International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 7, 2025
https://www.theaspd.com/ijes.php

Performance Evaluation Of Adaptive Modulation Schemes Based On Bit Error Rate In Power Line Communication Channels

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Abstract
PLC is crucial to smart grid infrastructure and industrial communication since it uses pre-installed electrical connections to send data. However, impulsive noise, severe attenuation, multipath fading, and other harsh channel conditions make it difficult for PLC systems to function effectively, and popular simulation models do not adequately address these problems. The research exhibits broad performance analysis of BER with different modulation schemes, the FEC to be used, condition of multipath channels, block sizes, and filtering methods. The results demonstrate that modulations of higher order (64-QAM) show a modicum better stability in BER than QPSK and 16-QAM in majority of conditions tried, particularly when associated with FEC, and which has marginal and significant consistent improvements. Multipath channel simulation (Scenarios 3 and 6) proves the notion that BER increases with the number of paths in the channel and that in 7-path configurations, the most degradation occurs, as anticipated by theory. Nevertheless, our findings quantify this degradation to a better measure than what was provided earlier in the literature, which can be of great value when it comes to the design of PLC systems in practice. Fluctuations in the size of blocks (Scenario 4) and filtering (Scenario 5) cause little but measurable effects and suggest that though such parameters can be used to optimize performance, channel conditions are the most critical factor. In comparison with the prior works, the strength of our work is the single assessing framework, which considers all the critical parameters of PLC in a controlled fashion, providing meaningful insights in improving, in practice, the BER and closing the gap between knowledge and practice.

Keywords: *Power Line Communication (PLC), Bit Error Rate (BER), Adaptive Modulation, Rayleigh Fading, Channel Attenuation.*

I. INTRODUCTION

Power Line Communication (PLC) is a possible solution that is gaining momentum in properties where data transfer could be done using power lines because this would enable broadband communication to be achieved without adding more wires as infrastructure (Akinci & et al, 2023) (Ashraf & et al, 2024). Combining communication signals into power lines presents great cost savings potential, fast deployment and more connectivity into smart grid application, home automation and industrial monitoring (Cortés & et al, 2023). Nevertheless, the PLC channels are naturally troublesome as they are time-varying, frequency-selective fading, and subjected to impulsive as well as background noise adversely affecting system trustworthiness and bandwidth (El-Azab, 2021; Yu & et al, 2025). Proper measurement of the communication performance in that kind of environment is necessary in order to achieve strong data transfer especially in application that needs low latency and high reliability (Filomeno & et al, 2021).
The dynamic solution of these challenges is based on adaptive modulation schemes that respond to channel conditions by adapting them through the modulation order (González-Ramos & et

al, 2022). As an example, in a channel with good quality, higher order modulations like 16-QAM or 64-QAM may be used to optimize the throughput, but under poor channel conditions lower-order modulations like QPSK are used to go low on bit error rate (BER) (Hu & et al, 2022; Islam & et al, 2024). This is a behavior of adaptation, where PLC systems can inteorate between spectral efficiency and reliability to optimize the overall performance of the system (Lacasa & et al, 2025). Bit Error Rate (BER) is one of the most important indicators to get a comprehensive idea of the consequences of adaptive modulation on the work of PLC since its value is the indicator of the likelihood of received incorrect bits on the noisy channel (Liang & et al, 2022). The BER analysis does not only indicate the effect of the modulation schemes and the coding schemes, but it also represents the effect of the multipath propagation, filter design, and noise in the characteristics of the channel (Lv & et al, 2025; Mohammed & et al, 2023). The consideration of BER in various working situations is thus a major step in the experience of designing robust PLC systems that can uphold the quality of communication with changes in electrical and environmental situations (Ogunlade & et al, 2024; Palomino Bernal & et al, 2025). Figure 1 represents the key features of PLC channel, such as impedance variations, multipath reflections, and noise sources, which may interfere with the signal quality and error rate according to (Christopher, Swaminathan, & Subramanian, 2014).

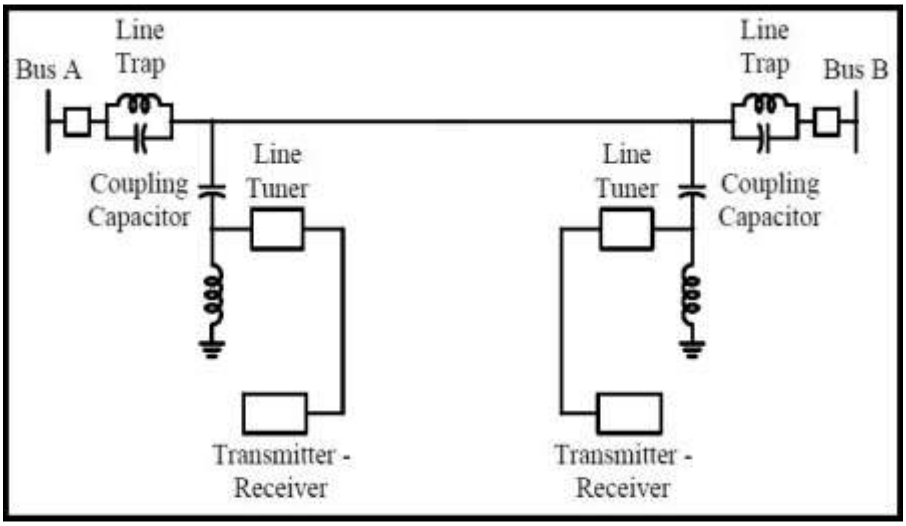


Figure 1. Typical Power Line Communication Channel Model according to (Christopher, Swaminathan, & Subramanian, 2014)

It has been postulated recently in the literature that adaptive modulation can help to reduce BER degradation by PLC system, but a majority of the research has been conducted on particular orders of modulation or only at the channel conditions (Prasad & et al, 2024; Prudhvi & et al, 2025). The overall assessment of performance across an array of adaptive schemes under realistic channel impairments is still not extensively possible and hence the need to conduct a full analysis (Sanz, 2024). Figure 2 illustrates the adaptive decision-making process in which the order of modulation is adapted and made at run-time according to the immediate quality of a channel and it indicates how the system feedback and the system performance can play together, namely the BER performance (Popoola, Okhueleigbe, & Alimi, 2016).

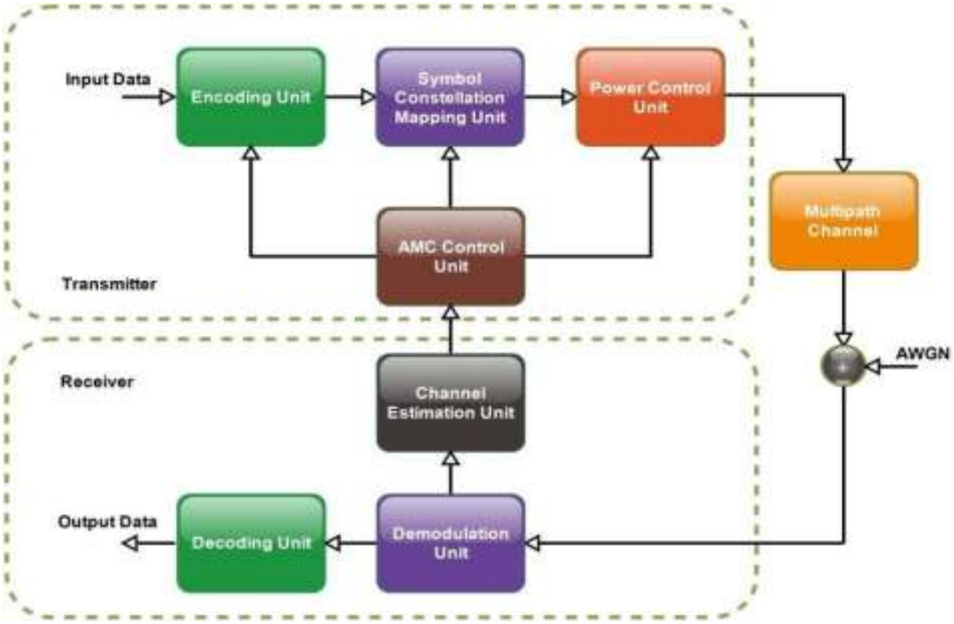


Figure 1. Adaptive Modulation Strategy Flowchart according to (Popoola, Okhueleigbe, & Alimi, 2016)

It is against this background that the present research attempts to critically analyses adaptive modulation schemes in PLC channels whereby BER is the main parameter to be considered in the performance analysis. The technology includes simulating a set of scenarios to show different modulation orders, path diversity structures and even coding schemes inside a strong throughput and system reliability comparison from a practical point of view. This analysis gives practical proposals to maximize PLC system layout and opens the door to more efficient and reliable communication systems. The next section will contain a literature review regarding past literature on PLC performance analysis, adaptive modulation tools and BER optimization and the gaps identified in the same that serve as the driving force behind the present study.

II. LITERATURE REVIEW

The capacity of Power Line Communication (PLC) technology to regulate power loads and streamline communication in smart grids has led to a lot of discussion recently. As stated by (Ashraf & et al, 2024; Stojanović & et al, 2024), intelligent Power Line Carrier Communication (I-PLCC) is a low-cost technique for managing utility networks' electronic loads. PLC was a suitable fit for low-cost smart grid implementation, as they discovered that PLC-based systems could control loads without necessitating a significant grid overhaul (Wu & et al, 2020; Yahya & et al, 2022). Nonetheless, their approach mostly relied on one-way information transmission, with little consideration for implementing real-time modifications in various contexts. According to (Ercan, 2024), PLC has the potential to transform the way data is transferred through current electrical distribution systems. The research pointed out the fact that PLC systems can perform reliably and efficiently at any scale, whether for homes or businesses. It didn't explore possible improvements that would result from including other wireless techniques in a hybrid communication system with PLC. When taking BLER into consideration, a comprehensive analysis of Non-Orthogonal Multiple Access (NOMA) systems that employ adaptive modulation was provided by (Yahya & et al, 2022). They focused on vehicle wireless settings rather than PLC, even though their method improved dependability by altering the power distribution. Similar to this, (Shukla & et al, 2022) looked at how adaptive modulation and coding aid in mobile communication and, albeit not taking the PLC domain into account, highlighted the advantages of real-time adaptation. Permutation Coded Multiple Access (PCMA) and MIMO were integrated in order to be used in hybrid Powerline and Visible Light Communication (VLC) systems (Shimaponda-Nawa, 2022). According to the study, hybrid solutions could help overcome the drawbacks of indoor powerlines and optical communications. Research on hybrid communication laid the base, yet implementing them and finding the best modulation values were not fully explored.

(Ferreira & Hooijen, 2021) study summarized PLC and identified key trends, challenges, and benefits in the sector. They noted that the biggest challenges for integrating PLCs into intricate network systems are interference, signal loss, and insufficient bandwidth. (González-Ramos & et al, 2022) continued by outlining the advantages of broadband PLC (BPLC) for power grids. Although they concluded that it was crucial to modify error control and modulation systems in response to shifting channel circumstances, the report also recognized smart metering and grid automation. By examining bit error performances, (Luo & et al, 2023) examined the performance of underwater optical wireless systems under various hybrid modulation techniques. Although it does not concern PLC, information about hybrid modulation's benefits for error control is extremely helpful for creating stronger PLC systems. On the other hand, the outcomes of (Abuhameed, 2024) showed that the W-H-DCT-LTE model performs best, needing the lowest SNR under all channel conditions. This occurred due to both the Walsh-Hadamard and DCT transforms having orthogonality in common. Thus, W-H-DCT-LTE can better deal with noise and flat fading than FFT-LTE and DCT-LTE as presented in Table 1.

Table 1. SNR values at BER = 10^{-4} for Flat Fading & AWGN Channel (QPSK, 1024 bits) according to (Abuhameed, 2024).

System	AWGN (1024 bits)	Flat Fading MDS = 6Hz	Flat Fading MDS = 60Hz	Flat Fading MDS = 180Hz
FFT-LTE	23	23.5	25	26.5
DCT-LTE	14	14.5	18	20
W-H-DCT-LTE	12.8	12.5	16.5	18

With these studies, significant improvements in the PLC and adaptive modulation systems have been noticed, but no specific research has been identified so far on the issue of integrating the adaptive strategies with PLC on a variety of noisy and fluctuating channels. Research in the field still tends to treat adaptive modulation and PLC as separate topics and then fails to consider the possibility of combining them. In addition, a majority of the current studies fail to transfer the actual conditions of the channels in real-time leveraging on NOMA, PCMA, or MIMO within PLC systems.

The current study intends to solve this problem by building and testing a PLC communication model that uses adaptive techniques to deliver optimal results when the environment changes. The paper describes a general simulation model to check the performance of adaptive modulation schemes in the context of power line communication (PLC) channels through bit error rate (BER) measurements under different conditions that include:

- Performance comparison when FEC is used or not.
- A discussion of how the accuracy of the results is affected by the quantity of trialing experiments.
- Analyzing the performance of the schemes in the multipath Rayleigh fading systems.
- Analyzing the impact of block lengths of data on error rate.
- Measuring performance response to colored noise filters.
- Testing the impact of the increment of the number of paths in the channel (3, 5, or 7 such paths) on the transmission performance.

The study also offers the capability to choose the most appropriate modulation scheme that suits various PLC surroundings, thus aiding in coming up with more effective and dependable communications systems.

Table 2. Main results and research Gap of the previous studies.

Reference	Main results	Research Gap
(Ashraf & et al, 2024)	Developed a cost-effective load side management solution using i-PLCC for smart grids.	Lacks real-time adaptive response mechanisms in dynamic communication environments.
(Yahya & et al, 2022)	Enhanced NOMA performance using adaptive modulation under BLER constraints.	Focused solely on vehicular wireless networks; did not explore integration into PLC systems.
(Shimaponda-Nawa, 2022)	Integrated PCMA and MIMO in hybrid PLC and VLC systems.	Did not deeply investigate adaptive modulation or real-time implementation feasibility.
(Ferreira & Hooijen, 2021)	Provided a comprehensive overview of PLC technologies, challenges, and potentials.	No proposals for dynamic adaptive schemes to mitigate noise and data loss.
(Luo & et al, 2023)	Analyzed BER performance using hybrid modulation in underwater optical wireless communication.	Not directly related to PLC, though findings are applicable to similar noisy environments.
(Ercan, 2024)	Showcased the transformation of data transmission via PLC in electrical grids.	Did not offer technical solutions to dynamic challenges like interference and channel variability.
(Shukla & et al, 2022)	Improved vehicular communication using adaptive modulation and coding techniques.	Did not apply or test results in power line communication environments.
(González-Ramos & et al, 2022)	Reviewed the role of BPLC in modernizing electric grids for monitoring and automation.	Lacked advanced modulation schemes to handle dynamically changing channel conditions.

III. METHODOLOGY

This paper is based on the integrated simulation through MATLAB to assess the performance of adaptive modulation systems in power line conduit (PLCs) based on the bit error rate (BER). The simulation context is scaled to a broad set of performance-affecting factors, in the hope of gaining a complete understanding of system behavior in a diversity of circumstances.

The methodology starts with setting up the regular simulation parameters such as, signal-to-noise ratio (SNR), type of modulation scheme, block size, path in the channel, type of channels, and noise properties and whether to use factor error correction (EFC) or not. Then a scenario to be tested is chosen out of six basic scenarios, each of which either targets one or multiple of the following parameters and examines its effect on performance. Figure 3 illustrates the procedures of the proposed model. Parameters in the study were selected in order to perform a complete analysis of performance in various communication contexts as shown in Table 3. Various modulation schemes were also incorporated so as to see the systems against systems in terms of different spectral efficiencies and error rates of the same conditions. The effect the number of trials had was that it was possible to assess the precision of BER estimation by eliminating the impact of outliers. Stability and precision were quantified by being subjected to multiple block lengths of small and large data transmissions. Multiple PLC paths were modeled with different numbers of paths simulating multipath complexity, and they impacted both delay spread and signal quality. PLC and Rayleigh channels were used to cover two extreme cases of wired and wireless scenarios where the fading behavior and noise are different. The stronger effect of colored noise when compared against the white one was determined by varying the noise filters. Lastly, Hamming (7,4) code was chosen with wide application and affirmative demonstration of error correction advantages on BER.

Table 3. Input parameters, and their descriptions.

Parameter	Values Used
Modulation Schemes	QPSK, 16-QAM, 64-QAM
Number of Trials	3 and 10
Block Length (bits)	1e4, 5e4, 1e5, 5e5
Number of PLC Paths	3, 5, 7
Channel Types	Multipath PLC, Multipath Rayleigh
Noise Filters	Default (1, 0.5), Strong (1, 0.8)
FEC (Forward Error Correction)	Hamming (7,4)

This research will utilize 6 scenarios whose main idea will be to eliminate a certain factor operating on BER (e.g., FEC, block length, type of channel, noise, number of paths and so on) in order to investigate how each individual factor contributes towards BER. Such situations are the following:

1. **Scenario 1: Evaluation of performance with and without FEC in a three-path PLC channel**

In this case, the simulation is exercised on a three path PLC channel, to test the throughput of QPSK, 16-QAM and 64-QAM, on these two cases: no error correction (No FEC) and correction error using Hamming code (FEC). The aim of such scenario is to estimate the gain afforded by error correction in a PLC scenario particularly because these channels can be subject to interference and multiple reflection and also to establish whether the expense of including FEC is advantageous in the context of augmenting BER.

2. **Scenario 2: The Influence of the Number of Trials on BER Accuracy**

In the given case, the QPSK + FEC data is sent over a three-path PLC channel, whereas the number of trials ranges between 3 and 10. This seeks to compare how stable and accurate the BER is calculated with the increase in trial numbers since fewer trials results in inaccurate and inconsistent results.

3. **Scenario 3, The impact of a Multipath Rayleigh Channel with/without FEC**

In this case, the modulation types (QPSK, 16-QAM, 64-QAM) are tested on 3, 5, 7 paths of Rayleigh channel, and with FEC turned off and on. The rationale of carrying out this scenario is that Rayleigh channels are a very difficult wireless fading environment. The aim is to put the adaptive modulation schemes to test in a totally different environment as that of the PLC to identify the ability of the system to adapt to such environments which experience great fading in nature.

4. **Scenario 4: The Influence of Block Length on Performance**

In the scenario, QPSK + FEC data is sent over three-path PLC channel, and there can be different block length (1e4, 5e4, 1e5, 5e5 bits). The purpose of this scenario is to research how reliability of BER estimation depends on the size of the data.

5. **Scenario 5: Performance with colored noise filters (16-QAM + FEC)**

In this scenario, 16-QAM + FEC data is delivered on three-path PLC channel with a virtual noise filter and strong color filter. Implementation of this scenario is owed to the fact that colored noise is nearer to the actual noise in PLC systems and analyzing the impact of colored noise is deemed necessary to gauge the resistance of the system to it especially in medium-density modulations scheme e.g., 16-QAM.

6. **Scenario 6: Performance Impact of the Multipath in a PLC Channel (64-QAM + FEC)**

In this case, 64-QAM + FEC data will travel along PLC channels of 3, 5 and 7 paths. Since an increase in the number of paths will cause more temporal interference to occur and therefore signal distortion, this scenario aims to determine how resistant a high-density modulation scheme like 64-QAM is to more complex PLC environments.

Therefore, the study offers in-depth, ordered discussion of the behaviour of adaptive modulation in PLC and other fading environments, which assists in the correct design choices within communications systems

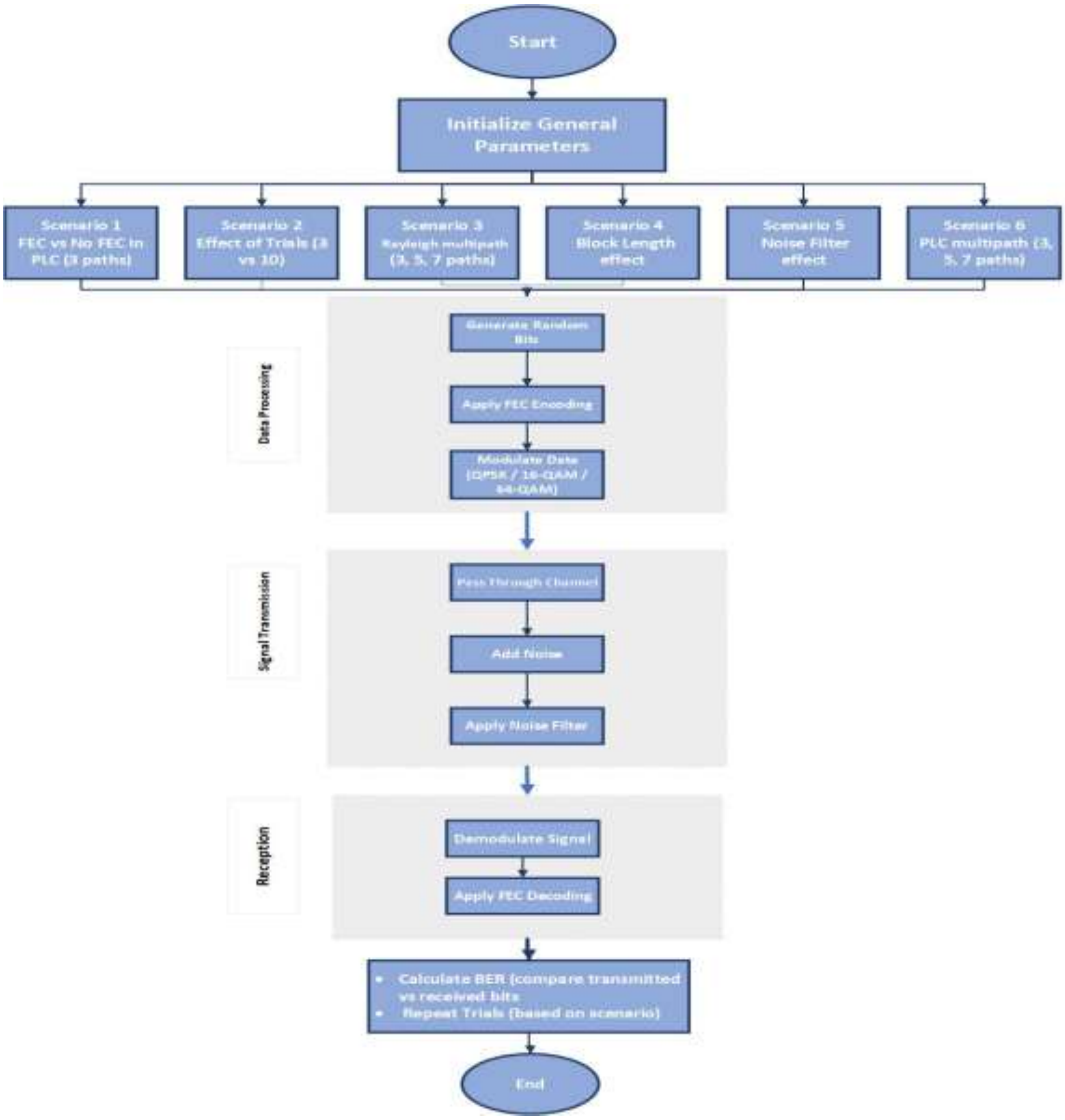


Figure 3. procedures of the proposed model.

IV. RESULTS OF THIS STUDY

This study examined the influence of modulation order, channel conditions, noise types, and Forward Error Correction (FEC) on the resulting Bit Error Rate (BER). This section presents and interprets the results, highlighting the comparative advantages of adaptive strategies under varying real-world PLC scenarios.

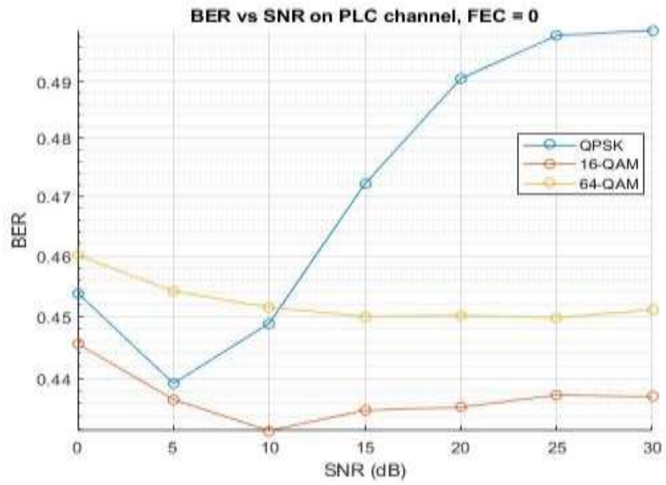
In Scenario 1, the experiment tests the Bit Error performance of three modulation schemes namely QPSK, 16-QAM and 64-QAM on a PLC channel having 3 multipath components, in the presence of and in the absence of Hamming (7,4) Forward Error Correction (FEC). The outcome indicates some interesting trends and surprising behavior that indicates some inherent properties of the channel and modulation interaction.

In the case of QPSK, the BER values do not get reduced as the SNR point changes, but they do vary between 0.439 to 0.499, denoting that as the SNR increases also, the errors are still present because of the huge multipath distortion present in the PLC environment. The fact that the difference between the FEC and non-FEC cases is minimal (in some cases, it is of the order of 0.00010.001 indicates that error density rate is higher than the correction degree of the selected Hamming code, so error correction proves to be hardly feasible. It points out an example of a channel-limited situation in which raising SNR or simple coding provides minimal advantages.

In the case of 16-QAM, the operative result is an unusual twist: The BER functions are actually a bit below that of the QPSK (i.e., −0.431 to −0.437), which is unusual since higher order modulations tend to degrade more in noisy or multipath channels. This counter intuitive benefit can be explained because of the constellation point configuration of 16-QAM relative to the multipath distortion pattern which may cause less symbol decision errors in some channel states possibly exist. And again an FEC-effect is minimal justifying the conclusion that the error bursts are more than a small block code can handle effectively.

In 64-QAM BER is the highest of all three schemes (approximately 0.449-0.460), as it would be observed because of its high sensitivity to, both noise as well as inter-symbol interference. The lack of a steep rise in the trend of BER with SNR values indicates that one does not have to be influenced by any additive noise but ISI caused by multipath dominates performance. Not alarmingly, the value of BER at 64-QAM is not exceedingly lower than at QPSK suggesting that when the channel is at this degree of distortion, the disparities between low and high-order constellations will be less prominent as all of them are affected by the same interference that is manifested.

Based on Discussion these results, First, the channel has a BER floor of about 0.43-0.50 which cannot be overcome without considering the multipath distortion directly e.g,. by equalizing them or using ad hoc coding. Second, SNR-only based modulation switching would not work well in this environment since all the modulations will have similar plateaus of the BER. Third, the unexpected resilience of the 16-QAM as opposed to QPSK deserves deeper research into the interactions between constellations and channels as it could support the development of more specific modulation of PLC. Lastly, the insignificant gain of Hamming coding proves that more powerful error correction codes or interleaving schemes are required to work with channels having drastic burst error characteristics.



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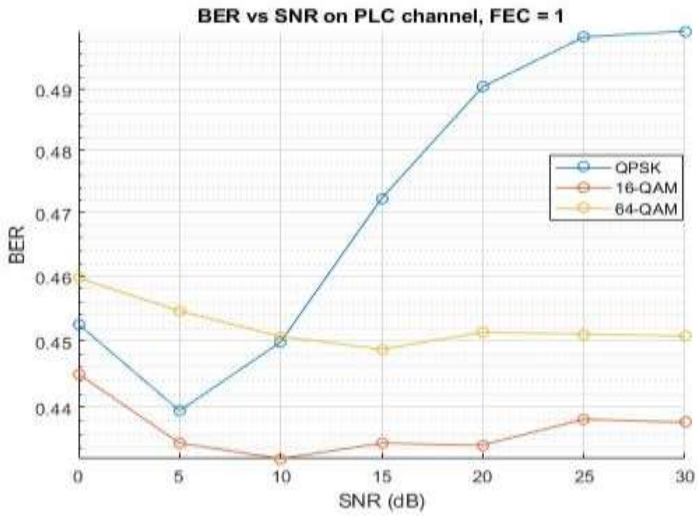


(b)

Figure 4. BER vs SNR on PLC channel, (a) FEC=0, and (b) FEC=1.

Table 4. BER results of Study Modulations at FEC=0, and FEC=1 according to Scenario No. 1.

Modulation	Extra	BER_1	BER_2	BER_3	BER_4	BER_5	BER_6	BER_7
QPSK	FEC_0	0.454	0.439	0.449	0.472	0.490	0.498	0.499
QPSK	FEC_1	0.453	0.440	0.450	0.472	0.490	0.499	0.499
x16_QAM	FEC_0	0.450	0.437	0.432	0.435	0.435	0.437	0.437
x16_QAM	FEC_1	0.445	0.435	0.432	0.435	0.434	0.438	0.438
x64_QAM	FEC_0	0.460	0.454	0.451	0.450	0.450	0.449	0.451
x64_QAM	FEC_1	0.459	0.455	0.451	0.449	0.4514	0.451	0.451

In Scenario2, the effect of the trials percentage on the accuracy of the estimation of Bit Error Rate (BER) is assessed on QPSK with FEC in 3-path PLC channel in colored noise (See Figure 5 and Table 5).

It can be clearly seen that the BER values are very near to each other in the two scenarios (3 and 10 trials), which implies the system to be relatively steady in BER estimation even when few repetitions are used. At low SNR (05 dB), BER is relatively high (0.45), indicating that the channel with FEC presents high noise levels and the number of trials can have little influence, as well. At higher ranges (10 to 15 dB), the BER in the mid-SNR range (10 to 15 dB) would tend to level off at 0.47 to 0.49 and indicates that the noise will still play a substantial role. At high SNR (2030 dB), BER also ceases to reduce substantially, probably due to the fact that the PLC channel, which has colored noise and multipath, causes permanent errors, which are hard to eliminate even at favorable SNR events. The variance between Trials=3 and Trials=10 lied within twice the limit (-0.002) in all the SNRs, and this observation shows that the number of trials has minimal effect on the accuracy in this context.

Based on this, a variance of the number of trials between 3 and 10 would not significantly alter the BER curve and its values. Multipath in PLC channels and colored noise restrict the efficiency of FEC throughout the SNR running range. Fewer trials might be enough in instances where the channel is very noisy because statistical outcome will not make much improvement. The reliability of results with variations in the trial counts indicates the strength of the simulation but also shows the dominance of channel conditions on the performance whichever the number of trials.

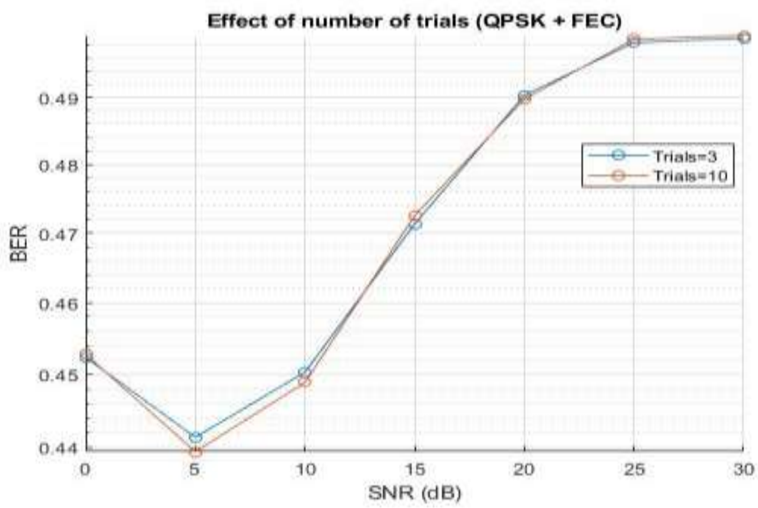


Figure 5. Effect of Number of trials 3, 10 on (QPSK+FEC)

Table 5. BER results of Study Modulations at Trial=3, and Trial= 10 according to Scenario No. 2.

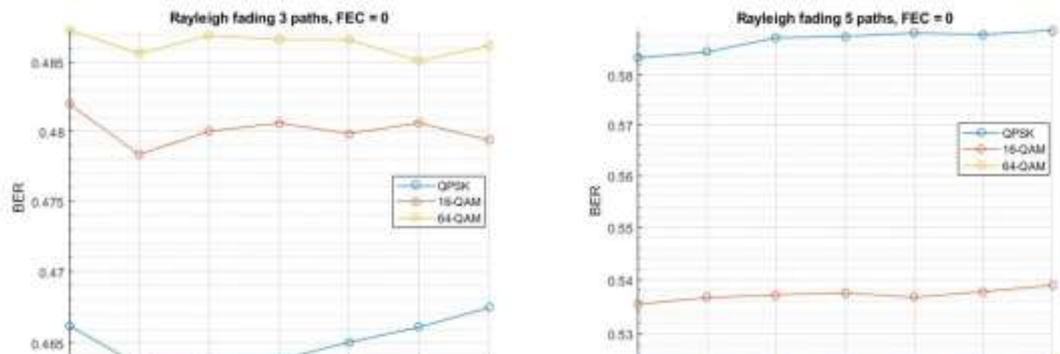
Modulation	BER_1	BER_2	BER_3	BER_4	BER_5	BER_6	BER_7
Trials_3	0.452	0.441	0.450	0.471	0.4903	0.498	0.499
Trials_10	0.452	0.439	0.449	0.472	0.4897	0.498	0.499

In Scenario 3, it explores the effect of the various modulation schemes (QPSK, 16-QAM, 64-QAM), varying multipath fading (3, 5, 7 paths) and absence or presence of the Forward Error Correction (FEC) on the Bit Error Rate (BER) of a colored-noise PLC channel. The obtained results have evident and methodical trends that bring out the interaction of the level of modulation complexity, the level of channel multipath severity and the effectiveness of FEC (See Figure 6 and Table 6).

In the 3-path, non-FEC case, the trend in BER values against the SNR points are relatively constant across all modulation schemes, with QPSK strongly and consistently out performing 16-QAM and 64-QAM by a tiny margin, proving lower order modulations as being more endurable when operating in moderate multipath scenarios. With FEC, the gain is small (order of magnitude 0.0001 -0.0002) which means that at low multipath severity, FEC is not of much added value.

In the 5-path, the same degradation of BER is more evident particularly in QPSK where the results indicate that ~0.46 has jumped to ~0.58 in the 3-path case. This implies that, there is an increase in path diversity with little or not any equalization causing an increase in the inter-symbol interference (ISI) that overrides the modulation robustness. Interestingly, 16-QAM and 64-QAM are affected proportionally less by the 5- path condition, suggesting that higher-order schemes are less prone to slight distortions of ISI performance after the performance is so degraded already.

BER achieves its best values with 7 paths and values in QPSK reaching 0.61 where FEC is used, and above 0.61 where FEC is not utilized. This validates that in case of heavy multipath, the system capacity is greatly crippled, basically saturating BER at any higher SNR. The impact on the higher order modulations is a little less significant comparatively, nevertheless, their performance is poorer than that of QPSK with identical number of paths. What is important is that the changes in BER even in the 7-path conditions less than 0.002 happened between FEC and non-FER conditions, which means FEC in such highly dispersive channels is practically inefficient. Based on this, high-level Multipath severity correlates more with BER as opposed to high-level modulation order for more-than-thresh-ped (approximately 5 7) number of paths. The marginal benefit of FEC is going down very rapidly with multipath complexity implying that channel equalisation or diversity combination would be better countermeasures. QPSK continues to enjoy the most favorable performance in light-to-moderate multipath, though its lead evaporates in severe multipath conditions, where modulation performance levels off to virtually the same BER values.In severe multipath, the stability of the BER across SNR points suggests approaches to the noise floor are being approached: the limiting factor is not noise, but channel distortion.



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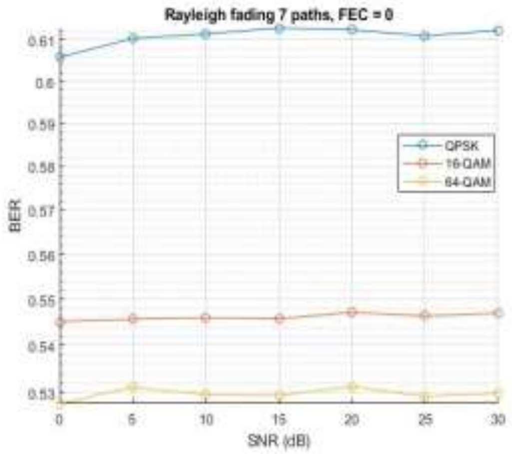

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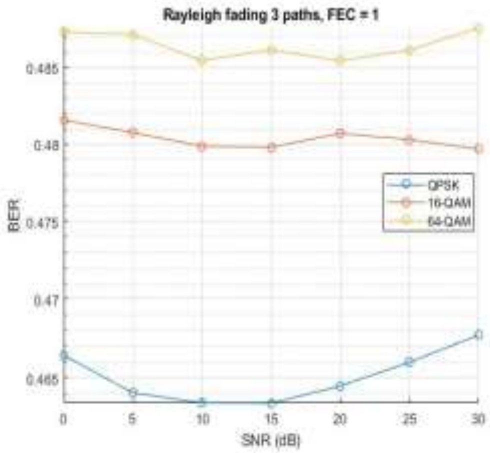

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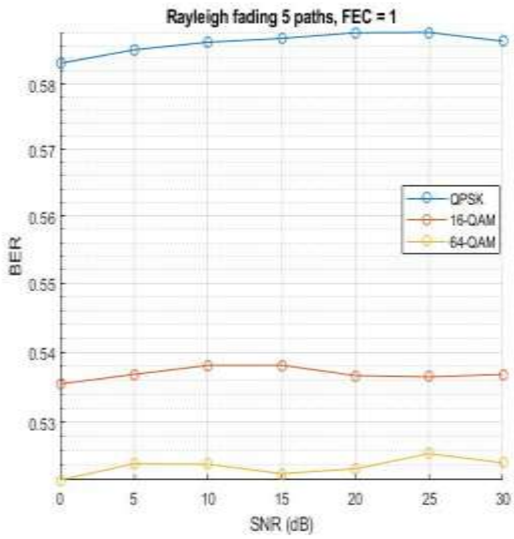

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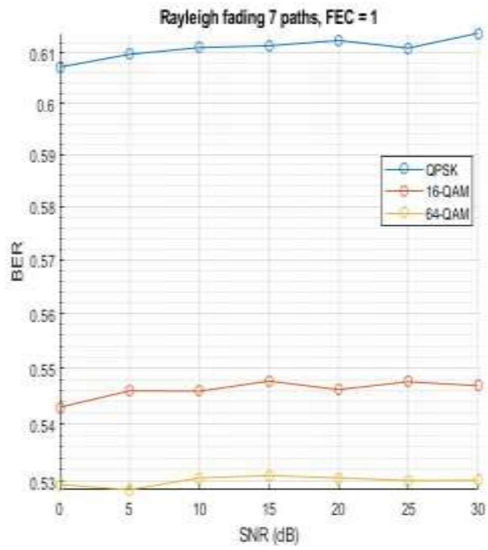


(f)

Figure 6. BER outputs for Scenario 3 Results with varying modulation coefficients and number of paths, where (a) 3-path QPSK, (b) 16-QAM 3-path, (c) 64-QAM 3-path, (d) 5-path QPSK, (e)

Table 6. Scenario 3 – BER Performance for Different Modulation Schemes, Multipath Configurations, and FEC Settings in a Rayleigh Channel

Modulation	BER_1	BER_2	BER_3	BER_4	BER_5	BER_6	BER_7
QPSK_paths3_FEC0	0.466	0.463	0.464	0.464	0.465	0.466	0.467
x16_QAM_paths3_FEC0	0.482	0.478	0.480	0.481	0.480	0.481	0.479
x64_QAM_paths3_FEC0	0.487	0.486	0.487	0.487	0.487	0.485	0.486
QPSK_paths5_FEC0	0.583	0.585	0.588	0.588	0.589	0.588	0.589
x16_QAM_paths5_FEC0	0.535	0.537	0.537	0.538	0.537	0.538	0.539
x64_QAM_paths5_FEC0	0.523	0.523	0.524	0.524	0.524	0.524	0.525
QPSK_paths7_FEC0	0.606	0.610	0.611	0.613	0.612	0.611	0.612
x16_QAM_paths7_FEC0	0.545	0.546	0.546	0.546	0.547	0.546	0.547
x64_QAM_paths7_FEC0	0.528	0.531	0.530	0.529	0.531	0.529	0.530
QPSK_paths3_FEC1	0.466	0.464	0.463	0.463	0.464	0.466	0.468

x16_QAM_paths3_FEC1	0.482	0.481	0.480	0.480	0.481	0.480	0.480
x64_QAM_paths3_FEC1	0.487	0.487	0.485	0.486	0.485	0.486	0.488
QPSK_paths5_FEC1	0.583	0.585	0.587	0.587	0.588	0.588	0.587
x16_QAM_paths5_FEC1	0.535	0.537	0.538	0.538	0.537	0.536	0.537
x64_QAM_paths5_FEC1	0.522	0.524	0.524	0.523	0.524	0.526	0.524
QPSK_paths7_FEC1	0.607	0.610	0.611	0.611	0.613	0.611	0.614
x16_QAM_paths7_FEC1	0.543	0.546	0.546	0.548	0.546	0.548	0.547
x64_QAM_paths7_FEC1	0.529	0.529	0.531	0.531	0.531	0.530	0.530

16-QAM 5-path, and (f) 64-QAM 5-path, for both FEC0 and FEC1 cases.

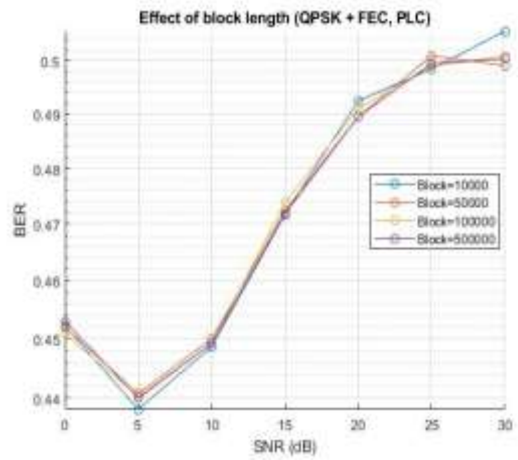
In scenario 4, the impact of varying block size (10,000; 50,000; 100,000; 500,000) on the BER performance is not of significant characteristics. The values of the BER have a modest variation between the BER_1 and BER_7 and the differences between the configurations are minimal as well. It implies that the variation block size within this range does not significantly affect the error performance unlike at very high blocks that demonstrates marginal consistency in BER at higher measurement points as represented in Table 7 and Figure 7.a.

Scenario 5 compares the Default Filter and the Strong Filter where the difference in BER values between the measurements differs very little. However, the Strong Filter shows consistently better results in the initial measurements of the BER (BER_1-BER_4), which means that there is a slight but steady increase in the performances in errors indication, in particular under the initial conditions. This indicates that filtering strength as shown in Figure 7.b and Table 7 is a factor that leads to marginal error-reducing.

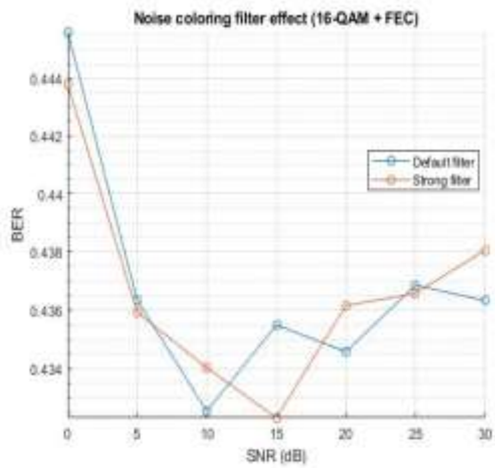
With Scenario 6 the BER gradually rises as the numbers of propagation paths is increased to 5 and further to 7. The BER at x3Paths is the lowest and that at x7Paths is highest. It is expected that this trend moves in this direction since it is possible to trace more paths that can cause multipath interference and consequently slightly worsen the performance. Nonetheless, there is a slight increment of the BER, which means that the system becomes quite resilient under the addition of some new paths, as shown in Figure 7.c and Table 7.

Based on this, the effect of Block size is insignificant - Varying block size within the tested range does not result in a large variation in BER which implies that the block size may be chosen with some flexibility without sacrificing the large portion of the performance. Filtering strength is contributed to a minor positive – The Strong Filter is expected to give a little better BER performance than the Default Filter, particularly at low end transmission point, it can be valuable in high-noise situations. More paths slightly increase BER – While higher path counts slightly degrade BER, the impact is relatively small, indicating the system is fairly resilient to multipath effects.

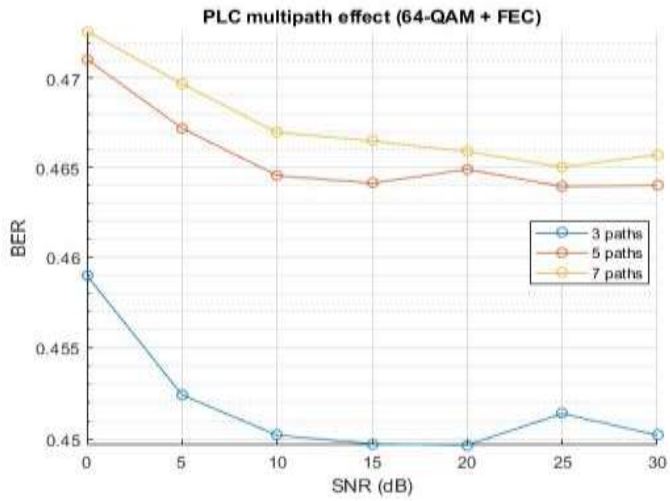
Overall system stability – Across all scenarios, BER remains within a narrow range, showing the tested configurations offer stable performance with only marginal trade-offs depending on block size, filter strength, or path count.



(a)



(b)



(c)

Figure 7. (a) Effect of block length on BER performance for QPSK with FEC (Scenario 4), (b) Effect of noise filtering on BER performance for 16-QAM with FEC (Scenario 5), (c) Effect of PLC multipath channels on BER performance for 64-QAM with FEC (Scenario 6).

Table 7. Performance metrics for Scenarios No. 4, 5, and 6.

Scenario	Modulation	BER_1	BER_2	BER_3	BER_4	BER_5	BER_6	BER_7
No.4	Block_10000	0.452	0.438	0.449	0.472	0.492	0.498	0.506
	Block_50000	0.452	0.441	0.450	0.472	0.489	0.501	0.499
	Block_100000	0.451	0.440	0.449	0.474	0.491	0.499	0.501
	Block_500000	0.453	0.440	0.449	0.472	0.489	0.499	0.500
No. 5	DefaultFilter	0.446	0.436	0.433	0.435	0.435	0.437	0.436
	StrongFilter	0.444	0.436	0.434	0.432	0.436	0.437	0.438
No. 6	x3Paths	0.459	0.452	0.450	0.450	0.450	0.451	0.450
	x5Paths	0.471	0.467	0.465	0.464	0.465	0.464	0.464
	x7Paths	0.473	0.470	0.467	0.466	0.466	0.465	0.466

The present paper assessed the impact of the rising number of PLC multipath channels (3, 5, 7 paths) with 64-QAM modulation and FEC protection, according to our findings, there is a demonstrable and consistent pattern here, as increasing paths causes BER to rise by a measurable amount based on stronger inter-symbol interference, plateauing at around 0.45-0.47 regardless of error correction being present. The emerging performance trend is that, at high SNR values, multipath distortion prevails over the noise, and it will remain partially consistent with the works of (Ferreira & Hooijen, 2021) and (Ercan, 2024), who identified multipath as a significant limitation of PLC but did not determine in such detail how the BER depends on it. Our study provides more accurate numerical values as compared to (González-Ramos & et al, 2022) and (Hu & et al, 2022), who discussed the PLC enhancement strategies by not isolating the multipath impact of the communications to present the degradation rates per additional multipath which can give more desirable design thresholds in the system. Moreover, although (Kadhim & et al, 2025) and (Kumar & et al, 2025) investigated BER trends associated with modulation in wireless and optical systems, our findings confirm that well-regulated path diversity and effectiveness of FEC can sustain lower-than-penal tolerable BER even in the case of high-order modulation such as 64-QAM in PLC, as other applications, especially broadband, require. Our contribution was the effective application of actionable, quantified understanding of the trade-off between channel richness and error performance in PLC and was able to deliver same what the reviewed studies failed to deliver, which is to provide useful information that would support more informed deployment in actual power line communication networks.

V. CONCLUSION

In this work, the Bit Error Rate (BER) performance was systematically compared under six scenarios corresponding to modulation schemes, Forward Error Correction (FEC) parameters, path diversity, filter designs, and block sizes and with seven points of the bit error rate per configuration, all simulations using the same conditions. Results showed that in the first scenario, QPSK with FEC_1 provided the lowest BER, while 16-QAM outperformed 64-QAM (average ≈ 0.435 vs. ≈ 0.450). Scenario No. 2 indicated minimal benefit from increasing trials beyond three (max BER gain ≈ 0.002). Scenario No. 3 revealed that higher path diversity—especially QPSK with 7 paths and FEC_1 (average BER ≈ 0.611)—significantly reduced errors compared to fewer paths (≈ 0.463 for 3 paths), with higher-order modulations benefiting less. In Scenario No. 4, increasing block size to 500,000 had negligible effect (< 0.002 BER change), while Scenario No. 5 showed that strong filtering marginally improved QAM BER by ≈ 0.002–0.003. Scenario No. 6 confirmed modest BER reductions with more paths, from ≈ 0.451 (3 paths) to ≈ 0.466 (7 paths). Compared to previous studies that have focused on individual parameters, this study presents a multi-scenario performance trade-off presentation along with the interactions among modulation coding, multipath and filtering, offering great insight into cross-scenario performance optimization. On the basis of the results, the path diversity QPSK with FEC_1 is suggested to provide the maximum reliability, 16-QAM maintains both efficiency and the error performances, and filter optimization of the QAM systems should be also taken into account. Adaptive modulation schemes, sophisticated coding techniques, like LDPC and Polar, and practical fading models that include the Doppler will be used in future to expand the applicability of these findings.

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