Interleaving and Nulling to Combat Narrow-band Interference in PLC Standard Technologies PLC G3 and PRIME

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***Abstract*—Three functional blocks of the PRIME and PLC G3 technologies (encoder/decoder, interleaver, and modulator) are studied in detail, for a PLC channel with narrow-band interference (NBI). The study reveals that these three blocks can be used together effectively so as to improve the performance of the overall system in the presence of NBI. We therefore present effective methods for combating NBI in PRIME and PLC G3, based on these three functional blocks.**

***Index Terms*—Powerline communication standards, Narrow-band interference, OFDM.**

I. Introduction

The PLC (powerline communication) technologies of the PLC standard, PRIME and PLC G3 are obviously designed for the PLC channel which, in addition to background noise, is characterised by impulse noise and narrow-band interferernce (NBI). These technologies put together systems, based on OFDM, that are meant to effectively combat the noise in the PLC channel. However, there is somehow a lack of detail in the functional blocks of the systems as well as no information on the performance assessment of these technologies under typical PLC noise. An article by Hoch [1] gave a holistic comparison of PLC G3 and PRIME systems in the presence of typical PLC noise and also gave some performance results.

In this work, we only focus on three system functional blocks which are common to both PLC G3 and PRIME (convolutional encoding, bit interleaving and PSK modulation), and show how these blocks can be effectively used together to enhance performance in the presence of NBI. Our suggestions on how to effectively combat NBI by focusing on these three blocks are simple known methods which do not require a change in the systems themselves.

Combating NBI for OFDM systems is nothing new. Galda and Rohling [2] gave an overview of three techniques used to combat interference in multicarrier transmission systems like OFDM, which are (a) Nyquist windowing (b) Interference cancellation (c) Modified soft decision. In [2], performance results were given for the modified soft decision approach. Even though Galda and Rohling [2] commented that most of the methods on NBI mitigation, based on some of the techniques they listed, are complex and some require prior knowledge of some of the NBI signal parameters (amplitude, phase and frequency), work continued in the area of NBI mitigation employing some of these techniques. In [3], a frequency domain interference cancellation scheme for OFDM systems is given, where a "canceller" subtracts LMMSE estimates of the NBI from the received signal by measuring the interference on a few modulated or unmodulated OFDM tones. Prior to the work in [3], the idea in of interference cancellation is found in [4] , where dummy subcarriers are used to estimate interference and then subtract the estimate from the received noisy signal. The system for which interference cancellation was done in [4] was DMT (discrete multitone). In [5], a spectrum spreading technique is demonstrated as another technique to reduce the effect of NBI in OFDM systems. Coulson [6] demonstrated that filtering the NBI in the time domain before the discrete Fourier transform of the OFDM receiver can reduce spectral leakage, hence improving the bit error rate performance. Coulson's [6] method of filtering was limited to BPSK modulated OFDM.

This paper uses a combination of well known methods to combat NBI. The methods suggested here are simple enough for implementation and do no require a change in the already existing OFDM systems for PLC. We suggest the depth of the bit interleaver that can be used in respect to each order of PSK modulation such that the convolutional decoder performs "optimally". We also advocate for signal nulling in the frequency domain as the best way to enable the convolutional decoder to effectively operate in soft-decision mode, hence improving performance.

II. Narrow-band Interference

For Narrow-band Interference (NBI) we use the model in [7], where some of the N OFDM subcarriers are affected by frequency interference with given probability P and average power $\sigma_N^2 = 1/T$, where $0 < T \leq 1$. Therefore, on average, $N \times P$ subcarriers are affected by NBI, where each carrier affected experiences average power $\sigma_N^2 = 1/T$. The $N \times P$ subcarriers can experience different average NBI power. In that case, the value of T can be randomly chosen in the interval $0 < T \leq 1$ for each subcarrier, according to some distribution. In this paper we will use a uniform distribution for randomly choosing the value of T. Alternatively, the value of T can be fixed to be the same such that all the approximately $N \times P$ subcarriers experience the same average NBI power. This case of fixed σ_N^2 for all subcarriers affected assumes that we have good statistical knowledge about the power of the NBI in the system. For simulation purposes, we shall take the NBI as uniformly distributed with variance σ_N^2 for both fixed and varying T cases. It should be noted that this NBI model is defined in the frequency domain and so are all specified parameters and their effect on the signal. This NBI model is memoryless, that is, it does not produce burst errors at symbol level. Fig. 1 shows how each symbol D is affected by NBI, where the channel also has additive white Gaussian noise (AWGN).

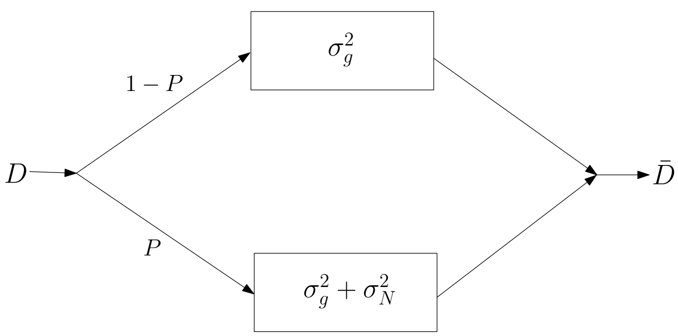

Fig. 1. Narrow-band interference model including additive white Gaussian noise (AWGN) power σ_g^2. At each transmission a data symbol D either enters a channel with AWGN (variance σ_g^2), with probability $1-P$, or enters channel with noise $\sigma_g^2 + \sigma_N^2$, with probability P. σ_N^2 is the variance of the NBI.

III. PLC G3 and PRIME

A. DPSK and PSK

It is known that PSK has a better performance in AWGN, in terms of bit error rate, than its variant differential PSK (DPSK). This is due to the fact that DPSK suffers from a problem of propagated errors, where one bit error likely results in another bit error. The PRIME technology specification [9] also confirms the superiority of BPSK over DPSK. However, DPSK maybe be preferred in some systems for its relatively less complex receiver compared to PSK, because unlike PSK, DPSK does not require the phase information of each symbol, but instead it relies on a reference phase from a previous symbol [8]. Another advantage of DPSK is the lack of phase ambiguities which can be experienced in PSK. The PLC G3 and PRIME technologies employ DPSK (DBPSK, DQPSK and D8PSK) for modulation. Note that in OFDM, DPSK can be performed in the frequency domain, f-DPSK or in the time domain, t-DPSK. PLC G3 employs t-DPSK, while PRIME employs f-DPSK. f-DPSK is the most commonly used type of DPSK in many communication systems and is easily implemented on one OFDM symbol while t-DPSK requires more than one OFDM symbol to work, and that makes it difficult to compare these two types of DPSK. It should be noted that PLC G3 overcomes the inherent problem of error propagation in DPSK by employing t-DPSK over many OFDM symbols. We shall only focus on f-DPSK because it easily allows us to relate the interleaver depth and the modulation as we will show in the next subsection. So whenever we make mention of DPSK we will be referring to f-DPSK.

B. Bit-interleaving under NBI

It is common practice to apply interleaving for channels with memory, more especially if convolutional encoding is employed because of its poor ability to handle burst errors. In both PRIME and PLC G3 a bit interleaver is employed before the output bits of the convolutional encoder are modulated. In PRIME technology [9] there is no detailed discussion about the details of bit interleaving. While in PLC G3 [10] a detailed description of interleaving is given, there is no explanation of how bit-interleaving is performed. In PLC G3, interleaving is performed such that an OFDM symbol is spread over several other OFDM symbol and at the same time each individual OFDM symbol is also interleaved. The interleaving in PLC G3 is described at modulation symbol level.

In this paper, we employ the typical interleaver where a serial stream of L bits is read into a I-row by J-column interleaver, column wise and then read out row-wise for transmission as shown in Fig. 2. By reading in column-wise we mean that one column is filled up before moving to the next one, and reading out row-wise means that symbols from one row are completely read out before moving to the next row. $I = L/d$ and $J = d$ such that $I \times J = L$, where d is the depth of the interleaver. This kind of interleaver is different to the one specified in PLC G3 and is more tractable, as such we are able to configure it according to the modulation used in the transmission. The PLC G3 interleaver has higher complexity and requires a lot of data to be effective, while it performs the same as the simple I-by-J interleaver proposed in this paper.

It should be noted that our suggested bit interleaver serves no purpose if BPSK modulation is used, under AWGN. However, for DPSK modulation under AWGN, the bit error performance at the convolutional decoder is slightly degraded compared to PSK, if no interleaving is done. So, our simple bit interleaver is able to improve the performance of DPSK even under AWGN. The degradation in performance of DPSK is obviously due to the fact one bit error in DPSK modulated data results in two bit errors. We are going to show that a simple interleaver for OFDM transmission can actually deal with both AWGN and NBI when its parameters are carefully chosen in consideration of the modulation used.

We simulated the interleaver in Fig. 2 for different values of I and J to see which interleaver depth might be most suitable for different PSK modulation schemes under AWGN and NBI. The simulated system was OFDM consisting of

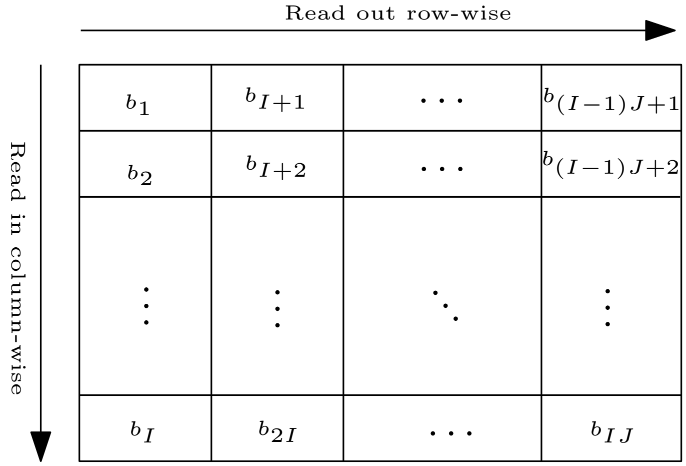

Fig. 2. I by J Interleaver with symbols read in column-wise and then read out row-wise.

a convolutional encoder/decoder, interleaver and PSK/DPSK modulation. In Figs. 3 and 4, the decoded bit error rate curves are plotted against the interleaver depth d for each modulation, in the presence of NBI with probabilities $P = 0.03125$ and $P = 0.0625$, respectively. The minimum of each curve indicates the optimal interleaver depth for that particular modulation.

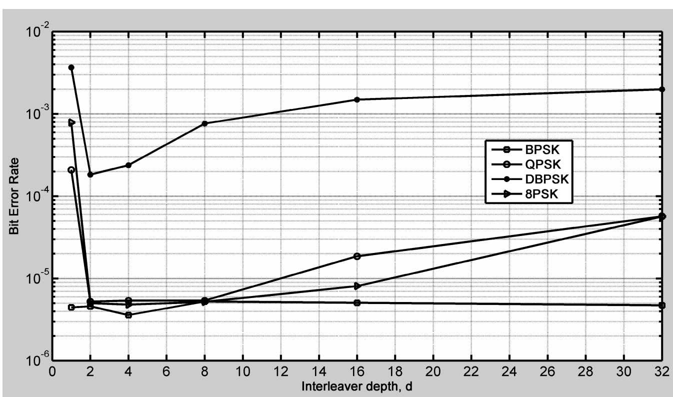

Fig. 3. Convolutional decoder bit error rate performance against interleaver depth for different PSK modulations. The NBI parameters are $P = 0.03125$ and $T = 2 \times 10^{-4}$.

From Figs. 3 and 4 we can draw the conclusion that the optimal interleaver depth, for the convolutional decoder under AWGN and NBI, for BPSK is any value of d (implying no interleaver), for both QPSK and DBPSK is $d = 2$ and for 8PSK is $d = 3$. This behaviour observed in Figs. 3 and 4, showing that the best interleaver depth is the order (or around the order) of the modulation for PSK and that for DPSK it is similar to QPSK, can be explained as follows. The NBI power is large enough that even the Gray-coding of PSK symbols does not prevent errors occurring between the symbols with larger Euclidean distances (opposite symbols of the PSK constellation). This would otherwise happen with a very small probability under AWGN noise when PSK symbols

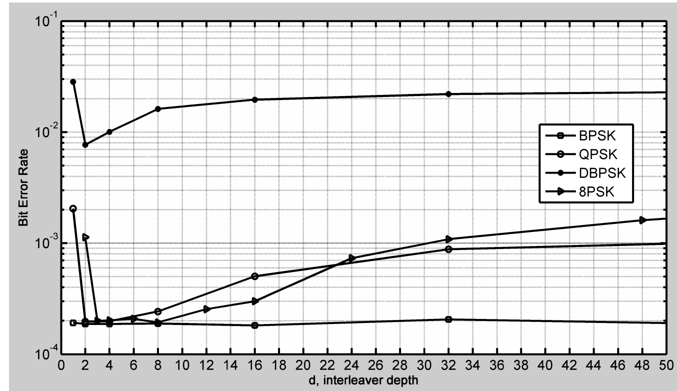

Fig. 4. Convolutional decoder bit error rate performance against interleaver depth for different PSK modulations. The NBI parameters are $P = 0.0625$ and $T = 2 \times 10^{-4}$.

are Gray-coded. The effects of the NBI therefore give rise to an increased number of double bit errors for QPSK, and even triple bit errors for 8PSK. To illustrate the effectiveness of the interleaver in relation to the order of modulation, we focus on QPSK. In QPSK, the $d = 2$ interleaver deals effectively with double errors because it separates them furthest apart, hence avoiding the concentration of bit errors in one $5K$ (K-convolutional encoder constraint length) decoding window in the trellis of the convolutional decoder. Using the $I \times J$ interleaver block as described in Fig. 2 where the stream of bits to be interleaved is of length L and the interleaver depth is d, the separation of bits of the same symbol is $L/2$ for $d = 2$, and $L/(L/2) = 2$ for $d = L/2$. So, in general the separation of bits from the same symbol is L/d for a sequence of length L and interleaver of depth d.

Example 1: For an L-bit serial stream B, let i be the position of the i^{th}-bit b_i in B, for $1 \leq i \leq L$. Then in the interleaved stream of bits $\tilde{B}$, we denote by $\tilde{i}$ the new position of b_i in $\tilde{B}$. For our example, the interleaver depth is $d = 2$. The relationship between the old position i and the new position $\tilde{i}$ is given by,

$$\tilde{i} = \begin{cases} 2i - 1, & i = 1 \ldots \frac{L}{d} \\ 2(i - \frac{L}{d}), & i = \frac{L}{d} + 1 \ldots L \end{cases} . \tag{1}$$

We can trace back the original position i for each b_i in the deinterleaved stream by manipulating (1) and solving for i to get

$$i = \begin{cases} \frac{\tilde{i}+1}{2}, & \text{for } \tilde{i} \text{ odd} \\ \frac{\tilde{i}}{2} + \frac{L}{d}, & \text{for } \tilde{i} \text{ even} \end{cases} . \tag{2}$$

To generalise Equation (1), for any d, which is a factor of L, we have

$$\tilde{i} = d(i - 1) + k(1 - L) + L, \tag{3}$$

where $(k-1)\frac{L}{d} < i \leq k\frac{L}{d}$ for $k = 1 \ldots d$. Equation (3) can also be manipulated to find each i corresponding to each $\tilde{i}$.

Another interesting thing to note about Fig. 4 is that with higher probability of NBI, the convolutional decoder reaches a point where it performs very poorly, especially for DPSK modulation, even with optimal spreading of the errors.

IV. Nulling to Combat Narrow-band interference

The two PLC standard technologies do not specify whether the convolutional decoder performs hard-decision or soft-decision. We therefore investigated this issue in the presence of NBI and observed that the soft-decision performance of the convolutional decoder is not as good as it should be. So to bring about improvement in the performance of the convolutional decoder, we sought to make soft-decision decoding more effective. Our quest to get the gain of soft-decision decoding was fulfilled by simply nulling the power in the frequencies affected by narrow-band interference. To do this we had to find a good threshold that can detect the presence of NBI and then apply nulling in the frequency domain. After nulling, then soft-decision decoding can be applied effectively.

To show why nulling improves the soft-decision decoding of the convolutional decoder in the presence of NBI, we first have to go back to the textbook description of how soft-decision decoding works. We are assuming that the reader has basic knowledge of convolutional encoding/decoding and the Viterbi algorithm. Now, For a rate $R = 1/2$ convolutional decoder, soft-decision decoding is performed by calculating the Euclidean distance between each pair of received symbols and a pair of reference symbols in each branch of the trellis and then after say, $5K$ pairs of symbols the path with the minimum accumulated Euclidean distance is chosen as the correct one. The reference symbols are the noiseless symbols from the constellation of the modulation used at transmission, for example, for BPSK modulation a reference symbol is either -1 or $+1$. To illustrate this soft-decision decoding procedure, let us look at the i^{th} branch of the trellis, where a branch processes a pair symbols. Assuming BPSK, reference symbol is either $s_0 = -1$ or $s_1 = +1$. Let y_{i1} and y_{i2} be a pair of received noise-corrupted symbols corresponding to branch i on the trellis. y_{i1} and y_{i2} can take any real value depending on the noise power. On branch i four Euclidean distances are calculated, as shown in (4), and used to accumulate the distance metric of corresponding paths.

$$\begin{aligned} d_{00} &= (y_{i1} - s_0)^2 + (y_{i2} - s_0)^2 \\ d_{01} &= (y_{i1} - s_0)^2 + (y_{i2} - s_1)^2 \\ d_{10} &= (y_{i1} - s_1)^2 + (y_{i2} - s_0)^2 \\ d_{11} &= (y_{i1} - s_1)^2 + (y_{i2} - s_1)^2. \end{aligned} \tag{4}$$

d_{00}, d_{01}, d_{10} and d_{11} are the calculated Euclidean distances, for received pair y_{i1} y_{i2}, corresponding to reference symbols s_0s_0, s_0s_1, s_1s_0 and s_1s_1, respectively.

Now, if we perform nulling on any of the symbols y_{i1} and y_{i2} if their values exceed a given NBI detection threshold γ, that nulled symbol value will not contribute to the calculation of the Euclidean distance in that branch. Hence the nulled symbol has minimal influence in the final path choice. For example, presume the received value of y_{i1} exceeds γ, then we set $y_{i1} = 0$ and the new Euclidean distances of the i^{th} branch become

$$\begin{aligned} d_{00} &= (-s_0)^2 + (y_{i2} - s_0)^2 \\ d_{01} &= (-s_0)^2 + (y_{i2} - s_1)^2 \\ d_{10} &= (-s_1)^2 + (y_{i2} - s_0)^2 \\ d_{11} &= (-s_1)^2 + (y_{i2} - s_1)^2. \end{aligned} \tag{5}$$

However, if the received symbol exceeding γ (implying NBI corrupted symbol) is set to any value other that zero, the performance of the soft-decision decoding of the convolutional decoder degrades compared to when nulling is done. Nulling of course gives the best performance when the modulation used has a symmetric constellation because all symbols in such a constellation have the same distance from the zero point.

To illustrate the effect of nulling on the performance of the convolutional decoder in the presence of NBI, we present simulation results for the two scenarios of the average NBI power, σ_N^2, mentioned in Section II. These scenarios are: (a) σ_N^2 randomly changes for subcarriers, and (b) σ_N^2 is the same for all subcarriers. The performance results for scenarios (a) and (b) are presented in Figs. 5 and 6, respectively. The same system parameters are used for both Figs. 5 and 6 which are BPSK-OFDM system with $N = 256$ subcarriers; convolutional encoder with the same parameters as in PLC G3 and PRIME: $R = 1/2$, $K = 7$ and $d_{\text{free}} = 10$ which are the rate, the constraint length and the free distance, respectively.

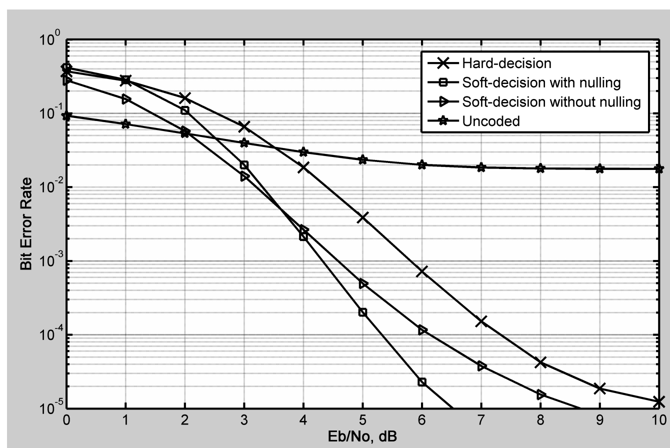

Fig. 5. $R = 1/2$, $K = 7$ and $d_{\text{free}} = 10$ convolutional decoder bit error rate performance comparison for hard-decision and soft-decision decoding with and without nulling. Probability of NBI was set at $P = 0.056$ and T was randomly chosen for each interference signal on a subcarrier. The NBI detection threshold was $\gamma = 2.5\sigma_s$. The modulation employed was BPSK and the FFT size for the OFDM system was $N = 256$.

Fig. 5 shows the performance comparison between soft-decision and hard-decision decoding with and without nulling applied. In Fig. 5, the probability of having narrow-band interference was set at $P = 0.056$ and T was randomly chosen in the interval $0 < T \leq 1$ for each interference signal on a subcarrier. The NBI detection threshold was $\gamma = 2.5\sigma_s$, as it was one of the best thresholds found. σ_s^2 is the variance of the transmitted signal. Generally, good thresholds were found from $2.2\sigma_s$ upwards.

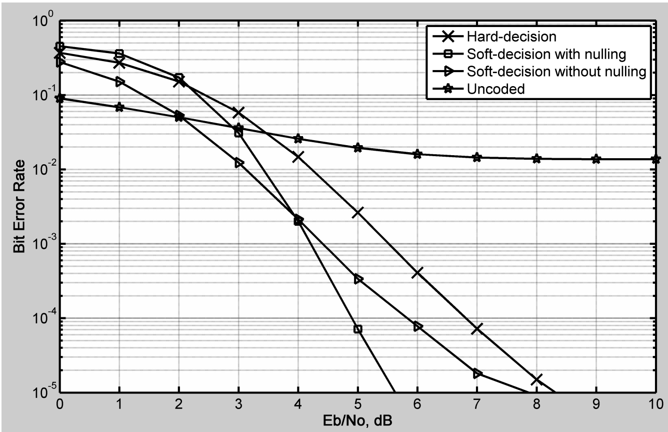

Fig. 6. $R = 1/2$, $K = 7$ and $d_{\text{free}} = 10$ convolutional decoder bit error rate performance comparison for hard-decision and soft-decision decoding with and without nulling. Probability of NBI was set at $P = 0.028$ and $T = 1/100$ for each interference signal on a subcarrier. The NBI detection threshold was $\gamma = 2.2\sigma_s$. The modulation employed was BPSK and the FFT size for the OFDM system was $N = 256$.

Fig. 6 shows the performance comparison between soft-decision and hard-decision decoding with and without nulling applied. The probability of having narrow-band interference for Fig. 6 was set at $P = 0.028$, which is half that of Fig. 5. The NBI detection threshold was $\gamma = 2.2\sigma_s$. In Fig. 6 the average NBI power was set at $\sigma_N^2 = 100$ for all affected subcarriers. Obviously, for a known fixed σ_N^2, the threshold γ should not exceed $\sigma_N + \sigma_s + \sigma_g$, otherwise the performance of soft-decision decoding with nulling approaches that of soft-decision decoding without nulling.

Clipping the NBI power in the frequency domain was also investigated, but nulling gave superior performance for all the cases in Figs. 5 and 6.

We can see from Figs. 5 and 6 that nulling improves the soft-decision decoding of the convolutional decoder. Note that if another higher order PSK modulation was used we would first use an interleaver, with the appropriate optimal depth as described in Section III-B, modulate and then apply nulling according to the NBI detection threshold.

V. Conclusion

We have implemented two simple and known techniques to improve the performance of PLC G3 and PRIME in the presence of narrow-band interference, by improving the performance of the convolutional decoder. We have suggested bit interleaving depths for PSK modulations such that the performance of a the convolutional decoder is improved under NBI. We also showed that nulling significantly improves the performance of the convolutional decoder as it allows for the effective application of soft-decision decoding.

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