

Experimental Evaluation of Preamble Power Scaling in an SDR-Based OFDM System

Viktor Szitkey

Dept. of Digital Infrastructure, IMICT
Faculty of Electrical Engineering and
Information Technology,
Slovak University of Technology
Bratislava, Slovakia
ORCID: 0000-0002-9376-0644

Tomáš Páleníč

Dept. of Digital Infrastructure, IMICT
Faculty of Electrical Engineering and
Information Technology,
Slovak University of Technology
Bratislava, Slovakia
ORCID: 0000-0003-3511-3390

Martin Rakús

Dept. of Digital Infrastructure, IMICT
Faculty of Electrical Engineering and
Information Technology,
Slovak University of Technology
Bratislava, Slovakia
ORCID: 0000-0003-1564-1524

Abstract—This paper investigates the impact of preamble power scaling in an orthogonal frequency division multiplexing (OFDM) system implemented using software-defined radio (SDR). The focus is on the relationship between preamble signal power, synchronization reliability, and channel estimation accuracy, and their effect on system performance metrics such as bit error rate (BER) and frame drop rate (FDR). Measurements are conducted in a controlled over-the-air environment with additive noise. The results show that the reliability of the preamble has a direct impact on receiver performance, with increased preamble power leading to improved synchronization and reduced error rates.

Keywords—OFDM, preamble, synchronization, SDR, BER, FDR

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is a widely adopted waveform in contemporary wireless communication systems due to its robustness to multipath propagation and efficient spectral utilization. It forms the basis of multiple generations of wireless standards and continues to influence the design of emerging waveforms considered for beyond-5G and 6G systems [1]–[4], where multicarrier techniques remain a key candidate for flexible and high-capacity communication. Reliable OFDM reception depends critically on accurate synchronization and channel estimation, which are typically initialized using known reference structures such as preambles or synchronization signals.

In conventional systems, such as IEEE 802.11a, the preamble supports timing synchronization, carrier frequency offset estimation, and initial channel estimation as defined in the IEEE 802.11 standard [5]. Classical synchronization techniques, most notably the method proposed by Schmidl and Cox [6], exploit repetitive structures in the preamble to enable coarse timing and frequency synchronization under noisy conditions. Subsequent work has proposed refinements to improve robustness and reduce ambiguity, including approaches based on alternative training sequences such as Zadoff–Chu sequences [7]. These methods highlight the critical role of preamble reliability in front-end receiver performance.

Channel estimation in OFDM systems is commonly performed using pilot subcarriers, whose arrangement and processing have been extensively studied. Pilot-assisted channel estimation and pilot arrangement strategies have been well established, including classical analyses such as [8], and remain a fundamental component of OFDM receiver design. In practical systems, these pilot-based methods are used to refine channel estimates obtained from the preamble, enabling reliable demodulation across multiple OFDM symbols.

In modern cellular systems, including 5G NR, the importance of reference signals is further emphasized through dedicated structures such as synchronization signal blocks (SSB) and demodulation reference signals (DMRS), which are essential for initial access and data demodulation [9]–[10]. These signals may be transmitted with different power levels relative to data, reflecting implementation-level trade-offs between reference signal reliability and overall system efficiency.

A substantial body of research has also addressed power allocation in OFDM systems, primarily focusing on subcarrier-level optimization. For instance, water-filling-based approaches allocate power across subcarriers to maximize capacity under channel constraints and have been implemented and evaluated in SDR environments [11]. However, these approaches primarily target payload data and pilot subcarriers and are typically evaluated under simulation or system-level assumptions.

Prior work on OFDM systems typically addresses synchronization and channel estimation separately, with emphasis on detection performance and pilot-assisted techniques. These aspects are often evaluated in simulation environments, where individual components can be analyzed in isolation. In practical SDR implementations, however, these components interact directly, and the effect of preamble power on overall link performance is not explicitly isolated.

This is particularly relevant in SDR-based implementations, where flexible system design enables controlled experimentation. GNU Radio-based OFDM systems have been widely used for prototyping and evaluation of wireless communication systems [12], providing a platform for detailed analysis of receiver behavior under controlled conditions.

Recent experimental studies have applied GNU Radio OFDM to acoustic communication [13], integrated sensing and communication [14], preamble/postamble design [15], and low-cost SDR platforms [16]. The reported configurations retain fixed pilot locations and do not describe pilot-position variation or the mechanism by which pilot observations are transferred to estimates of neighboring data subcarriers. This does not establish that pilot information was ignored; rather, it illustrates that effective pilot processing is not transparent from the GNU Radio demo flowgraph and is frequently not documented in sufficient detail to be reproducible. This distinction is important because the stock GNU Radio equalizers can update pilot-bearing subcarriers but provide neither frequency-domain interpolation nor common-phase correction across the data carriers.

This paper presents an experimental evaluation of preamble power scaling in a controlled SDR-based OFDM

system implemented in GNU Radio. The main contribution of this paper is a reproducible over-the-air (OTA) characterization of how preamble power affects acquisition, initial equalization, bit error rate (BER), and frame drop rate (FDR) under controlled noise conditions. In addition, the study separates bit-level performance from frame-level loss mechanisms using synchronization-trigger and decoded-frames counters, clarifies the pilot-processing behavior of the stock GNU Radio equalizers, and discusses how the one-symbol reference configuration generalizes to longer frames with and without effective pilot-assisted tracking.

The remainder of the paper is organized as follows. Section II describes the system model and design constraints. Section III presents the measurement setup and methodology. Section IV provides the experimental results and analysis, followed by the conclusions.

II. SYSTEM MODEL AND EXPERIMENTAL SETUP

A. GNU Radio OFDM Implementation

The GNU Radio OFDM reference implementation was used as the basis of the evaluated system. The implementation follows key design principles of IEEE 802.11a, such as a 64-point FFT and similar subcarrier allocation, but does not fully replicate the standard.

The relevant components of the system for this work are synchronization and equalization, as these directly influence the measured performance. The key system parameters used in this work are summarized in Table I.

TABLE I. OFDM SYSTEM PARAMETERS USED IN THE EVALUATION

Parameter	Value
Bandwidth	1 MHz
FFT length, N	64
Number of data / pilot / null carriers	52 / 0 / 12
Payload length	One OFDM symbol
Cyclic Prefix length	N/4
Payload modulation	4-QAM, 16-QAM
Preamble modulation	BPSK
Synchronization preamble	Two OFDM symbols
Header	One OFDM symbol

^a One payload symbol was selected to isolate the effect of the preamble-derived channel estimate and to avoid frame length dependent tracking or decision-feedback effects.

B. Equalization and Pilot-Processing Limitations

The evaluated GNU Radio implementation provides a static equalizer and a simple decision-feedback equalizer (DFE). Both equalizers accept pilot-carrier and pilot-symbol configurations and maintain a separate channel state $\hat{H}_k$ for every occupied subcarrier k .

For both approaches, the received frequency-domain symbol Y_k is equalized using the current state estimate:

$$\hat{X}_k = \frac{Y_k}{\hat{H}_k} \quad (1)$$

In the static equalizer, the channel state is initiated from the preamble and otherwise remains fixed for data carriers. When a known pilot P_k occurs on subcarrier k , the state of

that subcarrier can be updated from Y_k/P_k . No corresponding update is automatically applied to neighboring subcarriers [17]. The simple DFE additionally obtains a hard decision $\hat{X}_k$ for each data symbol and recursively updates the corresponding subcarrier state as:

$$\hat{H}_k^{(j)} = \alpha \hat{H}_k^{(j-1)} + (1-\alpha) \frac{Y_k}{\hat{X}_k} \quad (2)$$

where α is the GNU Radio smoothing parameter and j denotes the OFDM-symbol index. For a pilot carrier, the known pilot symbol replaces the hard decision in the update [18].

The stock equalizers' use of pilots is local to the subcarrier on which the pilot is transmitted. With the default fixed 802.11a-like allocation of this system, the pilot subcarriers remain reserved for pilots, and their updated states are not interpolated to adjacent data carriers and are not used to derive a common phase correction. The carrier-allocation in GNU Radio permits pilot positions to vary between OFDM symbols, allowing a subcarrier to be refreshed by a known pilot before that subcarrier carries data in a later symbol. More conventional use of pilots requires a custom equalizer that transfers pilot information to data carriers through frequency-domain interpolation, phase tracking, joint time-frequency estimation, virtual pilots, etc. Such processing is not provided by the evaluated stock equalizers. The lack of an explicit description of this step in recent GNU Radio OFDM studies [13]–[16] motivates the implementation-level clarification provided here.

C. System Configuration and Design Choices

To isolate the impact of preamble-based channel estimation, the system was configured as follows.

The received baseband signal r can be expressed as:

$$r[n] = (h[n] * s[n]) + w_{ch}[n] + w_{AWGN}[n] \quad (3)$$

where s is the transmitted OFDM frame, h represents the effective channel including hardware response, w_{ch} denotes background noise and hardware-related impairments, and w_{AWGN} corresponds to the controlled noise injected during measurements.

The channel is assumed to be quasi-static over the duration of each frame, consistent with the static indoor measurement environment. Although multipath propagation is present, the measurement methodology is designed such that the injected additive white Gaussian noise (AWGN) component dominates the calibration. As a result, the system's behavior approximates an AWGN-oriented performance evaluation under practical SDR conditions.

The transmitted signal consists of preamble and payload components, with independent power scaling. The preamble scaling is defined as:

$$G_{pre} = 10 \log_{10} \left(\frac{P_{pre}}{P_{payload}} \right) \quad (4)$$

and evaluated for values 0, 3, 6, 9 dB. This formulation enables direct comparison of receiver performance as a function of reference signal power while maintaining constant payload power.

One OFDM payload symbol was selected to isolate synchronization and the initial preamble-derived channel estimate. This configuration is a controlled reference case rather than a general recommendation for pilotless OFDM frames. For longer frames without pilot tracking, preamble power scaling would improve acquisition and the initial estimate, but its benefit would progressively diminish as residual phase error, decision-feedback errors or channel variation accumulate. In systems with pilot-assisted tracking, the concept of preamble power scaling can be extended to the pilots themselves, but performance will depend on additional factors like pilot density/placement and the tracking/interpolation algorithm.

Pilot carriers were disabled in the presented configuration because the evaluated stock equalizers update the channel state only on pilot-bearing subcarriers and do not interpolate those estimates to adjacent data subcarriers. For the one-symbol payload used here, retaining the pilot carriers would therefore provide no benefit to the data carriers. Keeping unused pilot carriers would therefore not improve the current receiver performance or channel estimate but would introduce unnecessary BPSK-modulated components affecting RMS measurements and overall signal properties. Reintroducing fixed or position-varying pilot carriers into the frame structure is straightforward. However, using them effectively in longer frames requires either coordinated pilot-position variation or custom pilot-assisted equalizer modifications, which is beyond the scope of this work and left for future study.

III. MEASUREMENT SETUP AND METHODOLOGY

A. Software and Hardware Testbed

The system is implemented in GNU Radio (v3.10.2) running on Ubuntu 24.04 with UHD 4.6 drivers. ZeroMQ (ZMQ) interfaces are used to transfer reference data and control information between nodes. Specifically, transmitted data and frame counters from the transmitter are forwarded to the receiver to enable centralized evaluation of performance metrics.

The experimental setup shown in Fig. 1 consists of three independent PC stations. The transmitter (PC1) generates OFDM frames and forwards reference data, via ZMQ, to the receiver (PC2), where all performance metrics are evaluated. A third station (PC3) controls an independent noise source used for controlled noise injection.

The RF front-end is implemented using two USRP N210 devices equipped with UBX-40 daughterboards for transmission and reception, and a USRP B210 acting as an OTA AWGN source. Transmission was performed over an indoor OTA channel in a small room environment. The transmitter and receiver were positioned approximately 1.5 m apart, with antennas intentionally oriented away from each other to reduce direct path dominance and allow finer control of the signal-to-noise ratio via the OTA AWGN injection.

All devices were synchronized using an external Ettus OctoClock-G providing a 10 MHz reference clock and a 1 PPS timing signal.

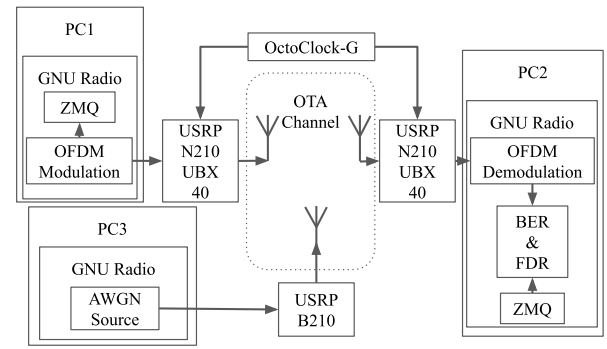


Fig. 1. Diagram of experimental testbed used for measurements.

B. Signal Model and Receiver Processing

The system bandwidth was set to 1 MHz. Each OFDM frame contained a single payload symbol, preceded by synchronization structures as defined by the system parameters in Table I.

AWGN was injected in-band using the B210 device, with noise bandwidth matched to the signal bandwidth. Noise power was controlled via the gain of the noise source.

At the receiver, signal processing follows a standard OFDM chain, including Schmidl and Cox synchronization and DFE equalization. The synchronization threshold defines the detection criterion in the Schmidl and Cox metric, where higher values reduce false detections at the cost of increased missed detections. Two threshold settings were evaluated. The stricter value 0.9 is used for the FDR graphs in Figs. 5 and 6. The value 0.7 is used for diagnostic decomposition in Table II because it exposes the transition from missed synchronization to post-trigger losses more clearly.

Performance metrics are evaluated after frame synchronization and demultiplexing. Payload RMS and BER are evaluated only for accepted payload data. Frames that do not produce a synchronization trigger or whose header is not successfully decoded contribute to FDR but do not enter the BER calculation.

C. Measurement Procedure

The E_b/N_0 range from 0 to 9 dB was evaluated in 1 dB steps, where E_b/N_0 denotes the ratio of energy per bit to noise power spectral density. For each measurement point, at least 30,000 frames were transmitted to ensure statistically meaningful results.

Let N_T denote the number of transmitted frames and N_D the number of frames whose headers were successfully decoded. The total FDR is defined as:

$$FDR = \frac{N_T - N_D}{N_T} \quad (5)$$

For deeper analysis, let N_R denote the number of received frames, or more specifically the number of trigger signals produced by the Schmidl and Cox synchronization. The failed synchronization and header loss rates are estimated as:

$$L_{Synch} = \frac{N_T - N_R}{N_T}, \quad L_{Dec} = \frac{N_R - N_D}{N_T} \quad (6)$$

These components identify where frame processing fails in the implemented receiver chain. BER curves were generated for two modulation schemes, square 4-QAM and 16-QAM, and for multiple preamble power scaling configurations.

D. Noise Calibration and E_b/N_0 Estimation

Accurate control of E_b/N_0 was achieved through a two-stage calibration procedure. The first stage served as a feasibility assessment to verify that the system could produce meaningful BER performance under controlled noise conditions. In this preliminary step, an approximate mapping between noise gain and system performance was obtained by adjusting the OTA AWGN injection to match selected BER points with theoretical expectations.

The second stage represents the primary calibration methodology used for all reported measurements. To improve accuracy, a reference scenario using baseband AWGN injection was introduced, and is described in Fig. 2. In this configuration, noise was applied selectively to the payload portion of the frame, while the preamble remained affected only by channel and hardware noise. This enabled generation of BER curves that closely matched the theoretical results.

The relationship between baseband-injected and OTA-injected noise was then established by aligning their corresponding BER curves. Due to hardware non-idealities and OTA channel effects, a consistent offset between theoretical and measured performance was observed. This offset was treated as an implementation-specific constant and applied across all measurements.

Signal and noise power levels were estimated using RMS measurements of payload samples after frame demultiplexing. Averaging was performed over long observation windows to reduce statistical fluctuations.

Using this calibrated mapping, all subsequent measurements were conducted using the OTA AWGN noise injection, with noise levels adjusted in 1 dB steps to obtain the desired E_b/N_0 range.

This calibration approach enables consistent comparison between theoretical and experimentally obtained BER curves despite hardware and channel non-idealities.

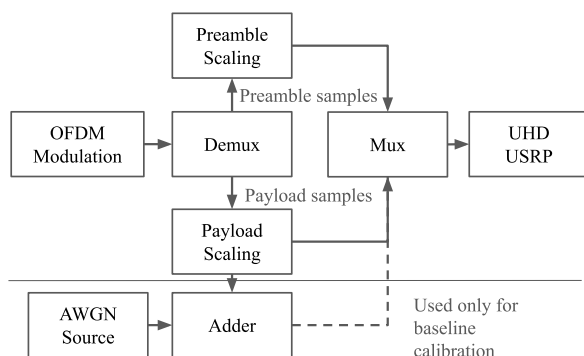


Fig. 2. Transmitter baseband structure with independent preamble scaling. Dashed path indicates optional baseband AWGN injection used for calibration.

IV. RESULTS AND ANALYSIS

This section presents the measured performance of the OFDM system as a function of preamble power scaling G_{pre} , with emphasis on BER and FDR. The baseline case, in which AWGN is applied only to the payload while the preamble remains unaffected, is used as the reference in all figures.

The BER performance for 4-QAM under different preamble power scaling values is shown in Fig. 3. The results show a consistent improvement in BER with increasing G_{pre} . At $\text{BER} = 10^{-3}$, the system with $G_{pre} = 3$ dB exhibits an E_b/N_0 penalty of approximately 1.5 dB relative to the baseline. Increasing G_{pre} reduces this gap, while the case $G_{pre} = 0$ dB does not reach this BER within the evaluated range. The BER performance for 16-QAM is shown in Fig. 4. Due to the higher sensitivity of this modulation scheme to phase error, comparison is performed at $\text{BER} = 10^{-1.5}$. An overall improvement with increasing G_{pre} is observed. At $\text{BER} = 10^{-1.5}$, the system with $G_{pre} = 3$ dB exhibits an E_b/N_0 penalty of 1.5 dB relative to the baseline, similar to 4-QAM. Increasing the power scaling reduces this gap, while at 9 dB the measured performance approaches or overlaps the baseline curve. The convergence toward the baseline indicates that, once the preamble-derived estimate is sufficiently reliable, AWGN source and remaining hardware/channel impairments dominate BER. Further scaling is limited by the transmitter dynamic range. In an additional measurement above the reported power scaling range, waveform deformation consistent with clipping was observed at the transmitter, indicating that excessive preamble scaling can eventually degrade both synchronization and estimation.

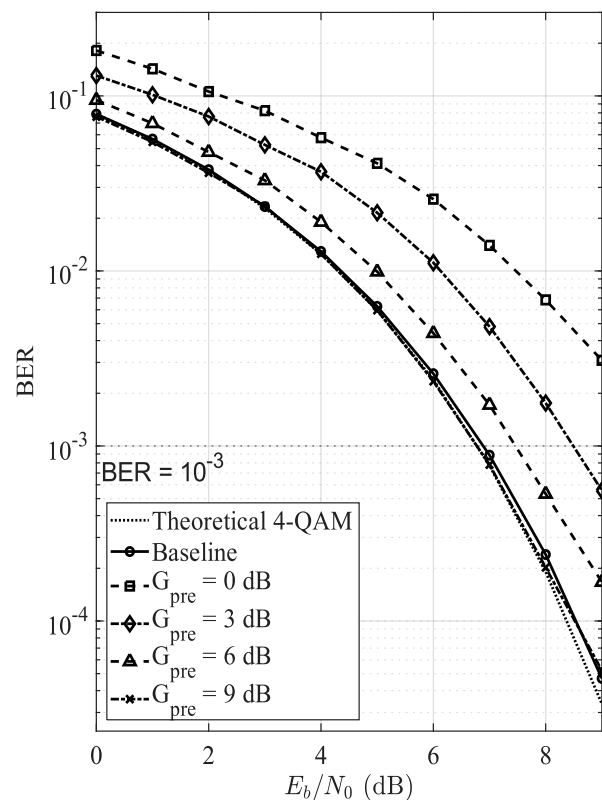


Fig. 3. BER performance of the 4-QAM OFDM system as a function of E_b/N_0 for different preamble power-scaling values.

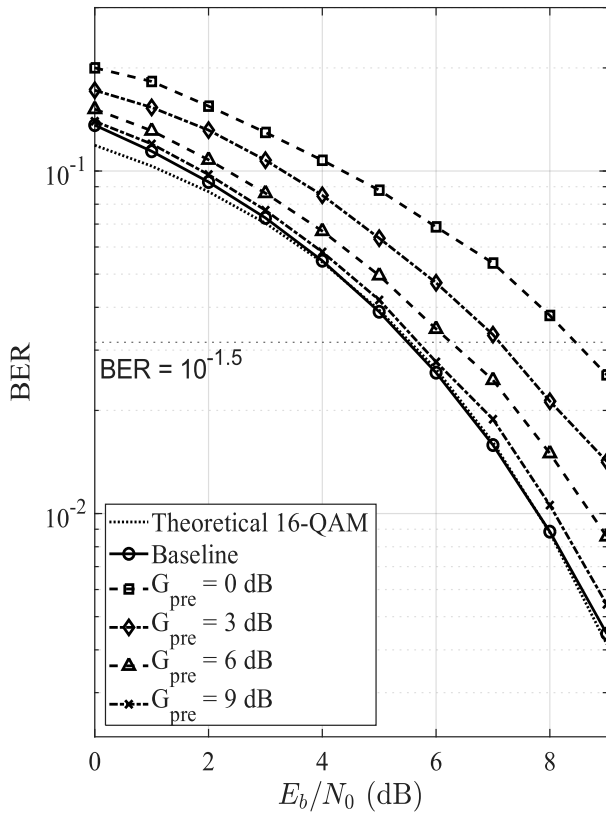


Fig. 4. BER performance of the 16-QAM OFDM system as a function of E_b/N_0 for different preamble power-scaling values.

The FDR performance at synchronization threshold 0.9 is shown for both 4-QAM and 16-QAM in Fig. 5 and Fig. 6, respectively. Increasing G_{pre} leads to an overall reduction in FDR, with the most significant improvement observed at lower E_b/N_0 values. As E_b/N_0 increases, synchronization stabilizes and residual losses are dominated by decoding errors.

Table II provides a diagnostic decomposition for selected 4-QAM operating points measured with threshold 0.7. The table jointly reports BER for accepted frames, missed-synchronization loss, post-trigger/header-decoding loss, and the accepted-frame rate.

TABLE II. REPRESENTATIVE 4-QAM LOSS DECOMPOSITION AT SYNCHRONIZATION THRESHOLD 0.7

E_b/N_0 (dB)	G_{pre} (dB)	BER	L_{synch}	L_{dec}	N_D/N_T
0	0	0.1818	86.59%	6.45%	6.96%
0	6	0.0948	0.03%	13.02%	86.96%
0	9	0.0761	0.00%	9.29%	90.74%
1	0	0.1429	56.75%	14.44%	28.80%
1	6	0.0697	0.15%	12.04%	87.81%
1	9	0.0546	0.05%	9.03%	90.92%

At $E_b/N_0 = 0$ dB and $G_{pre} = 0$ dB, 86.59% of transmitted frames do not produce a synchronization trigger, and only 6.96% are accepted. Increasing G_{pre} to 6 dB reduces the missed-synchronization rate to 0.03% and increases the accepted-frame rate to 86.96%. The remaining 13.02% loss

occurs after a trigger, primarily because the header is not successfully decoded. At $E_b/N_0 = 1$ dB, the same transition is observed: missed synchronization decreases from 56.75% at 0 dB power scaling to below 0.15% at 6 and 9 dB power scaling, while approximately 9–12% of frames are still lost after triggering. BER values provide complementary information because they are computed only from successfully accepted payloads. Therefore, missed synchronization does not directly enter the BER denominator. The continued BER improvement after synchronization losses have become negligible is consistent with a more reliable preamble-derived equalization state.

The observed saturation consequently has three distinct causes. First, FDR gains saturate when synchronization already succeeds for nearly all frames, leaving losses later in the receiver chain. Second, BER approaches the payload-noise baseline when the uncertainty of the preamble-derived estimate becomes small relative to payload AWGN and residual hardware/channel impairments. Third, the transmitter dynamic range sets an upper bound on useful scaling because clipping deforms the preamble at excessive power scaling values.

The results confirm that increasing preamble power consistently improves both synchronization reliability and channel estimation accuracy, leading to reduced BER and FDR. For BER, the improvement persists across the full range of G_{pre} , reflecting the continued impact of channel estimation accuracy on symbol detection. In contrast, FDR improvement saturates early, as synchronization becomes reliable even at moderate preamble power scaling levels.

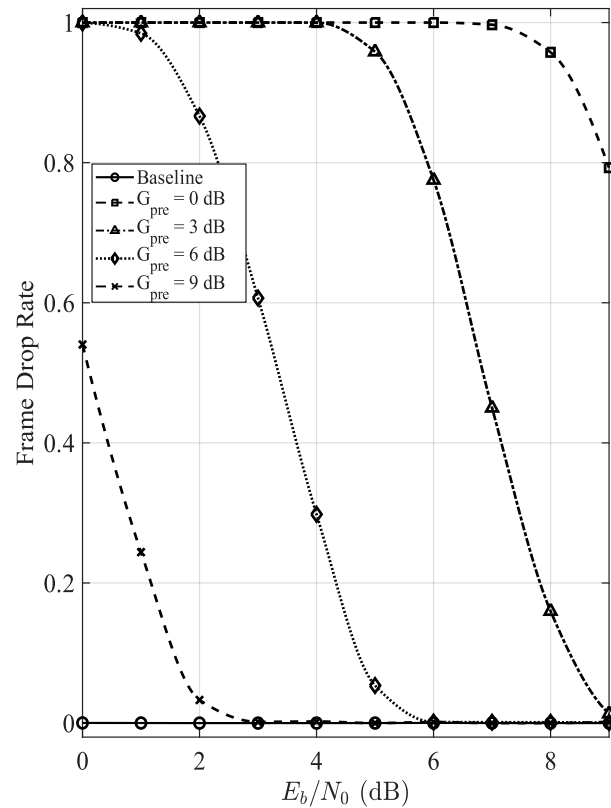


Fig. 5. Frame Drop Rate performance of the 4-QAM OFDM system as a function of E_b/N_0 for different preamble power-scaling values.

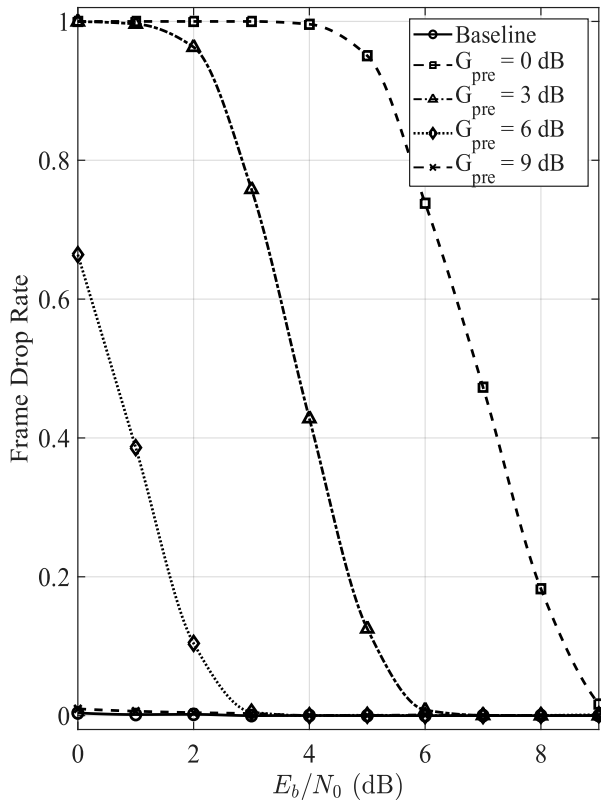


Fig. 6. Frame Drop Rate performance of the 16-QAM OFDM system as a function of E_b/N_0 for different preamble power-scaling values.

V. CONCLUSIONS

This paper presented an experimental evaluation of preamble power scaling in an SDR-based OFDM system. The main contribution of this paper is a controlled OTA evaluation of how preamble power influences synchronization reliability and channel estimation, as reflected in BER and FDR.

The results show that preamble power scaling reduces the performance gap relative to the reference case. FDR improvement saturates once synchronization becomes reliable, while BER remains dependent on the quality of the preamble-derived channel estimate.

Future work will focus on extending the system to include pilot-assisted channel tracking and investigating the trade-off between reference signal power and update rate, including the impact of pilot density and placement. Additional evaluation in dynamic channel conditions, such as Rayleigh and Rician fading and mobile scenarios, will be considered.

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