Selected Subcarriers QPSK-OFDM Transmission Schemes to Combat Frequency Disturbances

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***Abstract*—To combat the impairments caused by frequency disturbances in the power line communications (PLC), a modified conventional QPSK-OFDM transmission scheme is presented. The idea of this scheme is to first group the N OFDM subcarriers into groups of M and then transmit data by selecting a subset of the subcarriers in the group. Real and imaginary parts of QPSK symbols are independently assigned to the selected subcarriers in a group, such that the minimum squared Euclidean distance is maximised. With this kind of symbol assignment to subcarriers our scheme has no net loss in terms of SNR requirements, in AWGN, in comparison to the conventional QPSK-OFDM, even though it has half the data rate of the conventional QPSK-OFDM. We refer to the conventional QPSK-OFDM as Scheme A. Our scheme displays a superior performance over Scheme A and another scheme (Scheme B), in the presence of frequency disturbances and also frequency selective fading noise. We further modify Scheme B and come up with additional two new QPSK-OFDM schemes that have better performance than Scheme B in AWGN and impulse noise. To encode, we apply a (n, k) RS code and a simple permutation code on the conventional QPSK-OFDM scheme, which significantly improves the decoder's performance in the presence of frequency disturbances. A simple narrow band noise model is developed and presented.**

***Index Terms*—Selected subcarriers, QPSK-OFDM, frequency disturbances, narrow band noise model, concatenated RS-Permutation codes.**

I. Introduction

Researchers have recently been paying more attention to OFDM as the future PLC transmission scheme (see [1], [2] and [4]), and several techniques to combat PLC noise when using OFDM transmission have been proposed. Most of the work on combating PLC noise, when using OFDM transmission, in the literature focuses on impulse noise [2]–[5], as a result there is not much work on combating frequency disturbances in PLC using OFDM.

In [6], Wetz *et al*. presented an OFDM-MFSK scheme employing noncoherent detection, which they showed that it can provide robust transmission over fast fading channels. The OFDM-MFSK scheme in [6] introduces the grouping of IDFT subcarriers in which the IDFT subcarriers are grouped into N/M groups, where N is the IDFT size and M is the number of subcarriers in a group. On every transmission, a subcarrier from each group is selected by putting a non-zero value on the selected subcarrier and setting each of the other $M - 1$ unselected subcarriers to zero. Specifically, the non-zero value assigned to the selected subcarrier in the group is a 1.

The OFDM-MFSK scheme in [6] has been shown to perform well in fast fading channels, but conventional QPSK-OFDM has not been shown to exhibit such good performance in fast fading channels without the help of error control coding (ECC). However, conventional QPSK-OFDM scheme performs well in AWGN and impulse noise as the IDFT size gets large [7].

The first contribution of this paper is therefore to present an OFDM transmission scheme that combines the strengths of both OFDM-MFSK and QPSK-OFDM schemes. Our proposed scheme is capable of effectively reducing the error floor of the bit error rate curve in the presence of frequency disturbances and frequency selective fading noise, without ECC. On dealing with impulse noise, our scheme relies on the power of QPSK-OFDM with large N. The second contribution is the extension of an *OFDM-MFSK-like* scheme into two new QPSK-OFDM schemes with better performance than the original OFDM-MFSK-like scheme in AWGN. The OFDM-MFSK-like scheme only differs from the original OFDM-MFSK scheme in [6] by that the non-zero value assigned to the selected subcarrier is a QPSK symbol instead of just a 1. Thirdly, we present a simple channel model for narrow band noise. Another interesting interference model which our model has some similarities to can be found in [8]. Fourthly, a (n, k) Reed-Solomon (RS) code and a simple permutation code are employed on the conventional QPSK-OFDM, and the coded system is able to effectively combat frequency disturbances.

The rest of the paper is organised as follows: Section II, gives a brief background on the OFDM system and M-ary phase shift keying (MPSK), with our discussion limited to BPSK and QPSK. Three main QPSK-OFDM schemes, Scheme A, B and C are discussed in Section III, and a detailed description of our proposed scheme (Scheme C). Also in Section III-D, Scheme B is extended into two new

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schemes. Coding is discussed in Section III-E. The types of noise affecting transmission are discussed in Section IV, with emphasis on our proposed narrow band noise model in Section IV-B. Results are presented in Section V, and finally, concluding remarks in Section VI.

II. Background information

A. OFDM system model

OFDM is a multicarrier transmission scheme, where data is carried in several subcarriers which are orthogonal to each other to avoid mutual interference. In the OFDM system of interest, an IDFT (inverse discrete Fourier transform) takes in as input, D data symbols carried in vector X_k, from a phase-shift-keying (PSK) modulation scheme and produces a discrete sequence in the time domain, x_n. The relationship between X_k and x_n is represented by Equation (1).

$$x_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k e^{j2\pi nk/N}, \tag{1}$$

where N is the number of subcarriers used to carry data, and X_k, is of the same length as x_n. x_n is the complex baseband transmit signal from the output of the IDFT normalized by the factor $\frac{1}{\sqrt{N}}$.

B. M-ary Phase shift keying system

To describe our contribution, we first give a brief performance comparison between coherent Binary and Quadriphase Shift Keying (BPSK and QPSK) systems for single carrier modulation. We denote the transmitted signal energy per symbol as E_b and E for the BPSK and QPSK systems, respectively, where E_b is the bit energy. For a BPSK system, symbol and bit energy are the same, while for a QPSK system $E = 2E_b$, which implies that QPSK is 3 dB better due to bit rate. However, BPSK has a minimum Euclidean distance, d_E of $2\sqrt{E_b}$, while QPSK has $d_E = \sqrt{2E}$ (refer to [9]). Therefore, BPSK is 3 dB better than QPSK, where Euclidean distance is concerned. In effect, BPSK and QPSK have similar performances.

III. QPSK-OFDM schemes

We give a description of three possible transmission schemes for QPSK-OFDM and compare their performance in the presence of AWGN. To compare the schemes we need to define the following parameters per scheme: number of bits per subcarrier, R_b and the minimum Euclidean distance between symbols, d_E or minimum squared Euclidean distance, $d_E^2 = (d_E)^2$.

A. SCHEME A

We refer to the conventional QPSK-OFDM transmission as Scheme A. We shall use this scheme as a reference point for the comparison of other schemes because it is the commonly employed OFDM scheme. In the conventional QPSK-OFDM transmission all subcarriers carrying data are occupied by QPSK symbols chosen according to the transmit data bits. For the QPSK transmission, $R_b = 2$ bits and $d_E = \sqrt{2}$, hence $d_E^2 = 2$.

B. SCHEME B

Scheme B, OFDM-MFSK-like scheme, is similar to the OFDM-MFSK transmission scheme introduced in [6]. The OFDM-MFSK scheme itself is a modification of the conventional QPSK-OFDM scheme, where it is proposed in [6] that the elements of the vector X_k be divided into groups of M. In each group, only one element is set to a 1 according to the transmit data, while each of the rest of the group elements are set to a 0. The effect is that only N/M subcarriers are occupied for each X_k.

To make the comparison with Scheme A straight forward we adapted the OFDM-4FSK from [6] and employed it as QPSK-OFDM with the properties of the OFDM-4FSK scheme (OFDM-4FSK-like scheme). In this case we still divide the OFDM vector X_k into groups of $M = 4$ and only choose one subcarrier, per group of four, but transmit a QPSK symbol while setting all the other three remaining subcarriers to zero. The QPSK symbol in the chosen subcarrier carriers two bits of data and the choice of the subcarrier to be used among the four conveys two bits of data, and the net data transmitted per group is four bits. For this scheme then, $R_b = 4/4 = 1$ because there are four bits of data in a group of four subcarriers, and $d_E = \sqrt{2}$ since we are using QPSK, and hence $d_E^2 = 2$.

C. SCHEME C

To describe how the symbols are transmitted, firstly consider an MPSK-OFDM system with N subcarriers. In our system the subcarriers are divided into N/M groups of M as mentioned earlier. M is chosen such that it matches the modulation used in the OFDM system, for example, in QPSK-OFDM, $M = 4$ and in 8PSK-OFDM, $M = 8$. We limit our system to QPSK-OFDM, hence each group has four subcarriers. The process of assigning symbols in the group of subcarriers is the same for each group; it is therefore sufficient to give a description of our system for a single group of subcarriers.

The symbols in a group are assigned as follows: given a QPSK symbol, S to transmit in a group, we use two data bits to assign the real part of S in one of four subcarriers and another two bits of data to assign the imaginary part of S in one of the four subcarriers. It should be noted that the real and imaginary components of S are assigned to subcarriers independently, hence it is possible to have them occupying the same subcarrier, in such a case they are added together forming a QPSK symbol. The remaining subcarriers in the group carry the components of a QPSK symbol, S' which gives the maximum Euclidean distance between itself and S. This means that for each component of S assigned a subcarrier, there remains three subcarriers that are to be filled with the other value in the same dimension with that component (component of S'). For example, filling one subcarrier with the component of S being j, the three remaining subcarriers are filled with a $-j$ (imaginary component of S'). If the component of S being used is a 1 then the remaining three subcarriers will be filled with a -1 (real component of S'). This structured assignment of components to subcarriers results in the Euclidean distance between the real parts of S and S', and imaginary parts of S

and S' being maximised. If we define the QPSK symbols in complex notation as $S = x + yj$ and $S' = -x - yj$, where $x, y \in \{1, -1\}$, the condition for maximum separation between S and S' can simply be stated as follows:
$|\Re(S) - \Re(S')| = |\Im(S) - \Im(S')| = 2$, with $\Re(.)$ and $\Im(.)$ producing the real and imaginary values, respectively.

The following example illustrates the selection of symbols S and S', and how they are assigned subcarriers.

Example 1: Since there are four subcarriers in a group, for each of the real and imaginary component of S, two data bits are used to select the subcarrier to carry the components. To illustrate this, let us first define the mapping between data bits and the four subcarriers in a group, $C_1 \ldots C_4$ are) as follows: $00 \rightarrow C_1$, $01 \rightarrow C_2$, $11 \rightarrow C_3$, $10 \rightarrow C_4$, where the data bits indicate which subcarrier to carry either the real or imaginary component of S. Assume a portion of the data stream to be modulated is $d = \{01010011\ldots\}$ and that $S = 1+j$. The first two bits of d, 01, will assign $\Re(S) = 1$ to C_2 and the next two bits, 01, will assign $\Im(S) = j$ to C_2. This means that both components are in the same subcarrier, so they appear as $1+j$ in that subcarrier. The remaining subcarriers will be assigned -1 and $-j$ because for our choice of $S = 1 + j$ we have $S' = -1 - j$. If we let $X_k^g \subseteq X_k$ be the vector carrying the QPSK symbols for group g, where $1 \leq g \leq N/M$, then $X_k^1 = \{-1 - j, 1 + j, -1 - j, -1 - j\}$. This scenario is depicted in Fig. 1 representing a single group of four OFDM subcarriers, $C_1 \ldots C_4$, assigned QPSK symbols.

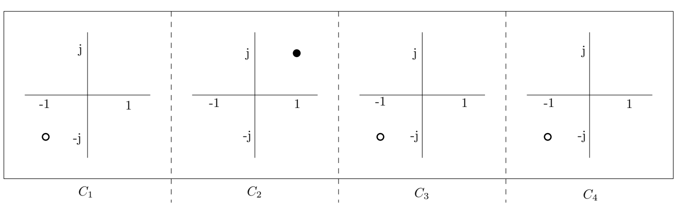

Fig. 1. QPSK symbols' constellations shown in OFDM subcarriers $C_1 \ldots C_4$.

For the next group, $g = 2$, data bits five to eight show a slightly different scenario, where bits 00 and 11 will assign $\Re(S) = 1$ to C_1 and $\Im(S) = j$ to C_3, respectively. Since $\Re(S) = 1$ is assigned to C_1, then $\Re(S') = -1$ will be assigned to C_2, C_3 and C_4, while $\Im(S') = -j$ will be assigned to C_1, C_2 and C_4, and $X_k^2 = \{1 - j, -1 - j, -1 + j, -1 - j\}$.
With this mechanism, our scheme can be seen as a code with $d_{\text{min}} = 2$, which allows for soft decision implementation at the receiver, based on the minimum squared Euclidean distance. Taking each vector X_k^1 and X_k^2, from Example 1, as a codeword, we can calculate the minimum squared Euclidean distance as follows. Firstly, the elements of each vector have to be normalised to a magnitude of one, which implies dividing the vectors by $\sqrt{2}$ element-wise, $X_k^1/\sqrt{2}$ and $X_k^2/\sqrt{2}$. The two positions where $X_k^1/\sqrt{2}$ and $X_k^2/\sqrt{2}$ differ, each contributes a Euclidean distance of $\sqrt{2}$ and the overall minimum squared Euclidean distance is $d_E^2 = (\sqrt{2})^2 + (\sqrt{2})^2 = 4$. $R_b = 1$ because there are four bits transmitted per group.

D. Possible variations of Scheme B

Having presented the three schemes (Scheme A, B and C), we further propose two more variations of Scheme B. As was shown earlier, in Scheme B, $d_E = \sqrt{2}$ and $R_b = 1$. We propose two cases of transmission: (a) in a group of four subcarriers, we allow two to carry QPSK symbols and set the remaining two to zero, and (b) in a group of four subcarriers, we allow three to carry QPSK symbols and set the remaining subcarrier to zero. We shall refer to the schemes in (a) and (b) as Scheme B1 and Scheme B2, respectively. For both Scheme B1 and B2, $d_E = \sqrt{2}$, which is the same as for Scheme A and B.

Scheme B1: For this scheme, the number of transmitted data bits per group is $R_g = \log_2(L) + b$, where $L = \binom{4}{2}$ because out of four subcarriers we choose two to carry QPSK symbols, and $b = 4$ bits because each of the two QPSK symbols transmits two data bits. $R_g = \log_2(6) + 4 = 6.6$ bits, which results into six bits for the purposes of implementation, and hence $R_b = R_g/4 = 1.5$ bits.

Scheme B2: For this scheme, the number of transmitted data bits per group is $R_g = \log_2(L)+b$, where $L = \binom{4}{3}$ because out of four subcarriers we choose three to carry QPSK symbols, and $b = 6$ bits because each of the three QPSK symbols transmits two data bits. $R_g = \log_2(4) + 6 = 8$ bits, and $R_b = R_g/4 = 2$ bits.

In Table I we give a summary of the theoretical comparison, in terms of SNR requirements, of all the schemes in the presence of AWGN.

TABLE I
COMPARISON OF SCHEME A, B, B1, B2 AND C IN TERMS OF SNR REQUIREMENTS IN AN AWGN CHANNEL

	d_E^2	R_b	E_b/N_O at $P_b = 10^{-5}$
Scheme A	2	2	≈ 9.6 dB
Scheme B	2	1	≈ 12.6 dB
Scheme B1	2	1.5	≈ 10.8 dB
Scheme B2	2	2	≈ 9.6 dB
Scheme C	4	1	≈ 9.6 dB

E. Coding for narrow band noise Scheme A

We use Scheme A to show the effect of coding in the QPSK-OFDM transmission in the presence of frequency disturbances. As done in one of the PLC standards, PLC G3 (see [4]), we employ concatenated coding of a shortened (n, k) RS code and a simple permutation code (instead of a convolutional code). The $(n,\ k)$ RS code has symbols of $m = 8$ bits, and the permutation code is of length $M = 4$ and minimum Hamming distance (d_{min}) of two or three. The performance results and discussion of the results of this coding are presented in Section V, for the case where the receiver has information about the position of the frequency disturbers and the case where the receiver has no information, informed and uninformed receiver, respectively.

Frame error rate (FER) is used to compare the performance of coding on QPSK-OFDM. When only the $(n,\ k)$ RS code is used, the FER due to frequency disturbances can be approximated by the first term in $\sum_{i=t+1}^{n} \binom{n}{i} P^i (1-P)^{n-i}$, where $t = (n-k)/2$ is the maximum number of correctable symbol errors for the RS code and P is the probability of the presence of frequency disturbers in the OFDM system. When a concatenation of the (n, k) RS code and the permutation code is employed, the FER due to frequency disturbances can be approximated by the first term in $\sum_{i=t+1}^{n} \binom{n}{i} (P')^i (1-P')^{n-i}$, where $P' = \sum_{j=e+1}^{M} \binom{M}{j} (P)^j (1-P)^{M-j}$, and e is the maximum number of correctable symbol errors for the permutation code. For the $d_{\text{min}} = 2$ permutation code, e is approximated to a 1 due to soft decision decoding. For the $d_{\text{min}} = 3$ permutation code, in the uninformed receiver case, $e = 1$ and in the informed receiver case, $e = 2$ because it can correct two erasures. These FER estimates are for high SNR.

IV. Types of noise and their effects

Some of the noise in the PLC channel include, AWGN, frequency selective fading, impulse noise and frequency disturbances. Our main interest is on frequency disturbances, and their model. Next we discuss impulse noise and the narrow band model.

A. Impulse noise

The Impulse noise power spectrum density (PSD) is considered to be flat and covering all frequencies with variance, σ_I^2 which is related to the AWGN variance as $T = \sigma_g^2/\sigma_I^2$, where $T < 1$ [7]. Since an impulse can affect more than one transmitted symbol, for simplicity, in this paper we use a Gilbert-Elliot model with the parameters defined as follows: G is good state, B is bad state, P_{gb} is the probability of moving from a good state to a bad state, P_{bg} is the probability of moving from a bad state to a good state, $1-k$ is the probability of being hit by impulses in a good state and $1-h$ is the probability of being hit by impulses in a bad state, where $0 \leq h < 1$. We assume that a good state is impulse-free, therefore $1-k = 0$.

B. Narrow band noise model

Another one of the most devastating types of noise found in the PLC channel is narrow band noise which appears as frequency disturbances. Narrow band noise is produced by interfering signals from systems sharing the same frequency spectrum as the PLC network in which the transmitter of information is connected, and some possible sources of this kind of noise are, TV vertical scanning frequency and its harmonics, radio amateurs and AM transmission [7]. We shall be referring to the interfering signals causing frequency disturbances as frequency disturbers. The problem of modeling frequency disturbances caused by these sources of narrow band noise is still an open one. In this subsection we propose a simple narrow band noise model for OFDM transmission schemes, taking a slightly different approach to the interference model presented in [8]. Since OFDM is a multicarrier (or multiple-tones) transmission scheme, the effect of narrow band disturbances can be seen as representing a case of *multiple-tone jamming*. Since the analysis of tone jamming is more complicated than that of simple noise jamming, without multiple tones, [10], we reduce the problem to a case of *partial-band noise jamming*. To reduce the problem to a case of partial-band jamming, we consider the power spectrum density (PSD) of each frequency disturber to be as shown in Fig. 2. W is the bandwidth of the frequency disturber, and P_0 is the strength of the frequency disturber, which is considered to be flat for the entire band W. The average normalised power, P_A, is the area under the graph ($P_A = WP_0$), which is kept constant.

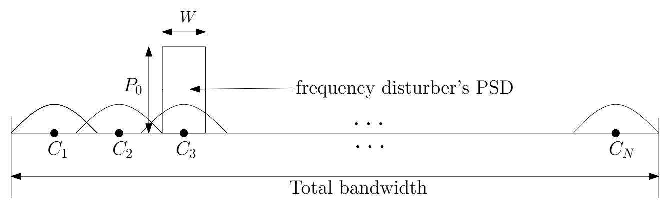

Fig. 2. Power spectrum density of a frequency disturber with strength P_0 and width W, on subcarrier C_3 of the N-subcarrier OFDM spectrum.

The frequency disturber of bandwidth W and strength P_0 can be found anywhere along the OFDM bandwidth N.To make the analysis easier, we restrict each frequency disturber to a single OFDM subcarrier that is, it cannot affect more than one subcarrier at a time. We now define the probability of frequency disturbances in the OFDM system, due to frequency disturbers, P_h as $P_h = AP$. P is the probability of the presence of frequency disturbers in the OFDM system, where the frequency disturber can be in any of the N subcarriers. A is the probability that a subcarrier is hit by a frequency disturber, which is a function of the frequency disturber's bandwidth W, such that increasing W results in an increased A. For the impulse noise model, the PSD, σ_I^2 is linked to the AWGN PSD, σ_g^2, by a factor T ($\sigma_I^2 = \sigma_g^2/T$) [7]. In the case of narrow band noise there is no link found between its PSD and that of AWGN, hence for each given A and T we take the PSD strength of the frequency disturber as $P_0 = 1/AT$, where $T < 1$ determines the level of the strength of the frequency disturber.

V. Simulation Results

Scheme A, B and C are compared in the following types of noise, AWGN, impulse noise, frequency disturbances and frequency selective fading. For all simulations, background noise, modeled as AWGN, is considered present with each of the other types of noise, hence we shall only mention the other types of noise when they are present with AWGN.

In Fig. 3, the results for the schemes in AWGN only closely match our SNR estimates in Table I. It can be seen that Scheme A and C have similar performances for both AWGN only and impulse noise, while Scheme B has the worst performance in both types of noise. Both Scheme B1 and B2 are better than the original Scheme B, in both AWGN only and impulse noise, and the performance of Scheme B2 is very close to Scheme A and C.

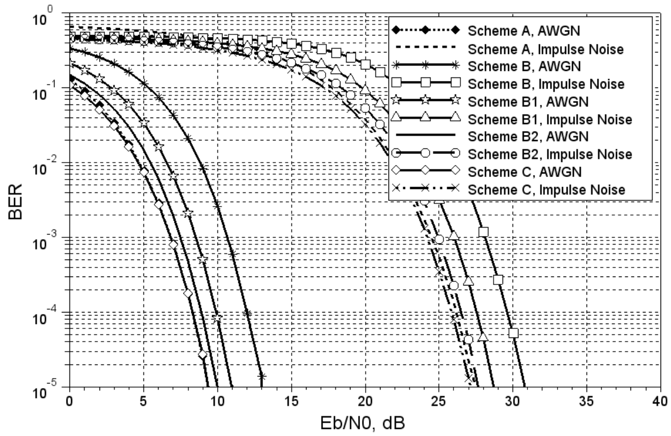

Fig. 3. Comparison of Scheme A, B, B1, B2 and C in the presence of AWGN only, and impulse noise with $P_{gb} = 0.1$, $P_{bg} = 0.9$, $T = 10^{-2}$, $k = 1$, $h = 0.5$.

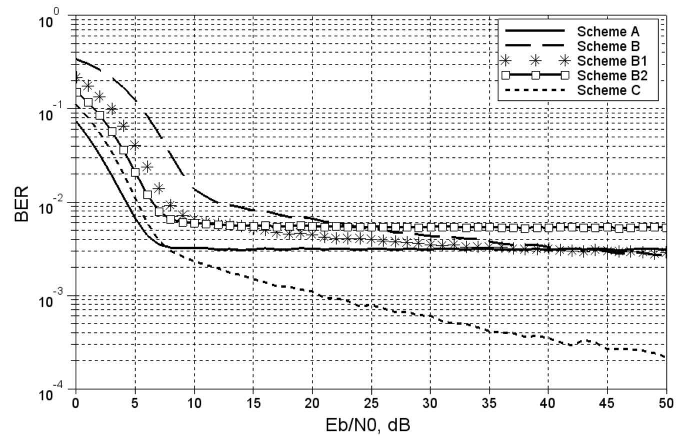

Fig. 5. Comparison of Scheme A, B, B1, B2 and C in the presence of frequency disturbances with $P = 4/256$, $A = 1$ and $T = 1$.

Taking Scheme A as an example, our narrow band noise model parameters are tested to observe their effect on the performance of OFDM transmission as shown in Fig. 4. It can be seen in Fig. 4 that a larger A which corresponds to larger frequency disturber's bandwidth, has more impact on the transmission than a smaller A, even though the frequency disturber with smaller A may have a larger strength, P_0. This is due to the fact that even though a frequency disturber of high P_0 can be more devastating to the subcarrier if hit, its probability of hitting a subcarrier is reduced with reduction in A. Increasing P, while keeping A and T fixed, results in a more devastating effect on the transmitted signal.

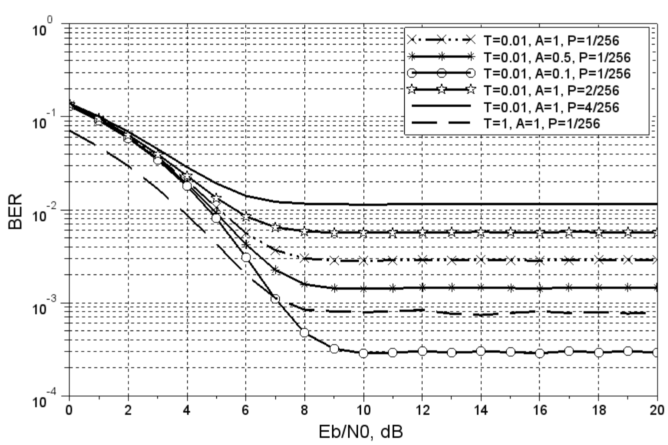

Fig. 4. Demonstration of the effect of the various parameters of the narrow band noise model (T, A, and P) on transmission, using Scheme A as an example.

In Fig. 5, our scheme (Scheme C) has the best performance against all the schemes in the presence of frequency disturbances. Scheme A and B, B1 tend to have the same performance in the presence of frequency disturbances at high SNR and outperform Scheme B2. The best performance of Scheme C over Scheme A is attributed to its better Euclidean distance, and at SNR values lower than 7.5 dB, Scheme A performs better than Scheme C because of its better data rate.

In Fig. 6, Scheme C outperforms both Scheme A and B when there is deep fading in some of the subcarriers. The deep fading effect was simulated by randomly selecting the number of subcarriers where fading is to occur, and on these subcarriers the power was set to zero to represent a deep fade such that any information transmitted in the faded subcarriers is lost. It is interesting to note that Scheme B outperforms Scheme A in the presence of frequency selective fading. This is due to the fact that in Scheme B some of the subcarriers in a group are already set to zero and as a result when fading occurs in those subcarriers the system can still correctly demodulate its transmitted symbols. The BER performance of Scheme B is four times better than that of Scheme A.

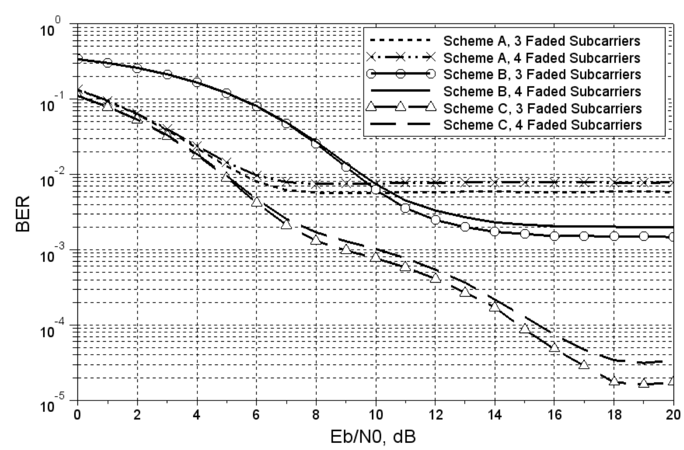

Fig. 6. Comparison of Scheme A, B and C in the presence of frequency selective fading where deep fading occurs on three or four subcarriers.

Fig. 7 shows the performance coded Scheme A, for an informed and uninformed receiver about the position of the frequency disturbers. For the uninformed receiver case, the (64, 48) RS code alone performs poorly compared to the concatenated (32, 24) RS code and ($M = 4$, $d_{\min} = 2$) permutation code (*RS + PC, uninformed*). This is consistent

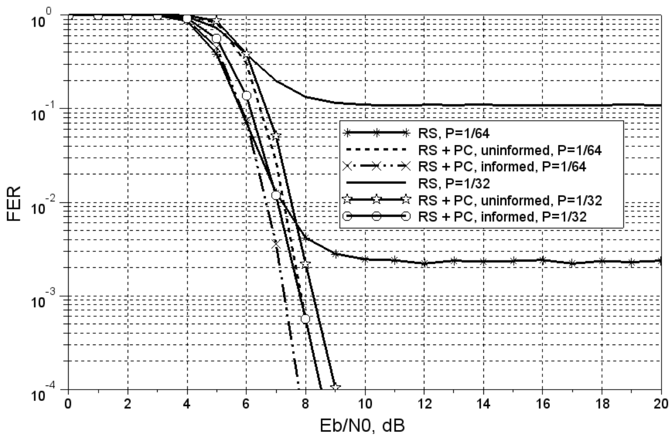

Fig. 7. Coded Scheme A, in the presence of frequency disturbances with $T = 0.01$ and $A = 1$, for an informed and uninformed receiver. A (64, 48) RS only, and a concatenated (32, 24) RS code and permutation code are compared for frame error rate.

with our approximations in Section III-E. It should be noted that the (64, 48) RS code can correct eight RS symbol errors, while the (32, 24) RS code can only correct four RS symbol errors. For the concatenated (32, 24) RS code and permutation code, we further show that the performance of the coded scheme is slightly improved when the receiver is informed about the position of the frequency disturbances (denoted, *RS + PC, informed* in the figure).

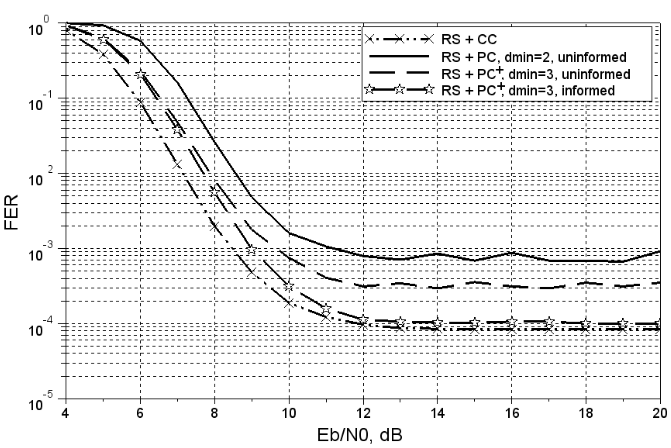

Fig. 8. A concatenation of: (32, 24) RS code and ($M = 4$, $d_{\min} = 2$) permutation code, (32, 24) RS code and ($M = 4$, $d_{\min} = 3$) permutation code, and (32, 24) RS code and ($R = 1/2, K = 7, d_{\text{free}} = 10$) convolutional code are compared on Scheme A in the presence of frequency disturbances, for $P = 1/16$, $T = 0.01$ and $A = 1$.

Since PLC G3, PLC standard, uses a convolutional encoder in concatenation with a RS code (see [4]), in Fig. 8, we show the performance comparison of the following codes in the presence of frequency disturbances: concatenation of, (a) a (32, 24) RS code and a ($R = 1/2, K = 7, d_{\text{free}} = 10$) convolutional code, (b) a (32, 24) RS code and a ($M = 4$, $d_{\min} = 2$) permutation code, and (c) a (32, 24) RS code and a ($M = 4$, $d_{\min} = 3$) permutation code [1]. R, K and d_{free} are the rate, constraint length and free distance of the convolutional code, respectively. The parameters of the convolutional code used here are the same as the ones used in PLC G3. It is important to observe that even though the convolutional code in (a) is more complex than the permutation codes in (b) and (c), its performance is similar to the code in (c) for the informed case.

VI. Conclusion

We proposed a QPSK-OFDM transmission scheme where the real and imaginary components of a QPSK symbol are transmitted in OFDM subcarriers independently, Scheme C. The scheme performed better than other QPSK-OFDM schemes in the presence of frequency disturbances and frequency selective fading. Two more variations of Scheme B were proposed which improved on the performance of the original Scheme B in AWGN only and impulse noise, and displayed performance that approaches that of Scheme A. A simple narrow band noise model which we implemented with all the schemes in the presence of frequency disturbances, was proposed. We also showed that a concatenation of a shorter (32, 24) RS code with a simple permutation code is effective in dealing with frequency disturbances in OFDM transmission over PLC, for both informed and uniformed receiver cases.

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[1]The ($M = 4$, $d_{\min} = 3$) permutation code is denoted PC^{+}, in the figure, because extra sequences of length 4 that are not permutations, are added to the permutation code to increase the cardinality while keeping $d_{\min} = 3$.