenomena



Source: authors based on the research data (2023)

Note: Figure 13 shows a value of $R_y^2 = 0.968205076471747$

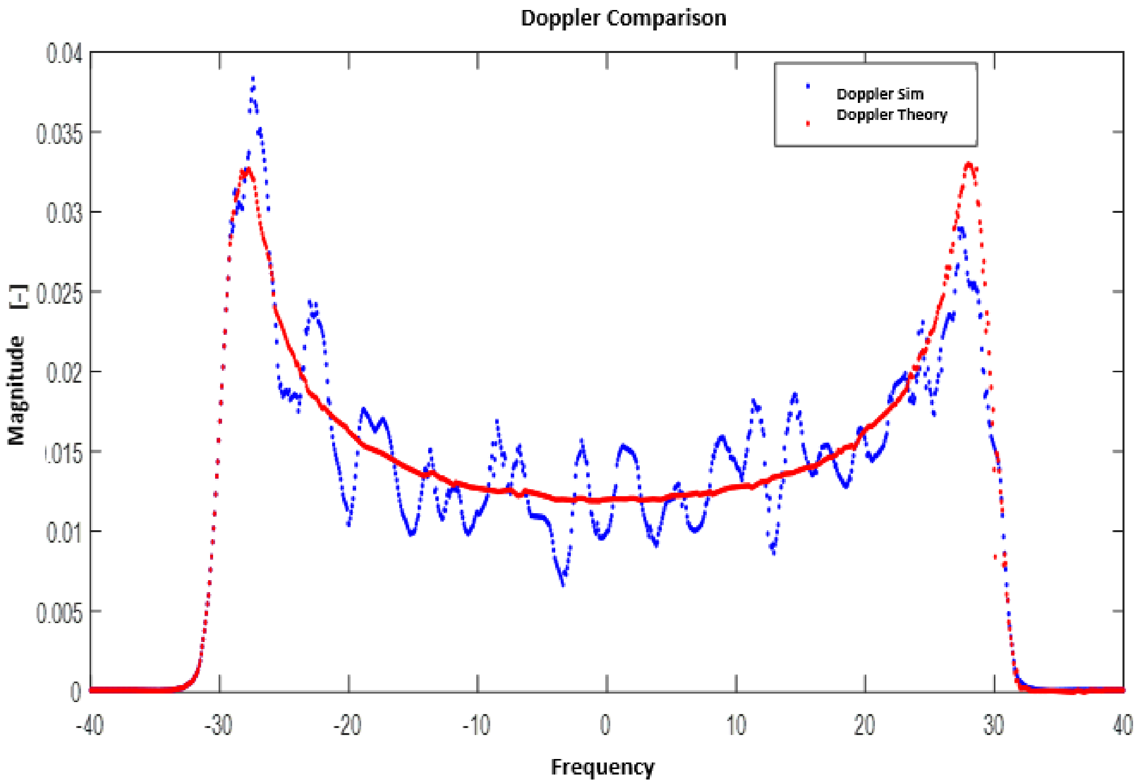
Figure 14 Doppler Comparison with Rician Phenomenon MIMO 3x3



Source: authors based on the research data (2023)

Note: Figure 14 shows a value of $R_y^2 = 0.9797666129314$

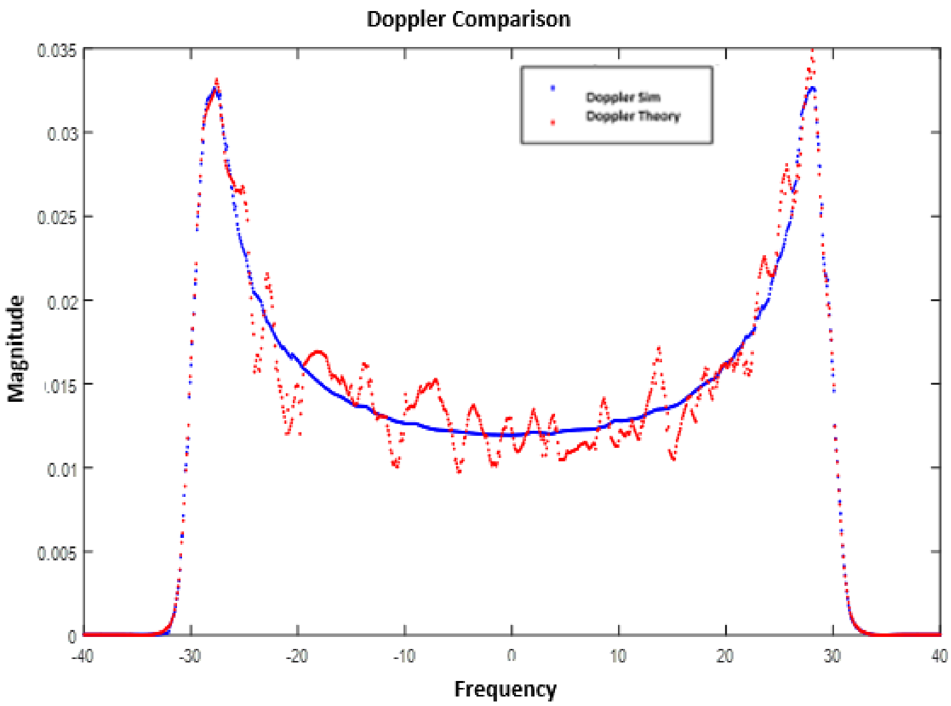
Figure 15 Doppler comparison with Rayleigh Phenomenon MIMO 3x3



Source: authors based on the research data (2023)

Note: Figure 15 shows a value of $R_y^2 = 0.975206217420933$

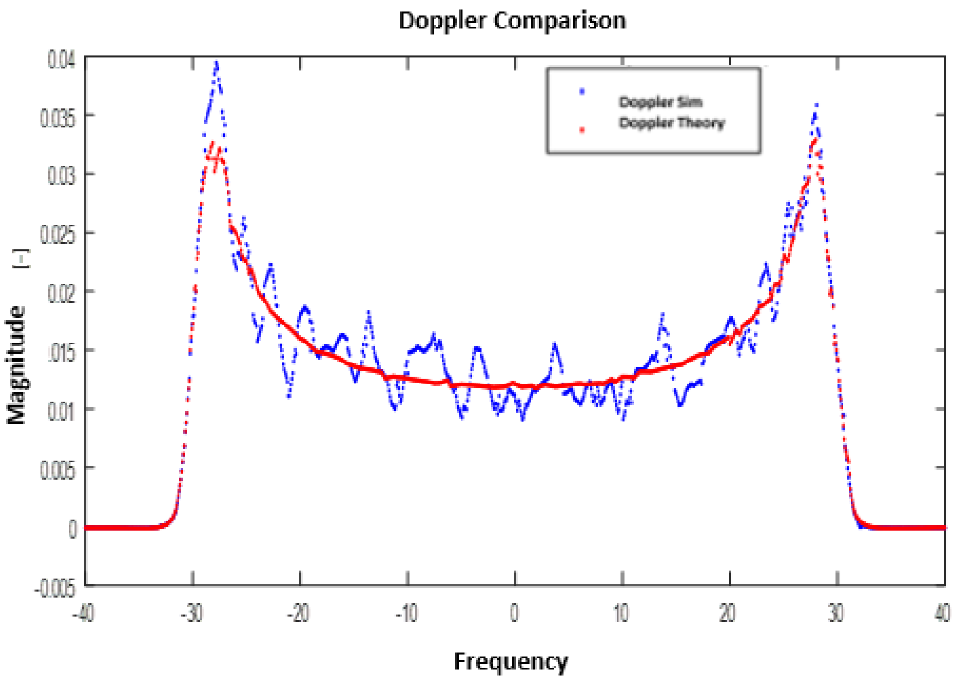
Figure 16 Doppler Comparison with Rician Phenomenon MIMO 4x4



Source: authors based on the research data (2023)

Note: Figure 16 shows a value of $R_y^2 = 0.991926286137174$

Figure 17 Comparison of Doppler with Rayleigh Phenomenon MIMO 4x4



Source: authors based on the research data (2023)

Note: Figure 17 shows a value of $R_y^2 = 0.984729640554956$

The results shows the efficacy of MIMO configurations in wireless communication systems, highlighting the superiority of the 4x4 MIMO setup, particularly in conjunction with the Rician channel, which exhibits significantly lower BER values. These findings align with prior research by Wang et al., (2022), underscoring the pivotal role of MIMO technology in enhancing reliability and spectral efficiency in communication systems. The study also follow results presented in Zhao et al,.

(2017), demonstrating that, under specific conditions, such as a smaller Line of Sight (LOS) power ratio, employing Rician fading leads to a diminished BER. Additionally, the nuanced impact of fading models and MIMO configurations, as portrayed in the comparison of scenarios, provides valuable insights for optimizing communication systems. The Doppler frequency analysis, introduced in this study, aligns with Rodriguez et al., (2018) approach to evaluating transmission quality metrics. These results collectively contribute to the growing body of literature on MIMO technology and fading phenomena, offering practical implications for the design and deployment of reliable wireless communication systems.

CONCLUSIONS AND FINAL REMARKS

In this paper we analyzed the capacity of systems with massive MIMO communications, using Rician and Rayleigh Multipath channels, where it was observed that the most efficient configuration is a 4x4 MIMO configuration, this means that if the number of antennas is increased, the BER will be lower, approximately 1 dB energy per bit / density ratio, between the 3x3 and 4X4 configuration; and approximately 2dB energy per bit / density ratio, with the 2x2 configuration respectively.

The most efficient channel turns out to be the Rician channel, since at 11.5 dB approximately 10^{-5} bits are lost, while with Rayleigh the loss is 10^{-3} bits.

From the Doopler study and its evaluation using the multivariate correlation factor, it can be concluded that this indicator can be used as a metric to assess the goodness of transmission quality under the criteria proposed in the experimentation, where the value closest to one is R^2_y= 0.991926286137174, using the Rician scattering phenomenon and a MIMO antenna configuration of 4 transmitters and 4 receivers.

In conclusion, this study presents a thorough investigation into the bit error rate (BER) performance in wireless communication systems, considering the impact of Rayleigh and Rician fading phenomena, diverse modulation techniques, and multiple input multiple output (MIMO) configurations. The findings reveal that the 4x4 MIMO configuration, particularly in conjunction with the Rician channel, emerges as the most efficient setup, showcasing significantly lower BER values. Notably, the research introduces a novel metric—the multivariate correlation factor—providing a nuanced understanding of transmission quality. The inclusion of Doppler frequency analysis further enriches the assessment criteria. These results not only contribute valuable insights into the design and optimization of communication systems but also highlight the prominence of MIMO technology in enhancing reliability and spectral efficiency.

Future research in wireless communication should focus on integrating machine learning for real-time adaptability, investigating security implications in various MIMO configurations, exploring cross-layer optimization for enhanced performance, and conducting user-centric studies to tailor systems to evolving needs. Real-world validations through field trials will confirm the practical applicability and robustness of these research directions. In the Table 1 above there are some research proposals for a possible future agenda of new studies.

Table 1. Proposed research agenda for future studies

Research Area	Focus
Machine Learning Integration	Explore real-time adaptability with machine learning algorithms, understanding causal relationships between models and communication system performance. Address unpredictability in fading conditions.
Security Implications	Investigate vulnerabilities introduced by specific MIMO configurations and fading models. Analyze causal links between security measures, like encryption protocols, and bit error rate (BER) in diverse communication scenarios.
Cross-Layer Optimization	Examine the interconnectedness of physical, link, and network layers for holistic optimization. Identify causal relationships to enhance resource allocation, reliability, and reduce latency.
User-Centric Studies	Explore causal relations between user-centric variables (e.g., data rate, latency) and optimal MIMO configurations for specific use cases. Tailor wireless communication systems to evolving user needs.
Real-World Validation	Conduct field trials and validations to confirm the practical applicability and robustness of simulation results. Ensure research findings translate effectively into solutions for diverse operational settings.

Source: own elaboration (2023)

Finally, the study may be limited by the simulation-based approach, lacking real-world complexities. Additionally, the chosen scenarios may not fully capture all possible deployment situations. Generalization of results to broader communication contexts may be constrained. Future studies aim to mitigate limitations by integrating real-world experimentation, diversifying scenarios, and incorporating additional variables for a more effective understanding and improved generalizability.

REFERENCES

Ajose, Simeon Olumide, Rasheed Alade Bakare, and Agbotiname Lucky Imoize. 2017. "BER Comparison of Different Modulation Schemes over AWGN and Rayleigh Fading Channels for MIMO-OFDM System." International Journal of Communication Networks and Distributed Systems 18(2):129–47. doi: 10.1504/IJCNDS.2017.082102.

Chandran, Indu, M. Raju, and K. Ashoka Reddy. 2018. "Comparative Analysis of Various Channel Estimations under Different Modulation Schemes." Proceedings - International Conference on Trends in Electronics and Informatics, ICEI 2017 2018-Janua(3):832–37. doi: 10.1109/ICOEI.2017.8300821.

GuptaP, Shavel, Lokesh BhardwajP, Abhishek AnandP, and Anand Singh RajpootP. 2016. "Comparison of BER Performance & Capacity Analysis of MIMO System with STBC & MRC to Improve Link Performance in Fading Environment." International Journal of Scientific Engineering and Applied Science (IJSEAS) (2):354–57.

Hama, Yuto, and Hideki Ochiai. 2019. "Performance Analysis of Matched-Filter Detector for MIMO Spatial Multiplexing over Rayleigh Fading Channels with Imperfect Channel Estimation." IEEE Transactions on Communications 67(5):3220–33. doi: 10.1109/TCOMM.2019.2892758.

Imoize, A. L., Orolu, K., & Atayero, A. A. A. (2020). Analysis of key performance indicators of a 4G LTE network based on experimental data obtained from a densely populated smart city. *Data in brief*, *29*, 105304.

Jangir, Dimple, Gori Shankar, Bharat Bhusan Jain, and Gaurav Kumar Soni. 2020. "Performance Analysis of LTE System for 2x2 Rayleigh and Rician Fading Channel." Proceedings - International Conference on Smart Electronics and Communication, ICOSEC 2020 (Icosec):961–66. doi: 10.1109/ICOSEC49089.2020.9215229.

Kaur, Simarjeet, Navdeep Singh, Gagandeep Kaur, and Jasbir Singh. 2018. "Performance Comparison of BPSK, QPSK and 16-QAM Modulation Schemes in OFDM System Using Reed-Solomon Codes." 2018 International Conference on Recent Innovations in Electrical, Electronics and Communication Engineering, ICRIEECE 2018 530–33. doi: 10.1109/ICRIEECE44171.2018.9008983.

Li, Chunxiao, Jie Yao, Haitao Wang, Usman Ahmed, and Shixiao Du. 2020. "Effect of Mobile Wireless on Outage and BER Performances over Rician Fading Channel." IEEE Access 8:91799–806. doi: 10.1109/ACCESS.2020.2994350.

Ogbebor, J. O., Imoize, A. L., & Atayero, A. A. A. (2020). Energy efficient design techniques in next-generation wireless communication networks: emerging trends and future directions. *Wireless communications and mobile computing*, *2020*, 1-19.

P, Sunil Kumar, Sumithra M.G, and Sarumathi M. 2016. "Performance Analysis of Rayleigh Fading Channels in MIMO-OFDM Systems Using BPSK and QPSK Modulation Schemes." The SIJ Transactions on Computer Networks & Communication Engineering 04(02):01–06. doi: 10.9756/sijcnce/v4i2/01010258.

Pushpalatha, Prathyusha, Sindhu, Mohd Javed Khan, Indrasen Singh, and Shubham Tayal. 2022. "BER Performance Using BPSK Modulation over Rayleigh and Rician Fading Channel." Proceedings - 2022 IEEE 11th International Conference on Communication Systems and Network Technologies, CSNT 2022 434–37. doi: 10.1109/CSNT54456.2022.9787656.

Rodríguez, D. Z., Pívaro, G. F., Rosa, R. L., Mittag, G., & Möller, S. (2018, September). Improving a parametric model for speech quality assessment in wireless communication systems. In 2018 26th International Conference on Software, Telecommunications and Computer Networks (SoftCOM) (pp. 1-5). IEEE.

Sah, M., and A. Chugh. 2021. "Performance Analysis of LTE System for 2x2 Rayleigh and Rician Fading Channel." Aptisi Transactions on Technopreneurship (ATT) 3(1). doi: 10.34306/att.v3i1.131.

Wang, B., Xu, K., Zheng, S., Zhou, H., & Liu, Y. (2022). A deep learning-based intelligent receiver for improving the reliability of the MIMO wireless communication system. IEEE Transactions on Reliability, 71(2), 1104-1115.

Wen, Hong, Guang Gong, and Pin Han Ho. 2010. "MIMO Cross-Layer Secure Communication Architecture Based on STBC." GLOBECOM - IEEE Global Telecommunications Conference (May 2014). doi: 10.1109/GLOCOM.2010.5684012.

Zhao, F., Lin, H., Zhong, C., Hadzi-Velkov, Z., Karagiannidis, G. K., & Zhang, Z. (2017). On the capacity of wireless powered communication systems over Rician fading channels. IEEE Transactions on Communications, 66(1), 404-417.

Contribution of each author to the manuscript:

	% of contribution of each author				
Task	**A1**	**A2**	**A3**	**A4**	**A5**
A. theoretical and conceptual foundations and problematization:	20%	20%	20%	20%	20%
B. data research and statistical analysis:	20%	20%	20%	20%	20%
C. elaboration of figures and tables:	20%	20%	20%	20%	20%
D. drafting, reviewing and writing of the text:	20%	20%	20%	20%	20%
E. selection of bibliographical references	20%	20%	20%	20%	20%
F. Other (please indicate)	-	-	-	-	-

Indication of conflict of interest:

There is no conflict of interest

Source of funding

There is no source of funding

Acknowledgments

There is no acknowledgments.