Performance Evaluation of Channel Estimation Techniques under Doppler Effects in IEEE 802.11 Rician Channels

Yusuf Emre BAYSAL
Electronics Engineering Department
İstanbul Technical University
İstanbul/Turkey
baysal24@itu.edu.tr

***Abstract*— This study evaluates three channel estimation techniques—MATLAB's built-in LS-based estimator, standalone LS, and MMSE—within the IEEE 802.11 Wi-Fi standard. Simulations in Rician and AWGN channels across varying Doppler shifts show similar performance among the estimators, with MMSE performing best and LS worst. All estimators suffer significant BER degradation beyond 1700 Hz Doppler. Reducing packet payload size improved preamble-based estimation at higher Doppler but remains impractical. The IEEE 802.11 standard, designed for static or low-mobility environments, is unsuitable for high-Doppler scenarios like LEO satellite communications. Optimized OFDM-based standards are needed to address such challenges.**

Keywords—OFDM, Doppler, Estimation, MMSE, Doppler, WiFi, IEEE 802.11, Rician Channel,

I. Introduction

Orthogonal Frequency Division Multiplexing (OFDM) has become a widely used technology in modern wireless communication systems due to its efficiency in high data rate transmissions. However, effects such as multipath fading and Doppler shift can significantly degrade the performance of OFDM signals, highlighting the critical importance of robust channel estimation techniques [2] [3].

Channel estimation algorithms like Least Squares (LS) and Minimum Mean Square Error (MMSE) are commonly employed in these systems. While MMSE provides higher accuracy with lower error rates, the simplicity and practicality of the LS method make it a preferred choice for many applications [2].

In Low Earth Orbit (LEO) satellite systems, categorized under Non-Terrestrial Networks (NTN), Doppler shifts caused by satellite motion can reach up to ±48 kHz. These shifts disrupt the orthogonality of OFDM signals, leading to significant performance losses. Addressing these shifts is essential to ensure the reliability of satellite-based communication systems. [3]

This study aims to analyze the impact of Doppler shifts on OFDM signals in LEO satellite communication systems and evaluate the performance of channel estimation techniques for mitigating these effects. The Rician channel model was chosen for this work as it effectively simulates satellite communication environments by incorporating both line-of-sight and multipath components.

MATLAB’s Communication Toolbox was utilized for the simulation, enabling the step-by-step modeling of OFDM signal transmission and reception based on the 802.11 standard [1]. The toolbox provided a foundation for signal generation, and the simulation incorporated Additive White Gaussian Noise (AWGN) and Rician channel effects to emulate realistic signal distortions. Using LS and MMSE channel estimation algorithms, the study seeks to recover the original signal from the distorted version, ensuring effective communication in challenging environments. Additionally, the estimation algorithm provided by MATLAB's Communication Toolbox will be compared as a third method to evaluate its effectiveness relative to LS and MMSE techniques.

II. Theoretical Background

A. *MATLAB IEEE 802.11 Transmission Example and the Custom Workflow*

The MATLAB IEEE 802.11 image transmission example and the custom workflow in this study align in their approach to simulating and analyzing wireless communication systems. Both workflows process data through MAC and PHY layers, introduce channel impairments, and perform signal recovery using estimation techniques.

In the MATLAB example, an image is segmented into Medium Access Control (MAC) Service Data Units (MSDUs), which are then converted to MAC Protocol Data Units (MPDUs) with sequential numbering. These MPDUs are passed to the physical (PHY) layer as Physical Layer Service Data Units (PSDUs), where they are processed into a baseband waveform using the *wlanWaveformGenerator* function. This waveform is transmitted through an Additive White Gaussian Noise (AWGN) channel, after which the noisy signal is decoded, and the image is reconstructed.

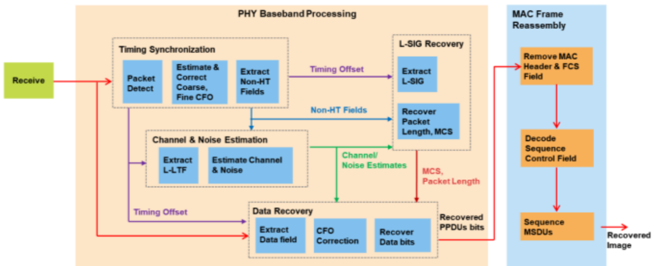

Figure 1 MATLAB Receiver PHY Baseband Processing

In this study, the workflow similarly starts with generating OFDM signals, but further incorporates advanced channel models such as Rician channels, which realistically simulate satellite communication environments. The transmitted signal is degraded by AWGN and Rician channel effects, representing typical impairments in LEO satellite communication. To recover the original signal, channel estimation algorithms, including Least Squares (LS) and Minimum Mean Square Error (MMSE), are applied. Additionally, the estimation algorithm provided by MATLAB's Communication Toolbox named *wlanLLTFChannelEstimate* is used for performance comparison.

By combining the robust PHY layer processing demonstrated in the IEEE 802.11 example with custom implementations for channel modeling and estimation, this study evaluates the effectiveness of different approaches in mitigating Doppler shifts and other channel distortions in satellite-based OFDM systems.

B. Least Squares Estimator

The Least Squares (LS) channel estimation is a fundamental technique in wireless communication systems and belongs to the class of classical estimation methods. It aims to estimate the channel response by minimizing the error between the observed and expected signals in the least squares sense, without relying on prior statistical information about the channel or noise.

1) Theoretical Basis

In the frequency domain, the relationship between transmitted signal **X**, received signal **Y**, and the channel response **H** is:

$$Y = H \cdot X + W$$

Where **W** is noise. he LS estimator calculates the channel response $\mathbf{H_{LS}}$ by assuming **X** is known and non-zero, leading the formula

$$H_{LS} = \frac{Y}{X}$$

This element-wise division computes the channel response for each frequency subcarrier.

2) Key Characteristics

- **Simplicity**: The LS method is computationally efficient, making it suitable for real-time applications.
- **Noise Sensitivity**: LS does not consider noise statistics, which can lead to performance degradation in low SNR conditions.
- **Wide Applicability**: It is versatile and widely used in systems where computational resources are limited.

C. Minimum Mean Square Error Estimator

The Minimum Mean Square Error (MMSE) channel estimation is an advanced technique based on the Bayesian estimation approach, designed to minimize the mean square error between the estimated and actual channel responses. Unlike the Least Squares (LS) method, MMSE incorporates noise statistics and prior information about the channel, making it more robust in noisy environments.

1) Theoretical Basis

In wireless communication systems, the received signal **Y** in the frequency domain can be represented as:

$$Y = H \cdot X + W$$

Where:

- Y: Received Signal.
- X: Transmitted signal (known pilot symbols).
- H: Channel frequency response to be estimated.
- W: Additive noise with variance σ^2

The MMSE estimator aims to estimate **H** by minimizing the mean square error. It is expressed as:

$$H_{MMSE} = H_{LS} \cdot \frac{|X|^2}{|X|^2 + \sigma^2}$$

Where:

- $H_{LS} = Y/X$ is the LS estimate of the channel.
- $|X|^2$ is the power of transmitted pilot symbols.
- σ^2 is the noise variance.
-

This equation adjusts the LS estimate by weighting it with a factor dependent on the signal-to-noise ratio (SNR). Higher SNR values give more weight to H_{LS} while lower SNR values reduce the influence of noisy observations.

2) Key Steps in MMSE Estimation

1. **Noise Variance Estimation**: The noise variance σ^2 is estimated based on the received training symbols.

2. **Weighting Coefficient Calculation**: The MMSE weighting factor is computed for each subcarrier as:
$$\alpha = \frac{|X|^2}{|X|^2 + \sigma^2}$$

3. **Channel Estimate Adjustment**: The LS estimate is scaled using the MMSE coefficient:
$$H_{MMSE} = H_{LS} \cdot \alpha$$

3) Advantages and Limitations

Advantages:

- Incorporates noise statistics for better performance in low SNR scenarios.
- Reduces estimation error compared to LS.

Limitations:

- Computationally more complex due to the need for noise variance estimation.
- Requires accurate noise power and pilot symbol information.

D. MATLAB’s Estimation Algorithm in MATLAB IEEE 802.11 Image Transmission Example

The *wlanLLTFChannelEstimate* function in MATLAB performs channel estimation for IEEE 802.11 WLAN packets using the Long Training Field (L-LTF). It employs the **Least Squares (LS) estimation** technique as its primary method and includes optional frequency smoothing for noise reduction.

1) Theoretical Basis

LS Estimation: The function computes the channel response using the LS method:

$$H_{LS} = \frac{Y}{X}$$

Where:

- **Y**: Received L-LTF symbols
- **X**: Reference L-LTF symbols

Time Averaging: If multiple L-LTF symbols are available, the function averages the estimates across symbols to mitigate noise.
Frequency Smoothing (Optional): A moving average filter can be applied across adjacent subcarriers to reduce noise further, particularly effective in correlated frequency channels.

E. *Preamble Signals in IEEE 802.11 to be Used to Estimate Channel*

1) *802.11a Packet Structure Review*

The 802.11a packet structure ensures reliable and efficient communication by dividing the packet into several fields, each with a specific purpose. The packet begins with the Short Training Field (STF) for initial synchronization, followed by the Long Training Field (LTF) for channel estimation and enhanced synchronization. The Signal Field (SIG) carries information about the transmission rate and packet length, while the Data Field contains the payload, including the Service field. Below, the detailed roles and compositions of the STF and LTF are outlined.

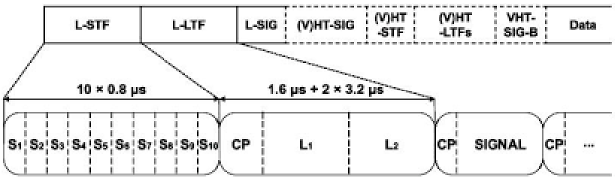

Figure 2 802.11a Non-HT Preamble Structure

2) *Short Time Training Field*

The Short Training Field (STF) is 8 µs in duration and plays a critical role in start-of-packet detection and automatic gain control (AGC) settings. It is also responsible for initial frequency offset estimation and time synchronization. In the time domain, the STF consists of ten repetitions of a 0.8 µs symbol, which provides the periodic structure necessary for efficient synchronization tasks.

3) *Long Time Training Field*

The Long Training Field (LTF) is also 8 µs in duration and is designed for channel estimation and improved frequency offset and time synchronization. It consists of two 3.2 µs long training symbols, each preceded by a 1.6 µs cyclic prefix. The cyclic prefix is derived from the second half of the long training symbol, ensuring resilience to multipath effects and maintaining synchronization in challenging wireless environments.

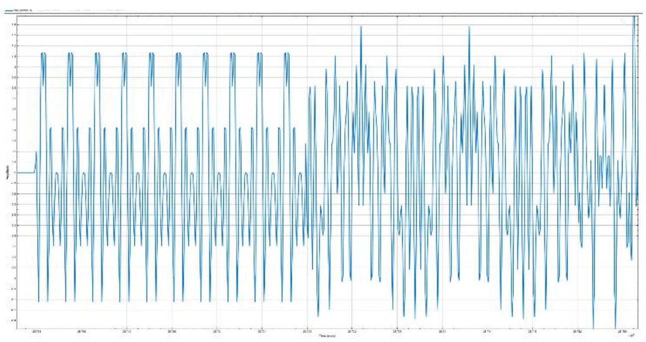
Figure 3 L-STF (Left) and L-LTF (Right)

F. *Doppler*

1) *What is Doppler?*

Doppler shift refers to the change in frequency of a signal caused by the relative motion between the transmitter and the receiver. In wireless communication, this effect occurs when either the transmitter, receiver, or both are in motion, altering the frequency of the transmitted signal as perceived by the receiver. For example, in satellite communications, the high speeds of Low Earth Orbit (LEO) satellites result in significant Doppler shifts that can reach up to ±48 kHz at 2 GHz carrier frequency.

2) *Why is Doppler Harmful?*

Doppler shift disrupts the orthogonality of OFDM subcarriers, a key feature of OFDM systems, leading to inter-carrier interference (ICI). This interference degrades signal quality and increases the error rate in data transmission. Furthermore, Doppler effects can cause inaccuracies in frequency synchronization and impair the overall performance of channel estimation techniques, particularly in high-speed communication environments like LEO satellites.

G. *What Happens When the Channel Changes Rapidly?*

When the channel changes rapidly due to high mobility or varying propagation conditions, the coherence time of the channel becomes shorter. This results in the following issues:

- **Outdated Channel Estimates**: The channel response estimated during one instance may no longer be valid for subsequent transmissions, reducing the effectiveness of techniques like LS and MMSE.
- **Increased Error Rates**: Rapid variations introduce time selectivity, making it challenging for the receiver to decode symbols accurately.
- **Synchronization Challenges**: Time and frequency synchronization becomes more difficult, further degrading system performance.

III. METHODOLOGY

In the MATLAB simulation for IEEE 802.11 image transmission, the steps performed were explained in the context of transmitter, communication channel, receiver, and estimation techniques. This section provides a detailed breakdown of each process within the simulation, outlining the design and implementation steps for each stage.

A. *Transmitter Design*

The transmitter design in the MATLAB simulation involves preparing the data, generating WLAN signals, and packing the data into 802.11a packets for transmission. The key steps are:

1. **Preparing the Image File**: The image is scaled to reduce its size, converted into a binary data stream, and segmented into smaller packets. This scaling affects the number of WLAN packets required for transmission, which is determined by factors like the scaling factor, MSDU length (data per packet), and the modulation and coding scheme (MCS). For example, setting the scaling factor to 0.2 and MSDU length to 2304 results in 11 WLAN packets.

2. **Generating the WLAN Signal**: Using the WLAN Toolbox, the binary data is packed into multiple 802.11a packets and converted into a baseband WLAN signal ready for transmission.

B. Communication Channel

In the communication channel, the signal first passes through a Rician communication channel, which simulates multipath propagation with a dominant line-of-sight component. Afterward, Additive White Gaussian Noise (AWGN) is introduced to the signal to simulate real-world noise and further degrade its quality for testing robustness.

C. Receiver Design

The WLAN receiver processes the transmitted signal through several key steps to recover the original image. After receiving the WLAN signal, either directly or via SDR hardware, the receiver performs the following tasks:

1. Detects a packet and establishes synchronization through coarse and fine carrier frequency offset estimation and correction.
2. Performs channel estimation using the L-LTF to determine the channel response.
3. Identifies the packet format and decodes the L-SIG field to extract the modulation and coding scheme (MCS) and the data length.
4. Decodes the data field, reconstructing the PSDU while verifying the frame check sequence (FCS) for errors.
5. Orders and combines the decoded MSDUs from all packets based on their sequence numbers to recreate the transmitted image.

Visualizations, including the power spectral density (PSD), equalized data symbols, and the received image, are provided for performance analysis.

D. Estimation Techniques in Receiver

The second step involves channel estimation using the L-LTF signals. Three different estimation approaches were used in this study: MATLAB's built-in estimator, LS (Least Squares), and MMSE (Minimum Mean Square Error). All three methods rely on the known L-LTF signals for channel estimation. For LS and MMSE, the L-LTF signals were manually provided, ensuring consistency across methods. The results of these estimators are compared in the Simulations and Results section.

IV. Simulations and Results

A. Simulations

Simulations are conducted using the parameters outlined below.

Variable	Value
Modulation	16 QAM
Coding Rate	1/2
Number of Transmitted Packets	11 packets
Payload Length (MSDU)	2304 bytes
Packet Length (MPDU)	2332 bytes
SNR Level	20 dB

Table 1 Simulation Parameters

Variable	Value
Sample Rate	20e6
Path Delays (seconds)	[0 0.5e-06 1.2e-06]
Average Path Gains (dB)	[0 -3 -6]
K-Factor	10
Direct Path Doppler Shift	0 Hz
Maximum Doppler Shift	0 Hz
Channel Filtering	true
Path Gains Output Port	true

Table 2 Rician Channel Parameters

Example Rician Channel Path Gains and Channel Filter Coefficients can be seen below.

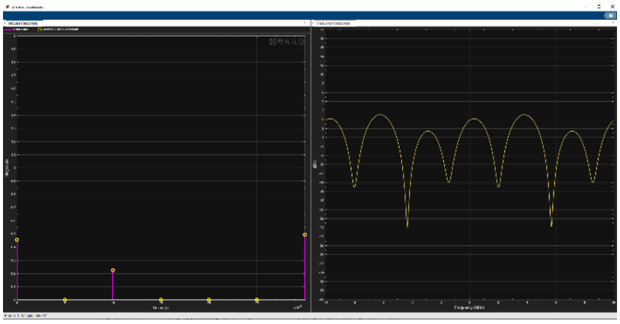

Figure 4 Rician Channel

Transmitted and Received real signals time scope can be seen below.

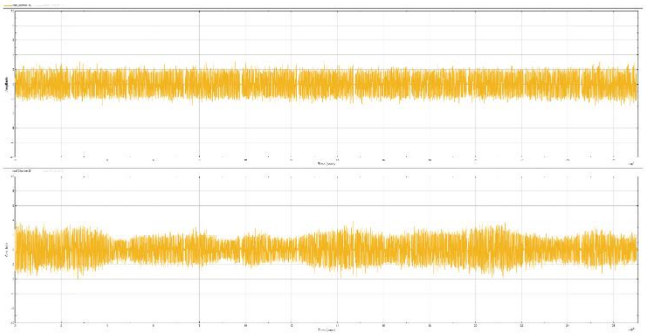

Figure 5 Transmitted and Received Real Signals Time Scope (Top: TX, Bottom: RX)

Transmitted and Received S-LTF and L-LTF signals (real) time scope can be seen below.

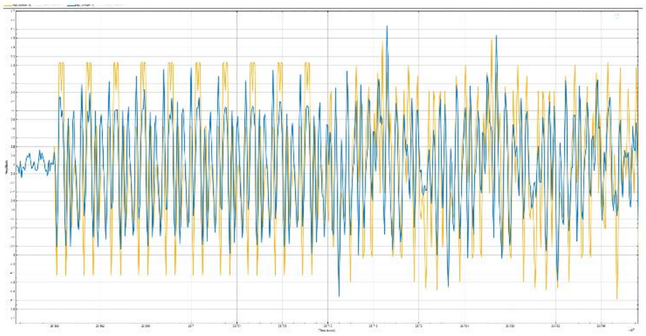

Figure 6 Transmitted and Received Real Signals Time Scope, S-LTF and L-LTF Fields (Yellow: TX, Blue: RX)

The resulting channel spectrum example is shown below. It is evident that the channel has degraded significantly and requires estimation.

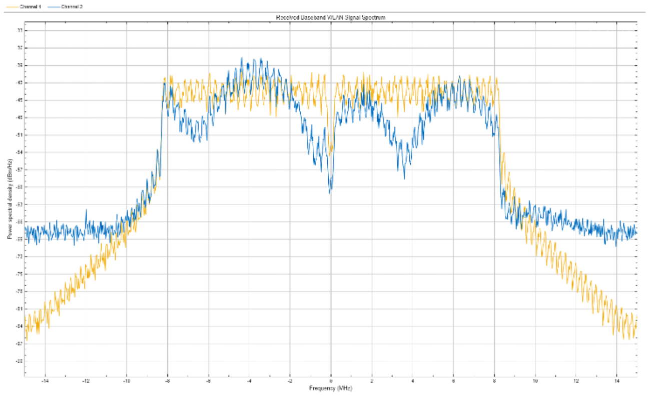

Figure 7 Channel Spectrum (Yellow 1: TX, Blue 2: RX)

The resulting constellation diagram without estimating channel can be seen below.

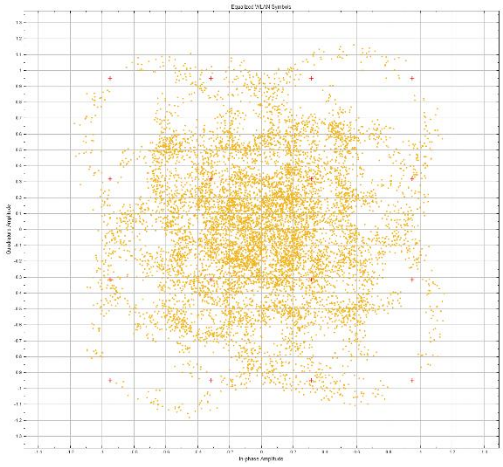

Figure 8 Constellation Diagram Without Estimating Channel

The resulting constellation diagram with MATLAB's estimator can be seen below.

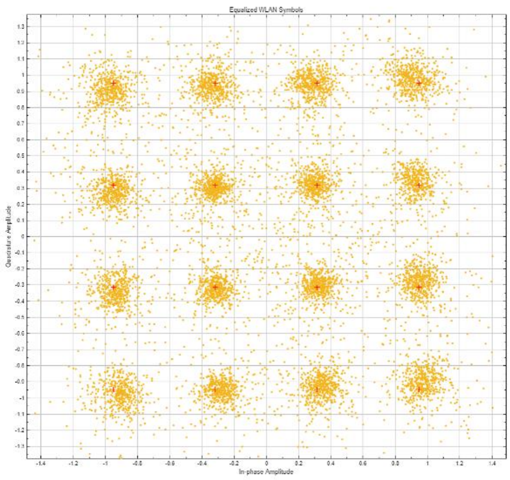

Figure 9 Constellation Diagram with MATLAB Estimator

The resulting constellation diagram with LS estimator can be seen below.

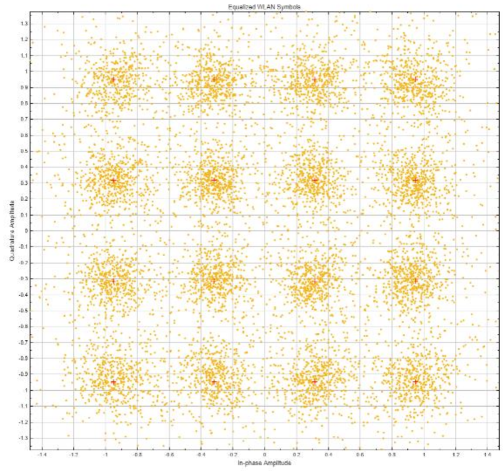

Figure 10 Constellation Diagram with LS Estimator

The resulting constellation diagram with MMSE estimator can be seen below.

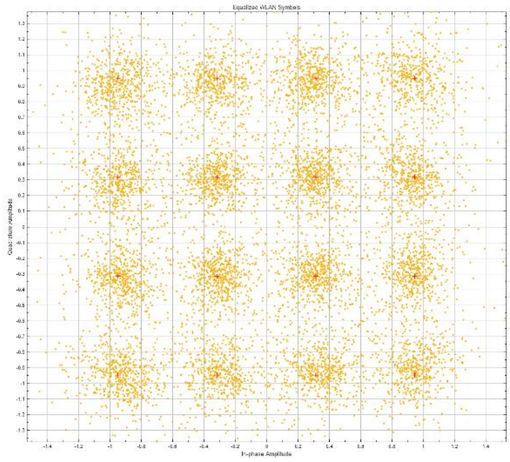

Figure 11 Constellation Diagram with MMSE Estimator

Transmitted and received image with estimator can be seen below. The BER was 0% for this image.

Figure 12 TX and RX Reconstructed Image. BER: 0

Transmitted and received images without estimator can be seen below. The BER was ~50% for this image, which means pure randomness.

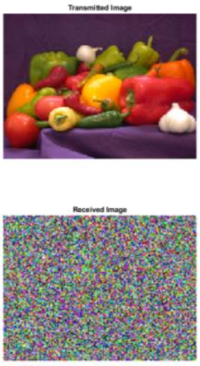

Figure 13 TX and RX Reconstructed Image. BER: ~0.5

From this point onward, the Doppler value is increased to observe its impact on the BER and the resulting reconstructed RX image. Also image size is decreased to shorten simulation time by decreasing source bytes. Simulations below are conducted with MMSE estimator.

Doppler: 500 Hz. BER: 0.00992

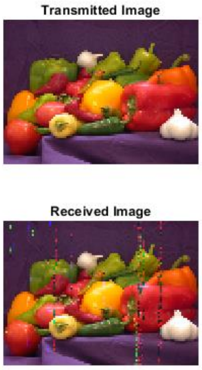

Figure 14 TX and RX Reconstructed Image. BER: 0.00992

Doppler: 1000 Hz. BER: 0.01676

Figure 15 TX and RX Reconstructed Image. BER: 0.01676

Doppler: 1500 Hz. BER: 0.04346

Figure 16 TX and RX Reconstructed Image. BER: 0.04346

Doppler: 2500 Hz. BER: 0.48775

Figure 17 TX and RX Reconstructed Image. BER: 0.48775

Doppler: 5000 Hz. BER: 0.49634

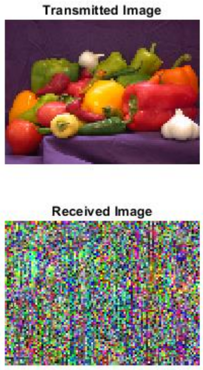

Figure 18 TX and RX Reconstructed Image. BER: 0.49634

B. Montre Carlo Simulations

In this part of the simulations, Monte Carlo simulations are conducted with varying Doppler values. Doppler values ranging from 0 to 5000 Hz are simulated in increments of 50 Hz, with each scenario repeated 100 times. The results are aggregated and visualized. To focus on the Doppler effect, the Rician channel conditions were made less severe rather than simulating a highly degraded channel. New simulation and Rician Channel parameters are below.

Variable	Value
Modulation	16 QAM
Coding Rate	1/2
Number of Transmitted Packets	233 packets
Payload Length (MSDU)	100 bytes
Packet Length (MPDU)	128 bytes
SNR Level	20 dB
Monte Carlo Iteration Count	200
Doppler Vector	0 to 5000 Hz, 50 Hz increments

Table 3 Simulation Parameters

Variable	Value
Sample Rate	20e6
Path Delays (seconds)	[0 0.1e-06 0.3e-06]
Average Path Gains (dB)	[0 -1 -2]
K-Factor	30
Direct Path Doppler Shift	0 to 5000 Hz, 50 Hz increments
Maximum Doppler Shift	0 to 5000 Hz, 50 Hz increments
Channel Filtering	true
Path Gains Output Port	true

Table 4 Rician Channel Parameters

The resulting BER-Doppler graphs are shown below. As observed, the performance of all three estimators is quite similar, with MMSE performing slightly better than the other two and LS being the worst. MATLAB's estimator falls in the middle. This is because MATLAB's estimator uses an LS approach combined with a better noise estimator, making it superior to standalone LS. MMSE, on the other hand, incorporates noise variance in its calculations, which explains why it achieves the best performance. To complement visual comparisons with numerical analysis, the average of 51 BER values measured across the 0-5000 Hz Doppler range was calculated, and the results are presented below. It should be noted that averaging BER values over a range does not necessarily provide a meaningful metric; this was done solely for comparative purposes.

- LS Mean BER : 0.284
- MMSE Mean BER : 0.279
- MATLAB Mean BER : 0.281

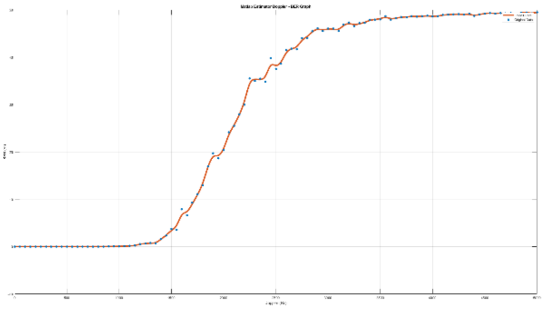

Figure 19 MATLAB Estimator Curve Fitted BER-Doppler Graph

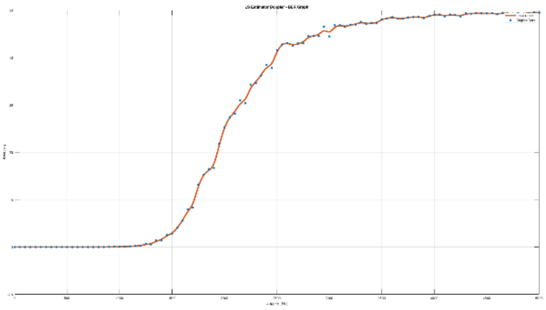

Figure 20 LS Estimator Curve Fitted BER-Doppler Graph

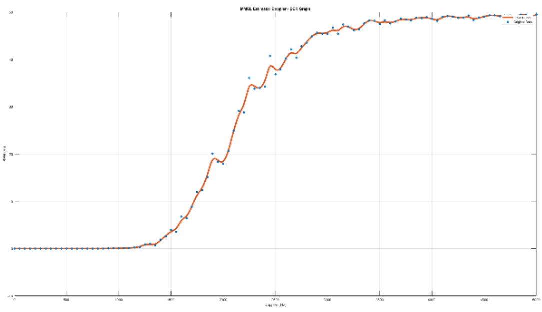

Figure 21 MMSE Estimator Curve Fitted BER-Doppler Graph

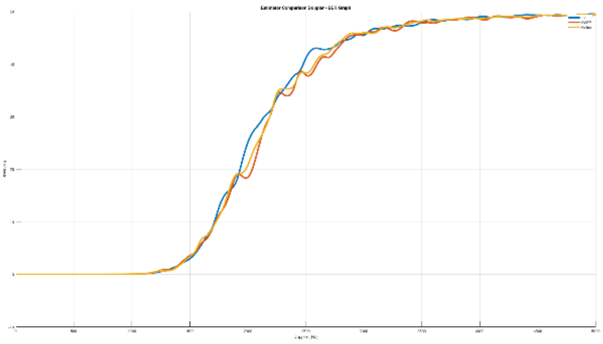

Figure 22 Combined BER-Dopler Graphs (Blue: LS, Red: MMSE, Orange: Matlab's Estimator)

V. Conclusion

In this study, the LS-based estimator used in MATLAB, the standalone LS estimator, and the MMSE estimator were compared in terms of their performance under the IEEE 802.11 Wi-Fi standard. Simulations were conducted in Rician and AWGN channels across varying Doppler levels, and performance was evaluated using the Bit Error Rate (BER) metric. The performance of all three estimators was tested both under static conditions and in environments with increasing Doppler shifts.

According to the results presented in the Simulations and Results section, all three estimators demonstrated very similar performance, while MMSE outperformed the LS and MATLAB estimators with slightly better results overall. Despite this, all estimators experienced a sharp increase in BER levels beyond Doppler frequencies of approximately 1700 Hz. In LEO satellite communications, Doppler shifts can reach as high as 48 kHz, which presents a significant challenge.

To mitigate this issue, the packet payload size was reduced to 100 bytes in the simulations. While this shorter payload allowed the preamble-based channel estimation to remain valid for longer durations, enabling marginally better performance at higher Doppler levels, packet sizes below 100 bytes are impractical for real-world applications. Even with these adjustments, the BER became prohibitively high at Doppler frequencies far below 48 kHz, making successful packet decoding impossible.

The primary reason for this limitation lies in the use of the IEEE 802.11 Wi-Fi standard in this study. The 802.11 standard is designed for short-range communication in static or low-mobility environments such as homes, offices, or outdoor hotspots. It was not developed to handle highly dynamic channels with large Doppler shifts as encountered in LEO satellite communications. Therefore, using the 802.11 standard for LEO satellite OFDM systems is not feasible.

To leverage the advantages of OFDM in LEO satellite communications, it is essential to adopt OFDM-based communication standards specifically optimized for such environments. These standards can provide the robustness needed to cope with the rapidly varying channels and high Doppler shifts inherent in satellite communication systems.

References

[1] MathWorks, "Image transmission and reception using 802.11 waveform with SDR." Accessed: Dec. 25, 2024. [Online]. Available: https://www.mathworks.com/help/wlan/ug/image-transmission-reception-using-802-11-waveform-sdr.html

[2] A. S. Ahmed, M. M. Hamdi, M. S. Abood, A. M. Khaleel, M. Fathy and S. H. Khaleefah, "Channel Estimation using LS and MMSE Channel Estimation Techniques for MIMO-OFDM Systems", *HORA 2022 – 4th International Congress on Human-Computer Interaction Optimization and Robotic Applications Proceedings*, 2022.

[3] Sriram Tadavarty and Nanda Kishore Chavali, "Estimation and Compensation of Doppler in 5G NR Based Non-Terrestrial Networks", *IEEE International Conference on Advanced Networks and Telecommunications Systems ANTS 2022*, pp. 135-140, December 18–21, 2022.

[4] Perahia, E., & Stacey, R. (2013). Next Generation Wireless LANs: 802.11n and 802.11ac. Cambridge University Pres