BER Reduction Using Precoded OFDM in Power-line Channel

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Abstract. Power-line Communications (PLC) effectively uses the pervasive power grid as a high data rate communication medium. Despite its advantages, the presence of severe multipath fading and susceptibility to impulsive noise make reliable communication in a PLC system challenging. In PLC systems, orthogonal frequency-division multiplexing (OFDM) is an attractive choice mainly due to its resilience to multipath fading. However, OFDM signals suffer from large peak-to-average power ratio (PAPR) thus resulting in non-linear signal distortions at the transmitter. Therefore, for an OFDM-based PLC system, the combined effect of large PAPR and the presence of impulsive noise results in high bit error rate (BER). This paper proposes the use of precoding at the transmitter to reduce PAPR, and blanking non-linearity at the receiver to mitigate impulsive noise. Precoding is a data-independent and robust PAPR reduction scheme that essentially distributes the power of the individual OFDM symbols over the entire OFDM block. Blanking is an effective impulsive noise mitigation technique that results in better BER performance at the receiver. Simulation results show that, with the combination of precoding and blanking, significant gains in BER performance for an OFDM based PLC system can be obtained with minimal increase of transceiver complexity.

1. Introduction
Over the last few years, the number of internet users worldwide has exponentially increased. As of 2016 it was estimated that there were 3.4 billion (46.1% of the global population) internet users [1] connected to the internet via 17.6 billion devices [2]. According to [3], this figure is expected to rise to 200 billion by 2020 with the advancement of Internet-of-Things (IoT).

Even though the communication sector has undergone numerous advancements over the years, the power transmission system remains generally unchanged. Power-lines are the most universal and pervasive network existing in the world and can be efficiently used as the infrastructure in an overall hybrid communication network. Thus, upgrading the current power transmission system to an intelligent and efficient smart grid has gained a lot of attentions in the recent decades [4]. A smart grid should essentially enable the entities connected to not only power up but also to enable data transfer between them. Powerline communications (PLC) is a promising solution that allows reliable data transfer between the devices connected in a smart grid [5].

PLC has been in operation since 1918 [6]. At the beginning, PLC started out as a low data rate medium supporting powerline voice communication. However, with the application of powerful
modulation schemes like orthogonal frequency-division multiplexing (OFDM) and robust error correction techniques, PLC is now able to provide high data rates making it a suitable provider for smart grid services, internet access, and local area networks (LANs). Despite the advantages provided by PLC, it is critical to note that PLC channel suffers from asynchronous impulsive noise and fading which can significantly increase the bit error rate (BER). In addition, the transmitted signal of an OFDM system suffers from large peak-to-average power ratio (PAPR) leading to large amplitude variations in the signal. These large amplitude variations will cause non-linearity when the signal is passed through a high-power amplifier (HPA) leading to an increase in the BER of the OFDM system. Therefore, it is of high importance that the issues of impulsive noise and high PAPR are addressed.

An impulsive noise mitigation technique has to be employed at the receiver to improve the system BER. Blanking non-linearity is a low complex and effective noise mitigation technique commonly used by many researchers [7], [8]. Blanking non-linearity detects the impulsive noise through the amplitude of the signal. As OFDM signal has large PAPR, the impulsive noise blanker may perform false alarms by detecting the signal, not the impulsive noise [9]. Therefore, an PAPR reduction technique may be incorporated at the transmitter to reduce the false alarm.

In this paper, we first investigate and compare the three PAPR reduction techniques, i.e. clipping, selective mapping, and precoding. It will be shown that precoding is more preferable over the other PAPR reduction techniques and we propose to use the precoding technique to reduce the PAPR of the OFDM system. Next, we evaluate the BER performance of blanking nonlinearity at the receiver for PLC system with precoding.

The rest of this paper is organized as follows. Section II discusses OFDM-based PLC system. Section III presents the overview of PAPR reduction techniques. PLC system with precoding along with the simulation results appear in Section IV. Finally, Section V concludes this paper.

2. OFDM-based PLC System

2.1. OFDM-based PLC System

At the transmitter, the input bits are grouped and mapped using digital modulation schemes such as QAM/QPSK to form data symbols. A block of such data symbols is given by,

\[
X = [X_0, X_1, \ldots, X_k, \ldots, X_{N-1}]^T
\]

where \((.)^T\) represents the matrix transpose. These data symbols, still being serial, undergo a serial to parallel conversion that divides the symbols into \(N\) parallel data streams where \(N\) is the number of sub-carriers. Each individual data stream then undergoes an IFFT operation resulting in \(N\) orthogonal sub-carriers with different frequencies. A cyclic prefix is added to the OFDM symbol and the resulting transmitted signal is given by

\[
x(t) = \sum_{k=0}^{N-1} X_k e^{j2\pi kt/T}, \quad -T_g \leq t \leq NT,
\]

where \(T_g\) is the time guard interval and \(T\) is the OFDM time interval. This signal is then transmitted across the PLC channel which can be perceived to have frequency flat fading across each sub-carrier. The signal gets contaminated by the presence of noise in the PLC channel. Assuming that the cyclic prefix is long enough, the \(k^{th}\) sample of the received signal after discarding the cyclic prefix is given by

\[
r_k = h_k \otimes x_k + n_k
\]

where \(x_k\) is the sampled OFDM signal, \(h_k\) is the channel impulse response coefficient, \(n_k\) represents noise, and \(\otimes\) represents circular convolution.
At the receiver, the parallel streams are processed by an FFT module to extract the information on each sub-carrier. The output of the FFT operation, along with channel information is then used to reconstruct the data symbols. Since the data symbols are distorted by the presence of noise, a minimum mean-square error (MMSE) equalizer is used to estimate the original data symbols. The estimated data symbols then undergo a parallel to serial conversion. The serial data stream is finally demodulated using the QAM/QPSK baseband demodulator.

2.2. PLC Channels
A channel model is a mathematical representation of the channel, usually in the form of a frequency response, that scientists and engineers have developed to approximate the real-world environment. The presence of an accurate channel model is critical in analyzing the performance of any communication system. In this paper, we use the PLC model in [10] given by

\[ H(f) = \sum_{i=1}^{P} g_i.e^{-(a_0+a_1f^k)d_i}.e^{-j2\pi f(d_i/v_p)} \] (4)

The parameters are given in Table 1.

| Parameter | Description |
|-----------|-------------|
| \( P \)   | Number of paths |
| \( a_0, a_1 \) | Attenuation parameters |
| \( k \)   | Exponent of the attenuation factor, \(0.5 \leq k \leq 1\) |
| \( g_i \) | Weighting factor for path \( i \) |
| \( d_i \) | Length of path \( i \) |
| \( \tau_i \) | Delay of path \( i \) |

2.3. PLC Noise
Unlike the conventional wired and wireless communication channels, the noise in a PLC network cannot be described exclusively through an additive white Gaussian noise (AWGN) model. According to [11], in general, the noise in the PLC systems can be categorized into background and impulsive noise. Therefore, the total PLC noise, \( n_k \) can be expressed by

\[ n_k = w_k + i_k, \]

where \( w_k \) is the background noise which can be modeled as AWGN with zero mean and variance \( 2\sigma_w^2 \) and \( i_k \) is the impulsive noise which is modeled by Bernoulli Gaussian process as follows

\[ i_k = b_k g_k. \]

In (6), the random variable \( b_k \) represents a Bernoulli process which is in fact an independent and identically distributed (i.i.d) sequence of ones and zeros where the probability of an occurrence of one is given by \( \Pr(b_k = 1) = p \) and \( g_k \) is modeled as complex white Gaussian noise with zero mean and variance \( 2\sigma_i^2 \). The model described in (6) can be perceived as a noisy environment where the transmitted signal is hit independently by an impulse with amplitude \( g_k \).
with a probability of occurrence $p$. Based on this model, probability density function (PDF) of $n_k$ is given by [12],

$$P_{n_k}(n_{kR}, n_{kI}) = (1 - p)G(n_{kR}, 0, \sigma_w^2)G(n_{kI}, 0, \sigma_w^2)$$

$$+ pG(n_{kR}, 0, \sigma_w^2 + \sigma_i^2)G(n_{kI}, 0, \sigma_w^2 + \sigma_i^2),$$

(7)

where $n_{kR}$ and $n_{kI}$ represents the real and imaginary components of $n_k$ respectively; and the function $G(x, m_x, \sigma_x^2) \Delta = \frac{1}{\sigma_x \sqrt{2\pi}} e^{-\frac{(x - m_x)^2}{2\sigma_x^2}}$ represents the Gaussian density with mean $m_x$ and variance $\sigma_x^2$.

It is common practise to denote the impulsive noise variance, $\sigma_i^2$ as a function of the background noise variance $R \sigma_w^2$ where,

$$R = 1 + \frac{\sigma_i^2}{\sigma_w^2}$$

(8)

Thus, (7) can now be written as,

$$P_{n_k}(n_{kR}, n_{kI}) = (1 - p)G(n_{kR}, 0, \sigma_w^2)G(n_{kI}, 0, \sigma_w^2)$$

$$+ pG(n_{kR}, 0, R \sigma_w^2)G(n_{kI}, 0, R \sigma_w^2)$$

(9)

3. Peak-to-Average Power Ratio

The PAPR of the transmitted signal in (2) can be written as,

$$PAPR = \frac{\text{Peak power}}{\text{Average power}} = \frac{\max |x(t)|^2}{\mathbb{E}\{|x(t)|^2\}},$$

(10)

where $\mathbb{E}\{\cdot\}$ denotes expectation. PAPR is more meaningful to be represented by means of a statistical distribution. The complementary cumulative distribution function (CCDF) is commonly employed for this purpose. CCDF displays the amount of time, or the probability, that a signal spends at or above a given threshold and is given by

$$P_{PAPR} = Pr(PAPR \geq PAPR_0),$$

(11)

where $PAPR_0$ is the threshold.

There are various PAPR reduction techniques and in this paper, clipping [13], selected mapping (SLM) [14] and precoding [15] will be investigated.

3.1. Clipping

Clipping is considered as the simplest technique for PAPR reduction. In clipping, a threshold amplitude value is determined and the peak envelope of the input signal is limited or clipped at the threshold. The output of the clipping module can be represented mathematically as

$$B(t) = \begin{cases} x(t), & |x(t)| \leq A \\ Ae^{j\phi(x(t))}, & |x(t)| > A, \end{cases}$$

(12)
where $A$ is the predefined clipping level and $\phi\{x(t)\}$ denotes the phase of $x(t)$. The value of $A$ is usually expressed as a normalized clipping level referred to as the clipping ratio (CR) and is given by [16],

$$\text{CR} = \frac{A}{\sigma}, \quad (13)$$

where $\sigma$ is the root mean square (rms) power of the OFDM signal. From Eq.(13), it can be noted that for signals with the same rms power, a lower CR will result in a lower $A$. The maximum peak of the clipped signal will be at $A$ and therefore the PAPR will be reduced. i.e. in other words, the lower the CR, the greater the PAPR reduction.

Clipping is simple and effective at reducing PAPR. However, this simplicity comes with additional consequences. Clipping causes distortion of the signal that gives rise to both in-band and out-of-band radiation. The out-of-band radiation can be reduced using the clipping and filtering technique suggested in [16]. However, this does not eliminate the in-band distortion. In-band distortion results in a degradation of the BER performance in the OFDM system. As shown in [16], at a BER level of $10^{-2}$, the degradation is less than 1 dB for CR $\geq 1.4$, however for lower CR values such as 0.8 (hard clipping), the degradation can exceed 4 dB at the same BER level. Therefore, in clipping, a trade-off exists between the amount of PAPR reduction achieved and the BER performance.

### 3.2. Selected Mapping

In selected mapping [14], different copies of the original data block are generated. These candidate data blocks will essentially represent the same information and will be multiplied by a unique phase sequence that will result in data blocks with different PAPR values. These data blocks then pass through an evaluating procedure to identify the data block that is most favorable for transmission (lowest PAPR).

Each different data block is multiplied by a unique phase sequence,

$$\mathbf{B}^{(u)} = [b_{u,0}, b_{u,1}, ..., b_{u,N-1}]^T,$$

for $u = 1, 2, ..., U$, each with length $N$, to produce $U$ modified data blocks. $\mathbf{B}^{(1)}$ is set as a unit vector in order to include the unmodified data block within the set of data blocks. The modified data blocks belonging to the $u^{th}$ phase sequence can now be denoted as

$$X^{(u)} = [X_{0}b_{u,0}, X_{1}b_{u,1}, ..., X_{N-1}b_{u,N-1}]^T,$$

for $u = 1, 2, ..., U$. After the IFFT operation, the OFDM signal can now be represented as

$$x^{(u)}(t) = \sum_{n=0}^{N-1} X_{n}b_{u,n}e^{j2\pi n\Delta f t}, \quad 0 \leq t < NT,$$

for $u = 1, 2, ..., U$.

The PAPR of each data block is evaluated and the one with the lowest PAPR is then transmitted. To recover information from the received signal, the receiver requires information about the phase sequence used to modify the data block. This information has to be included as overhead in the data block and therefore this will reduce the efficiency of the OFDM system.

Several promising solutions to generate phase sequences are presented in the literature. When SLM was first introduced in 1996, the authors chose the phase sequence set randomly from $[\pm 1, \pm j]$. Over the years, other promising phase sequences, such as Hadamard sequence [17] and Riemann sequence [18], have been proposed to be applied on SLM.

SLM is a promising technique that results in significant PAPR reduction. However, the PAPR reduction capability of SLM depends on the number of phase sequences used. The number
of phase sequences is directly related to the system complexity due to the number of IFFT computations required to select the one with minimum PAPR. Therefore in SLM, a trade-off exists between PAPR reduction achieved and the system complexity.

### 3.3. Precoding

Precoding is a PAPR reduction scheme where the power of each modulated symbol is distributed over the OFDM block by multiplying the modulated data by a predefined precoding matrix [15]. Once determined, the same precoding matrix can be reused for all OFDM blocks at both the receiver and the transmitter. This eliminates the need for both block-based optimization and receiver-transmitter handshake. Therefore, with the use of a good precoding matrix, significant reduction of the PAPR can be achieved with the expense of a slight increase in overhead.

For a data block of \( N \) symbols, the precoding matrix \( P \) is defined as

\[
P = \begin{bmatrix}
  p_{0,0} & p_{0,1} & \cdots & p_{0,N-1} \\
  p_{1,0} & p_{1,1} & \cdots & p_{1,N-1} \\
  \vdots & \vdots & \ddots & \vdots \\
  p_{L-1,0} & p_{L-1,1} & \cdots & p_{L-1,N-1}
\end{bmatrix}
\]

where \( L = N + N_p \) is the total number of sub-carriers and \( N_p \) is the extra sub-carriers required.

The transmitted signal \( x(t) \) in a precoded OFDM system can be written as

\[
x(t) = \sum_{m=0}^{N-1} X_m \left( \sum_{i=0}^{L-1} p_{i,m} e^{j2\pi i t} \right), \quad 0 \leq t \leq T,
\]

where \( p_{i,m} \) are the entries of the precoding matrix. The PAPR of such a system at a given time instant \( t \) can be upper bounded as

\[
\text{PAPR}(t) \leq \frac{1}{N} \left( \sum_{m=0}^{N-1} \left| \sum_{i=0}^{L-1} p_{i,m} e^{j2\pi i t} \right| \right)^2.
\]

By defining a set of time limited complex functions \( p_m(t) \) as

\[
p_m(t) = \begin{cases} 
  \sum_{i=0}^{L-1} p_{i,m} e^{j2\pi i t}, & 0 \leq t \leq T \\
  0, & \text{otherwise}
\end{cases}
\]

Note that (19) can be rewritten as

\[
\text{PAPR}(t) \leq \frac{1}{N} \left( \sum_{m=0}^{N-1} |p_m(t)| \right)^2.
\]

To satisfy the above criterion, Slimane [15], chooses \( p_m(t) \) in such a way that their peak amplitudes do not occur at the same time instant. This requirement will ensure that the amplitudes do not sum up, and therefore will reduce the PAPR. The author also states that in such a scheme, the entries of the precoding matrix are related to each other and by finding the first column of \( P \), the rest of the entries can be evaluated as follows,

\[
p_{i,m} = p_{i,0} e^{-j2\pi \frac{im}{N}} = e^{-j2\pi \frac{im}{N}} \frac{1}{T} \int_0^T p(t) e^{-2\pi i \frac{t}{T}} dt
\]
In conventional OFDM, each symbol is transmitted over a different sub-carrier. Due to the orthogonality between each sub-carrier, the symbol can be easily separated at the receiver. However, in precoded OFDM, each symbol is spread over more than one sub-carrier and the orthogonality between sub-carriers is not sufficient to separate the symbols at the receiver. As a solution to this problem, the author specifies a second requirement where the selected precoding matrix should be an orthogonal matrix satisfying the following relation,

\[ \mathbf{P}^* \mathbf{P} = \mathbf{I} \]

where \( \mathbf{I} \) is the \( N \times N \) identity matrix and \( \mathbf{P}^* \) denotes the Hermitian transpose of \( \mathbf{P} \). It has been proved in [15], that for a function \( p(t) \) satisfying Eq.(22), the symbol-separability is achieved when,

\[
\int_0^{(1+\beta)/T_s} |P(f)|^2 e^{j2\pi(m-k)Tsf} df = \begin{cases} T_s, & m = k \\ 0, & m \neq k \end{cases}
\]

where \( P(f) \) is the Fourier transform of \( p(t) \) and \( \beta = \frac{N_p}{N} \) is the system overhead. Two possible base functions, \( P(f) \) that satisfy Eq.(22) and Eq.(24) are the raised cosine function and square root of a raised cosine function given by [15]

\[
P_{rc}(f) = \begin{cases} T_s \sin^2 \left( \frac{\pi f T_s}{2 \beta} \right), & 0 < f \leq \frac{\beta}{T_s} \\ T_s, & \frac{\beta}{T_s} \leq f \leq \frac{1}{T_s} \\ T_s \sin^2 \left( \frac{\pi (fT_s - 1)}{2 \beta} + \frac{\pi}{2} \right), & \frac{1}{T_s} < f \leq \frac{1+\beta}{T_s} \end{cases}
\]

\[
P_{src}(f) = \begin{cases} T_s \sin \left( \frac{\pi f T_s}{2 \beta} \right), & 0 < f \leq \frac{\beta}{T_s} \\ T_s, & \frac{\beta}{T_s} \leq f \leq \frac{1}{T_s} \\ T_s \sin \left( \frac{\pi (fT_s - 1)}{2 \beta} + \frac{\pi}{2} \right), & \frac{1}{T_s} < f \leq \frac{1+\beta}{T_s} \end{cases}
\]

A precoded matrix meeting both the stated requirements will result in a significant reduction of PAPR without ceasing any of the properties or structure of an OFDM system. Since the precoding matrix can be independently generated both at the transmitter and the receiver, this technique adds minimal overhead to the system. Furthermore, once the precoding matrix is generated, the same matrix can be reused thus reducing the computational complexity of this scheme.

3.4. Simulation Results

The PAPR of the OFDM system using different clipping ratios \( CR = \{0.5, 0.8, 1.2, 2.0\} \) is illustrated in Fig. 1. The results of Fig. 1 shows that clipping can significantly reduce PAPR. It is observed that the results are consistent with Eq.(13) which suggests that a lower clipping ratio will lead to a greater reduction in PAPR. It can be noted that the clipped OFDM signals display an instant vertical drop rather than the conventional OFDM signal which follows a smoother curve. Hence, despite the fact that clipping can significantly reduce the PAPR of the OFDM signal, the clipped amplitude in the signal will cause in-band and out-of-band distortion which will lead to a degradation of the OFDM system performance [19].
Fig. 1 illustrates the PAPR reduction achieved by the random, Hadamard and Riemann phase sequences with $U = 4$. It can be seen that the random sequence has the best PAPR reduction capability followed by Riemann and Hadamard, respectively. It is however important to note that the generation of the random sequence is completely independent and therefore, requires the transmission of the entire information relating to the encoding phase sequence in order to allow the receiver to decode the received signal. Thus, when the random phase sequence is used for SLM, the overhead required is significantly high. On the contrary, the Hadamard and the Riemann sequences can be generated both at the transmitter and receiver, thus, the complete information about the encoding sequence is not required to be transmitted. Rather, an index corresponding to the used phase sequence can be transmitted which can then be used by the receiver to identify the encoding sequence [19]. Therefore, in practice, the Hadamard and
Riemann sequences are preferred over the random phase sequence.

Figs. 3 and 4 show the PAPR simulation results for RC and SRRC with different levels of overhead, $\beta$. These results illustrate significant reduction in PAPR in comparison to the conventional OFDM system and thus, illustrates the potential of the precoding scheme. The level of the PAPR reduction achieved is dependent on the amount of overhead used. However, it can be observed that even with 10% overhead, considerable PAPR reduction can be achieved. From the simulation results, it can be noticed that when $\beta = 10\%$, the SRRC pulse achieves a PAPR level of about 6.2 dB at a CDF value of $10^{-3}$ while the RC pulse achieves about 6.7 dB at the same CDF value. It can therefore be concluded that the SRRC outperforms the RC pulse in terms of its PAPR reduction capability.

In the precoding scheme, the main pulse is shifted in every sub-carrier. This means that
there is minimal increase of system complexity for larger sub-carriers as the same pulse is used for every sub-carrier. Thus, it is important to note that increasing the number of sub-carriers do not significantly increase the complexity of the precoding scheme. The effect of the number of sub-carriers on the performance of the precoding scheme is illustrated in Fig. 5.

It can be seen that precoding is more preferable over the other PAPR reduction techniques due to its PAPR reduction capability, minimal increase of system complexity, robustness and BER performance in multipath-fading channels. Therefore, it is proposed to use the precoding technique to reduce the PAPR of the OFDM system.

4. Proposed PLC System

The proposed system model is shown in Fig. 6. After the precoding process, the resulting vector of length $L$ is given by,

$$Y = PX = \begin{bmatrix} Y_0 & Y_1 & \ldots & Y_{N-1} \end{bmatrix}^T$$

(27)

where

$$Y_i = \sum_{m=0}^{N-1} p_{i,m} X_m, \quad i = 0, 1, \ldots, L - 1$$

(28)

The precoded symbols are then modulated onto the different sub-carriers using the IFFT module as discussed in Section II. At the receiver, we add a blanker to mitigate the impulsive noise. Blanking non-linearity applied on the received signal $r_k$ is given by

$$y_k = \begin{cases} r_k, & |r_k| \leq T_h \\ 0, & \text{otherwise} \end{cases}$$

(29)

where $T_h$ and $|r_k|$ denote the blanking threshold and amplitude value of $r_k$, respectively. In essence, blanking-non linearity will identify signals with amplitude values greater than the threshold as impulsive noise and those signals will be nulled.

It is important to note that the efficiency of the blanking technique depends on the blanking threshold, $T_h$. If the value of $T_h$ is too small, not only the impulsive noise, but also the received samples of the OFDM signal will be set to zero. On the other hand, if the value of $T_h$ is too
large, impulsive noise samples will not undergo blanking causing impulsive noise to be present in the detected signal. Failure to choose an appropriate blanking threshold can therefore lead to poor BER performance thereby degrading the performance of the PLC system. Hence, it is important to determine the blanking threshold $T_{opt}$.

Several techniques to determine the optimal blanking threshold are available in the literature [20], [21]. With the assumption that the information about the variance of noise ($\sigma_w^2$ and $\sigma_i^2$) and the probability of occurrence of impulsive noise $p$ is available to the receiver, we use the following equation to determine the threshold value [20]

$$T_h = \frac{2(1 + \sigma_w^2)(1 + \sigma_w^2 + \sigma_i^2)}{\sigma_i^2} \times \ln \left( \frac{1 + \sigma_w^2 + \sigma_i^2}{1 + \sigma_w^2} \right)^2 \left( 1 - \sigma_w^2 - \sigma_i^2 \right) \frac{p - 1}{p}. \quad (30)$$

After the blanking operation, the signal undergoes a FFT operation for OFDM demodulation and the resulting signal in the vector form is given by,

$$D = \sqrt{T}HY + N = \sqrt{T}HPX + N \quad (31)$$

where $H$ is a $L \times L$ diagonal matrix of the channel coefficients and $N$ is the resulting noise vector after blanking non-linearity. Note that the noise sample after blanking is similar to that of the background noise. Therefore, to detect the symbols correctly, an MMSE detector with a one-tap equalizer per sub-carrier is applied. In this detector, vector $D$ is weighted using a weighting matrix given by [15]

$$G = \frac{\hat{H}^*}{|\hat{H}|^2 + \sigma_w^2/\sigma_s^2}. \quad (32)$$

where $\hat{H}$ is the diagonal matrix of $H$ and $\sigma_s^2$ is the variance of the transmitted signal. In essence, the weighting matrix reduces the detection errors by compensating for the channel phase and
minimizing the interference between the OFDM symbols. The resulting matrix is then multiplied by the inverse precoding matrix $P^*$ to produce [15]

$$ V = P^*GD = \sqrt{T}P^*GHPX + N'. \quad (33) $$

Vector $V$ then undergoes QAM/QPSK demodulation to generate the output bits.

In order to determine the effectiveness of the solution, the BER of the received signal is plotted against different values of signal-to-noise ratio (SNR).

The effect of impulsive noise on the OFDM-PLC system is analysed in Fig. 7 with $R = 100$ and $p = 0.1$. It can be seen from Fig. 7 that an OFDM-PLC system affected by impulsive noise can reach significantly higher BER values when compared to an OFDM-PLC system affected by AWGN noise. For instance, at an SNR value of 30 dB, the BER of the AWGN affected system is 0.02 while the BER of the impulsive noise affected system is 0.03. This corresponds to a 33.3% increase in the BER. The graphs in Fig. 7 also suggest that the BER difference between the two systems is even higher for larger SNR values. Hence, it can be clearly seen from the results that the impulsive noise has a severe negative effect on the BER performance of the OFDM-PLC system, especially at higher SNR values.

The effectiveness of the proposed solution is illustrated in Fig. 8 which compares the effect of precoding and blanking on an OFDM based PLC system with $N = 64$ sub-carriers. At an SNR value of 30 dB, the four graphs in Fig. 8 are observed to have BER values as listed in Table 2.

| Graph                      | BER   | % decrease of BER |
|---------------------------|-------|-------------------|
| Conventional OFDM         | 0.0219| -                 |
| with no Blanking          |       |                   |
| Conventional OFDM         | 0.0099| 54.79%            |
| with Blanking             |       |                   |
| Precoded OFDM             | 0.0014| 93.61%            |
| with no Blanking          |       |                   |
| Precoded OFDM             | 0.0001| 99.54%            |
| with Blanking             |       |                   |

The values in table suggest that blanking alone can reduce the BER by 54.79%, while
Effect of Precoding and Blanking on BER performance for OFDM based PLC systems

Figure 8. Effect of precoding and blanking on conventional OFDM based PLC systems

precoding alone can reduce the BER by 93.61%. Furthermore, with the combination of the two methods, the BER of the proposed system is observed to be 99.54% less than that of a conventional OFDM system with no blanking. In addition, the percentage decrease of BER achieved through the proposed solution is observed to increase with the SNR. i.e., BER improvements that are greater than 99.54% can be achieved for SNR values above 30 dB. Therefore, the results show that the proposed solution has great potential in improving the BER performance of an OFDM-PLC system.

5. Conclusion
We have evaluated the BER performance of precoded OFDM-based PLC with blanking nonlinearity. In particular, the system employs signal precoding at the transmitter to reduce the PAPR of the transmitted OFDM signal and blanking non-linearity at the receiver to mitigate impulsive noise in impulsive noise environments. We have shown through simulations that the combination of precoding at the transmitter and blanking at the receiver can improve the BER performance of the PLC system under impulsive noise environment.

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