Impulsive noise mitigation based adaptive filtering and Reed Solomon coding for power line communication

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ABSTRACT

In the realm of power line communication (PLC), impulsive noise is often regarded as the most difficult challenge to face in PLC. The impulsive noise effects are reduced by employing a combined adaptive least mean square (LMS) filtering and Reed Solomon (RS) coding. As a result, the bit error rate (BER) and throughput performance over this channel are enhanced. The results of a MATLAB computer simulation indicated that a significant improvement is achieved by utilizing the LMS adaptive filter in conjunction with the RS code. This is in contrast to a system that utilizes RS code alone or a system that utilizes the conventional time domain clipping approach.

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1. INTRODUCTION

Recently, power-line networks have become an attractive option for data transmission because of the already existing infrastructure. It has the potential to significantly reduce costs [1]–[5]. At its maximum, this power line communication (PLC) system is capable of sending and receiving several bits of data per second [6]. However, issues like noise, attenuation, and interference limit the usefulness of its high data rate [7], [8]. When these disturbances are present in PLC networks, the performance can be seriously harmed [9]. The two distinct types of noise that can be distinguished from each other are the background and the impulsive types. There are other subsets of both of these main groups. Both artificial and natural noise tend toward impulsive behavior with long tails, which has been shown to amplify interference in PLC networks. In order to better understand and optimize the performance of PLC networks, an in-depth investigation of impulsive noise is required [10]. Reed Solomon (RS) coding has been found to be superior to impulsive noise reduction procedures like clipping, blanking, nulling, time/frequency-domain approaches, and recursive detection methods [11]–[13]. Time domain clipping is one such approach, but at typical data rates it is ineffective against severe PLC channel conditions. While ambient noise might be distracting, it's the sudden bursts of volume that really get under the skin. Filtering out the aperiodic impulsive noise is one way to further boost the efficiency of PLC networks. An adaptive technique is necessary in order to effectively eliminate periodic impulsive noise. This research provides an evaluation of the effectiveness of the RS coding/least mean square (LMS) hybrid approach.

The remaining sections of this paper are organized as follows: section 2.1 describes the impulsive noise model, subsection 2.2 explains the PLC-based orthogonal frequency division multiplexing (OFDM) system, subsections 3.1 and 3.2 give some simple details of the RS coding and LMS adaptive filter principles, respectively, and subsection 3.3 describes the combined RS coding/LMS filter. Section 4 explains the simulation results obtained using MATLAB, and finally, section 5 gives some concluding remarks obtained from this work.

2. IMPULSIVE NOISE MODEL AND PLC-BASED OFDM SYSTEM

2.1. Impulsive noise model

Figure 1 shows the PLC channel affected by different types of noise. These are impulsive noise, narrow band noise, and colored background noise. The impulsive noise is classified into periodic impulsive noise synchronized with the main supply, periodic impulsive noise not synchronized with the main supply, and asynchronous impulsive noise that occurs due to random high-power switching. For analysis purposes, these three types of impulsive noise can be summed up together as the impulsive noise occurs randomly according to a certain distribution, such as the poisson distribution, giving the probability of k impulses occurring in a second:

$$\mathrm{p(k\ impulses)} = \mathrm{p(x = k)} = \mathrm{e}^{-\lambda}\frac{\lambda^k}{k!} = p_k, k = 0, 1 \tag{1}$$

The height of the impulse is assumed to follow a Gaussian distribution with a mean of zero and variance σ_i^2. The two background noises are also summed up together and assumed to be one background Gaussian noise. Hence, the average impulsive noise power will be ($p_k\ \sigma_i^2$) and the average background noise power will be σ_w^2. If the total signal power is p_x, then the average signal to noise ratio (SNR) will as in (2):

$$SNR = \frac{p_x}{\sigma_w^2 + p_k\ \sigma_i^2} \tag{2}$$

Also, a parameter B is described as the ratio between the power of impulsive noise and the power of Gaussian noise; it may therefore be used as a measure of the relative strength of these two types of noise.

$$B = \frac{p_k\ \sigma_i^2}{\sigma_w^2} \tag{3}$$

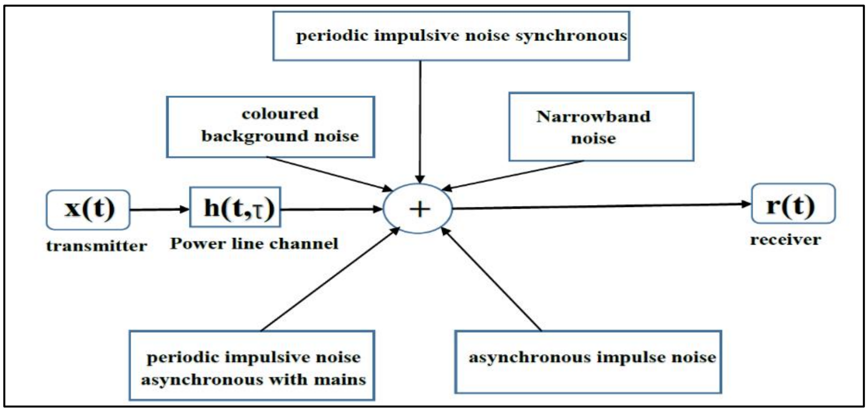

Figure 1. Power line noise kinds

2.2. PLC-based OFDM system

OFDM is often regarded as the most effective option for PLC systems due to its robustness against multipath, selective fading, and other forms of interference. Wideband digital communication systems, including digital audio broadcasting (DAB), terrestrial digital television (DVB-T), wireless local area networks (LANs), and Wi-Max, all employ OFDM since it is a well-established multicarrier transmission method. OFDM performs better than single-carrier systems [2], [4], [14] when exposed to impulsive noise. This is because OFDM, using the discrete fourier trasform (DFT), distributes the influence of impulsive noise across several symbols. Furthermore, the use of a cyclic prefix (CP) in OFDM signals can help to reduce the effects of multipath. Despite OFDM's advantage in the presence of impulsive noise, mitigating strategies must be used to further limit its impact on data transmission. Figure 2 shows the basic block diagram of an OFDM system based on quadrature phase shift keying (QPSK) modulation.

OFDM manages the spectrum by applying several overlapping orthogonal subcarriers. The frequency selectivity fading and the presence of multipath propagation over the PLC channel render OFDM-based solutions invaluable for transmitting at higher data rates. A robust and efficient data recovery technique is imperative to establish reliable data transmissions over severe PLC channels. OFDM is a high-performance multi-carrier transmission technology that works well on PLC channels. The inverse discrete fourier transform (IDFT) is used in OFDM systems to divide an increased serial data stream that is being input into a number of parallel slow data streams that are conveyed in numerous orthogonal subcarriers. OFDM's extended symbol period has the effect of reducing the influence of inter-symbol interference (ISI) generated by signal multipath.

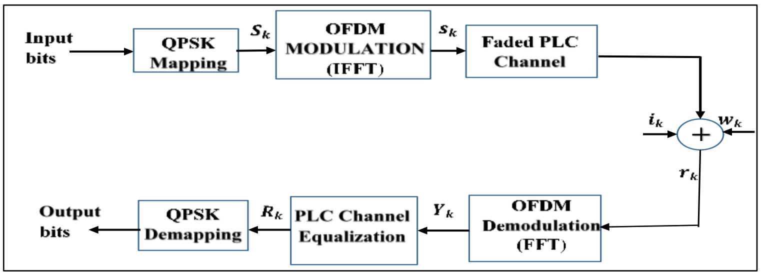

Figure 2. Block diagram of OFDM system

The discrete-time OFDM signal is written as (4):

$$s(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} s_k \, e^{j2\pi \frac{k\,n}{N}}, 0 \leq \mathrm{n} \leq \mathrm{N} - 1 \quad (4)$$

S_k is a series of symbols mapped from binary data. In this work, QPSK mapping is used with N carriers. In order to get rid of inter-channel interference (ICI) and inter-symbol interference, OFDM uses a CP at the beginning of the OFDM transmissions (ISI).

3. NOISE REDUCTION IN PLC

3.1. Impulsive noise mitigation using RS coding

Clipping, nulling, and RS coding methods were presented and developed in [15]–[17]. The amplitude of the signal is reduced by clipping and nullification. Once it reaches a certain level, a restriction is placed on the signal. The performance of the bit error rate (BER) is impacted by the in-band distortion that occurs during this operation. When compared to other noise reduction methods in [11], the RS coding approach provided superior impulsive noise abatement. During data transmission across noisy and faded communication channels, RS coding is utilized to detect and repair data mistakes. The PLC impulsive noise can thus be reduced by using this method. Using this method, the sender includes mistake correction information in the form of redundancy bits, while the receiver ignores the latter. Here, the redundancy bits let the receiver identify data problems and make necessary corrections without requiring retransmission. In Figure 3, one can see the fundamental steps of the RS encoding process.

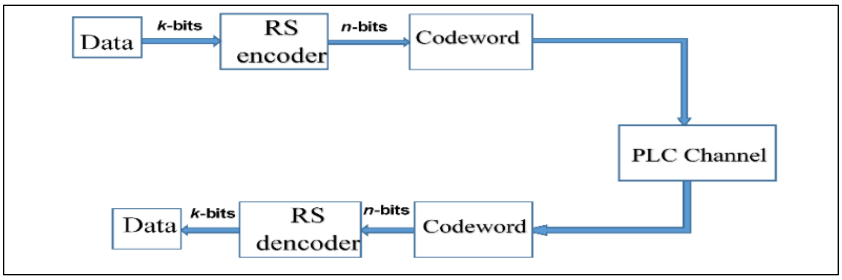

Figure 3. The RS coding basic block diagram

A codebook is utilized to convert k-bit data sequences to n-bit code words. The t-error RS code is defined as (n, k) code where n=2^m-1 (m is an integer, m≥3) and k<n. The parity symbol is r=n-k, and the

ratio (k/n) is called the code rate. Dealing with this code as a non-binary error correcting code over galois field (GF) (2^m), then this RS code can correct up to [18], [19].

$$t = \left(m \times integer(\tfrac{n-k}{2})\right) bits \tag{5}$$

3.2. Impulsive noise mitigation based adaptive least mean square filtering

For many filtering algorithms, optimal filter coefficient values are unknown in real-world applications. Because of this, it is necessary to be adaptable. Such issues can be resolved using the LMS filtering method. The filter coefficients of an adaptive LMS filter are recalculated in response to the filter's inputs [20]. There are two sections to this adaptive filter. Because of the benefits and stability of the finite impulse response (FIR) filter, the initial component of the filter is often made up of this type of filter [21]. The adaptive algorithm is employed in the second half of the filter. The adaptive method used in this research will be the LMS algorithm. Figure 4 depicts the main building blocks of this LMS adaptive filter.

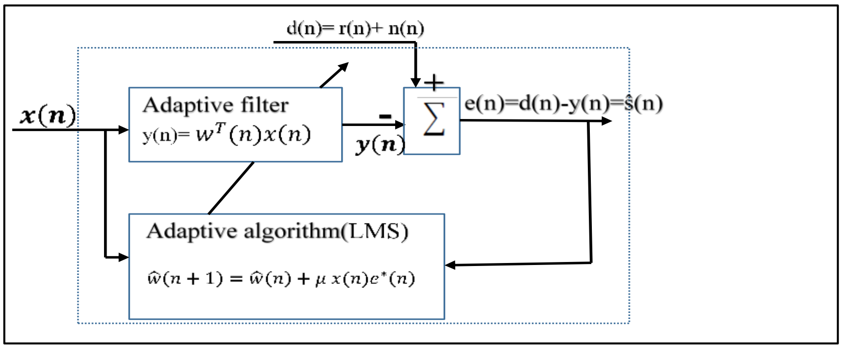

Figure 4. Main building blocks of an adaptive filter

In general, there are two inputs to this adaptive noise reduction filter. These are $d(n)$ and $x(n)$. If $d(n) = r(n) + n(n)$, which is the corrupted PLC signal, and $x(n)$ is the corrupted PLC signal due to different types of noise, then $y(n)$ is the estimated noise by this adaptive filter. The generation of the error signal e(n) occurs when the output signal y(n) is subtracted from the desired signal d(n). In every iteration, the weight function w adjusts the old value to get a whole new weight value. As a result, it may be inferred that the LMS algorithm's coefficients can be changed. The adaptive filtering algorithms are subjected to a filtering and adaptation process as a result of their development. Two estimates are made throughout the filtering process. The first step is to create the filter output value.

$$y(n) = \sum_{i=0}^{M-1} w_i\, x(n-1) = w^T(n)x(n) \tag{6}$$

With the LMS algorithm, the tap weight vectors are adjusted to reduce the mean square error. At that time $(n+1)$, the tap weight is re-adjusted as (7):

$$\hat{w}(n+1) = \hat{w}(n) + \mu\, x(n)e^*(n) \tag{7}$$

When μ determines the interval between each step. By deducting the filter output from the desired response, one may calculate the error's magnitude. The adaptive procedure involves the filter adjusting its parameters to get the desired response.

$$e(n) = d(n) - y(n) = d(n) - w^T(n)x(n) \tag{8}$$

The adaptive filter's LMS algorithm's acronyms are shown in Table 1.

Table 1. LMS algorithm parameters

Inputs		Outputs	
$\boldsymbol{x}$	PLC noise	$\boldsymbol{y}$	Outcome of the filter
d	Received corrupted signal	e	error signal
M	The length of the filter	ŝ	Estimated signal
µ	factor of step size		
w	weight function		

3.3. Proposed combined rs coding and adaptive LMS technique

To cope with impulsive noise, it is suggested that adaptive filtering methods and RS techniques are better suited for impulsive noise mitigation in PLCs. Figure 5 shows the block diagram of OFDM-based combined RS coding/adaptive filtering. The two types of impulsive noise are: the periodic component has an aperiodic component that is both periodic and periodic, with the periodic component exhibiting more pronounced spikes. Periodic, impulsive noise drastically degrades the network's efficiency, and it is difficult to remedy this issue [22]. In particular, aperiodic impulsive noise may be mitigated by RS coding but not periodic noise [22]. It may, however, be used in conjunction with alternative noise suppression techniques and methods to greatly reduce impulsive noise that occurs periodically.

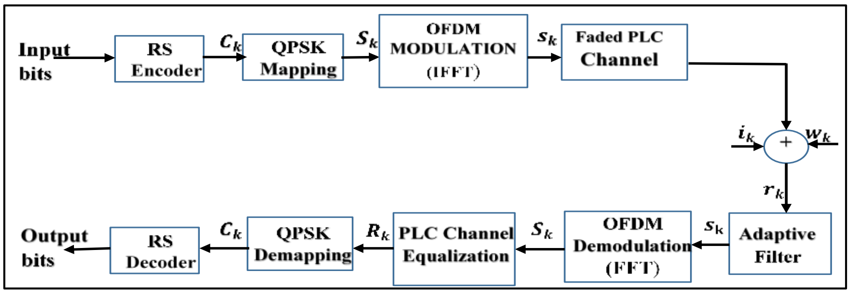

Figure 5. Block diagram of OFDM-based combined RS coding/adaptive filtering

Adaptive filtering was demonstrated in [23] to be effective in reducing periodic impulsive noise. If the adaptive filter detects periodic impulsive noise, the signal above a specific threshold frequency is filtered [24]. A combined RS coding/LMS adaptive filtering noise mitigation strategy is therefore essential in order to properly attenuate the aperiodic and periodic components. A two-phase noise mitigation approach utilizing a mix of RS coding and LMS adaptive filtering has been presented. The system is divided into two phases: the first phase uses RS coding, while the second phase uses an adjustable LMS filter. The adaptive LMS filter is used in this method to further enrich the enhanced data from RS coding (it is necessary to remove the periodic impulsive noise that remains after filtering out the aperiodic impulsive noise and applying RS coding to remove the periodic impulsive noise) [15], [25]. An adaptive LMS filter filtered out the impulsive noise left unfiltered by RS coding. As a result, precision is improved. One of its drawbacks is RS coding's inability to fix some mistakes as the quantity of data bits rises. These constraints can be overcome with the help of the suggested combined technique. It combines the RS's coding efficiency with the LMS filter's stability and computational economy.

There is an analogue-to-digital conversion of the power-line channel's data stream at the outset so that it may be used for RS coding. To complete the RS encoding process, the k-bit data from the transmission side is converted to the n-bit code word using a codebook. A power-line channel contaminated by impulsive noise is allowed to carry the n-bit code word. Data transmission will be compromised by random noise and a misspelled code phrase (error data) [26]. In this case, mistakes are fixed by calculating the Hamming distance between each pair of code words. The receiver uses the shortest possible Hamming distance to select the valid code word (data free of errors) in place of the invalid code word (data containing errors). In this way, the recipient receives error-free data (also known as "improved data"). Figure 6 shows how the combined RS coding/LMS adaptive noise mitigation are embedded in the OFDM system.

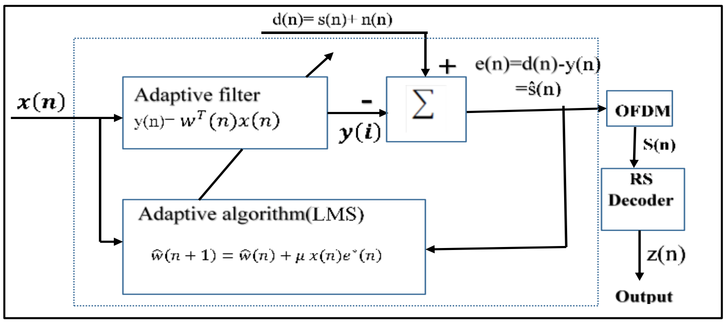

Figure 6. Combined RS coding/LMS adaptive filter block diagram

4. RESULTS AND DISCUSSION

MATLAB m.files are used to simulate: i) the transmitter with RS coding, ii) receiver with combined RS decoding plus LMS adaptive filtering, and iii) the faded PLC channel affected by background noise as well as impulsive noise. Iterations were run using the following inputs: QPSK modulation, 256 carriers, 10,000×256 bits broadcast, 4 paths via the fading channel, a 16-bit CP in OFDM, and 2 pilot carriers are all part of the design. Table 2 displays a common bit-mapping setup for converting QPSK symbols to voltages.

Table 2. QPSK bit-mapping

Baseband bit block	I channel	Q channel
00	−3	−3
01	−1	−1
10	+1	+1
11	+3	+3

A variety of simulations were done with varying impulsive noise levels (p and B given in (1) and (3), respectively). Also, the RS code rates and length were varied to test their effects. Also, the aforementioned configuration of LMS adaptive filtering was also implemented. The following variables specify the RS coding used:

$$(n.k) = (2^m - 1.2^m - 1 - 2t)$$

where

$$n = 2^m - 1$$

and

$$k = 2^m - 1 - 2t \quad (9)$$

where each symbol is formed from an m-bit sequence.

4.1. Test 1: p=1%; B=10 with (63,41) RS code

Test 1's settings are as follows: impulsive noise events have a p=1% chance of occurring, and impulsive noise power is 10 times the background noise power. Given the predicted impulsive noise characteristics, the length of RS redundancy is set at n-k=22. The length of each code word is 63. Figure 7 depicts the outcomes of BER simulations. Using only an adaptive LMS filter on a QPSK demodulation process is shown in the first simulation. The adaptive LMS filter's ability to improve the clustering of QPSK constellation points may be clearly recognized. The BER performance of many types of OFDM with adaptive LMS filters, RS-OFDM, and RS-OFDM with adaptive LMS filters is examined and compared in the second simulation. In these experiments, the adaptive LMS filter-OFDM system outperformed the OFDM system. The combined adaptive LMS filter and the RS coding procedure increase the impulsive noise resistance of the OFDM system. The combined RS coding/adaptive LMS filter-OFDM system clearly outperforms earlier strategies in terms of BER improvement.

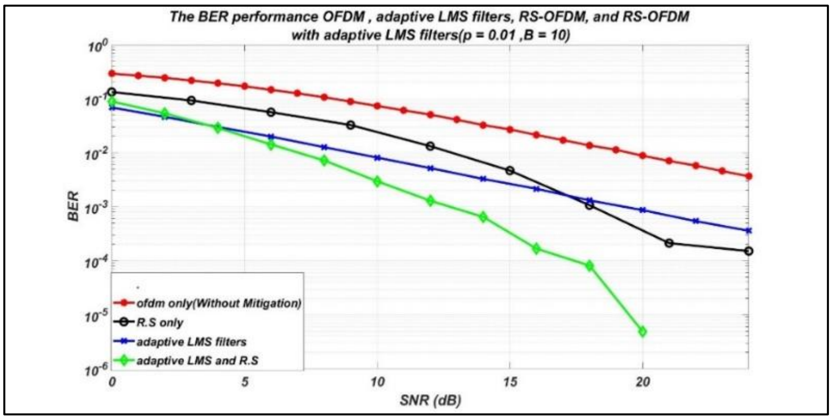

Figure 7. The BER performance of OFDM, adaptive LMS filters, RS-OFDM, and RS-OFDM with adaptive LMS filters is evaluated and compared (p=0.01, B=10)

4.2. Test 2: p=10%; B=10 with (63,41) RS code

Test 2 settings are as follows: impulsive noise events have a p=10% chance of occurring, and impulsive noise power is 10 times the background noise power. Given the predicted impulsive noise characteristics, the length of RS redundancy is again set at n-k=22. Figure 8 shows the BER simulations for this case. The BER performance of several variants of OFDM with adaptive LMS filters, RS-OFDM, and RS-OFDM with adaptive LMS filters is evaluated and compared. The adaptive LMS filter-OFDM system performs better than the OFDM system in these tests. The combined adaptive LMS filter and the RS coding method both increase the impulsive noise resistance of the OFDM system. Even with a 10% probability of impulsive noise, the combined RS coding/adaptive LMS filter-OFDM system provides the best BER improvement over prior approaches.

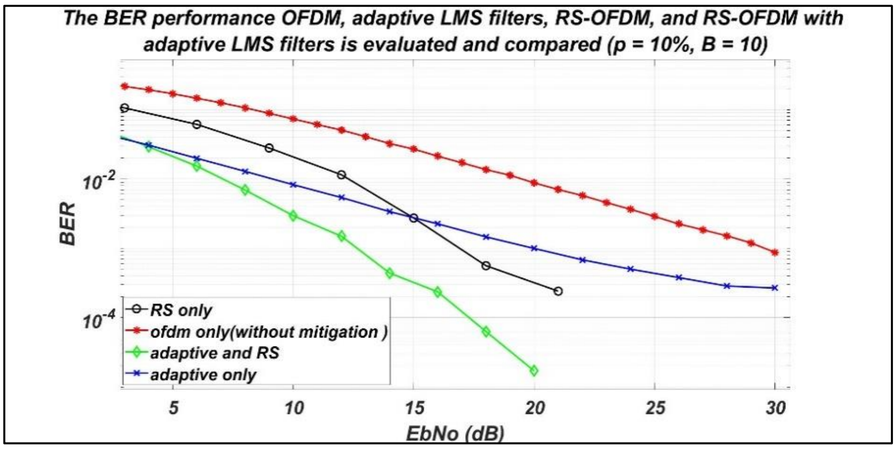

Figure 8. The BER performance OFDM, adaptive LMS filters, RS-OFDM, and RS-OFDM with adaptive LMS filters is evaluated and compared (p=10%, B=10)

4.3. Test 3: p=1%; B=10, n=31, k=29, 21, 11

The simulation parameters are as follows: the probability of impulsive noise events happening is set to p=1% and B=10, the code word length is set to 31, and the length of the data symbols k is set to k=11, 21, or 29. This test is provided to demonstrate the impact of modifying the data length k for a fixed code word length n. The noise duration must be a tiny percentage of the code word period for an impulsive noise coding scheme to operate. To compensate for this additional processing expense, increasing the code block's size should improve its capacity to repair errors. Here, we simulate RS-OFDM with adaptive LMS filters with different RS redundancies, and the results are shown in Figure 9. The results show that the rate 11/31 code provides the optimum performance based on theoretical predictions.

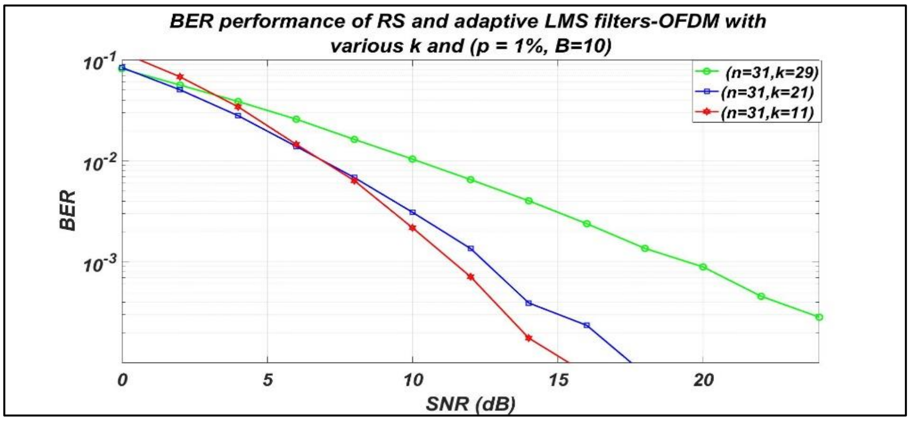

Figure 9. BER performance of combined RS coding/adaptive LMS filters with various RS redundancies (p=1%)

4.4. Test 4: p=1%; B=10; (n, k)=(63,31), (31,15), (15,7)

The parameters for the experiment are as follows: at p=1% and B=10. The code rate r=(k/n) is fixed approximately at r≈ 0.5. For such choices, (n, k)=(63, 31), (31, 15), and (15, 7) were used. This test is given to show that, as long as the code rate is almost constant, the BER performance is very close to that suggested by simpler RS codes, such as the (15,7) RS code, instead of the larger code length (63, 31) RS code. Figure 10 shows the BER performance for such a case.

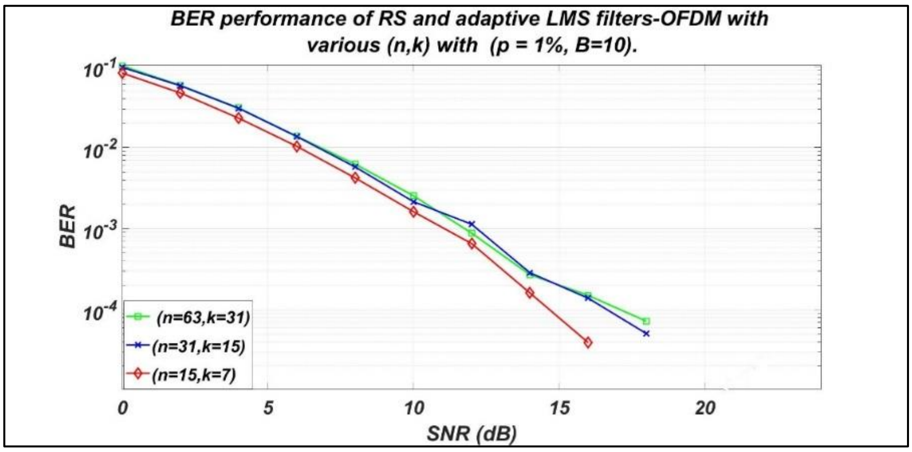

Figure 10. BER performance for a fixed code rate r≈0.5

4.5. Test 5:p=1%;B=10;(n,k)=(63, 31), (31, 15), (15, 7) comparison with time domain mitigation

The parameters for the experiment are: at p=1% and B=10. The purpose of this test is to compare the BER performance of the combined RS coding/LMS adaptive filtering with the traditional simple time domain mitigation. This is shown in Figure 11, where the difference in BER performance is very clear.

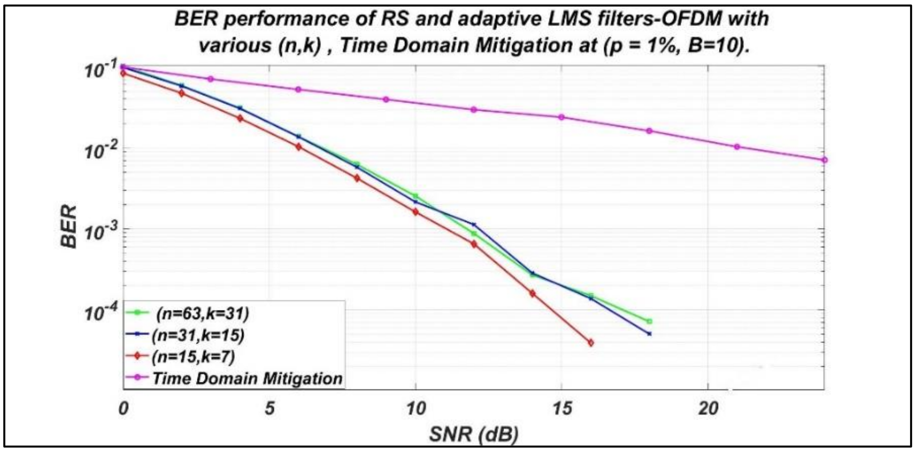

Figure 11. BER performance comparison of combined RS coding/adaptive LMS filters with time domain mitigation

5. CONCLUSION

This study proposed a combined protection strategy to reduce the impact of impulsive noise on PLC-OFDM systems. The effectiveness of adaptive LMS filters and the RS coding method are theoretically explored and verified via simulation. Good resistance to impulsive noise is provided by OFDM, allowing for further performance advantages over other currently available impulsive noise suppression methods like RS and adaptive LMS filters. Variations in impulsive noise levels were one of several environmental factors investigated.

The following concluding remarks can be drawn from this work: i) the RS code word and redundancy extension must be examined if there is a greater chance of impulsive noise. Increased redundancy can correct more mistakes, but it is still necessary to have limited redundancy in order to get the maximum possible coding rate; ii) RS decoding techniques fail to decode based on both simulation findings and a theoretical study. In light of this, it is important to analyze the likelihood of decoding failure of the proposed RS decoding algorithms under different occurrence probabilities of impulsive noise; and iii) as compared with traditional time-domain techniques, the combined RS coding/LMS adaptive filtering give a considerable BER performance. Digital subscriber line (DSL) impulsive noise abatement research directions are talked about. These include noise modeling for using parametric mitigation, hybrid mitigation techniques, and impulsive noise abatement helped by machine learning.

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