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Improving bit error rate under burst noise in OFDM power line communications

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A B S T R A C T

Noise in Power Line Communications is typically impulsive, with impulses being a fraction of the OFDM symbol length. Because of their large duration the impulse can also be called bursts. The short duration of the burst compared with the OFDM symbol length implies that there is a strong correlation between the noise at different carriers, given a determined burst position. The position can be determined using an estimate of the noise after a first demodulation. The high correlation is used to develop demodulators with a reduced bit error rate in comparison with conventional demodulators, so increasing the capacity. The demodulators use a smoothed estimate of the noise signal or a new metric for the distance based on the new correlation matrix. About half of the bit errors can be corrected in this way, corresponding to a 1 dB improvement in Signal Noise Ratio (SNR). How to split the OFDM symbol without increasing the overhead due to the circular prefix is also shown. Noise measurements in power lines are presented. These measurements are used in the simulations.

1. Introduction

Power Line Communications (PLC) [1,2] offers a network with no new wires and so it is a competitor with wireless, ADSL and other technologies to provide a network either to our and in our homes. However, the PLC channel is a difficult one. It has varying characteristic impedance, exhibits frequency selective fading, nulls in its frequency response, and high noise at low frequencies. The frequency selective fading can be dealt with using Orthogonal Frequency Division Multiplexing (OFDM) with adaptive modulation or other [3–5]. In the paper OFDM modulation is assumed. The power line channel is very noisy at low frequencies. The noise is mostly impulsive [6,7], with impulses with a relatively long duration, but much shorter than the OFDM symbol length. Because of the long duration this could also be called bursts. Through the paper the words impulse or burst will be used interchangeably. In the paper we present techniques to improve the Bit Error Rate (BER) resulting in an increase in capacity under this kind of noise. Note that the algorithms presented are only capable of reducing the noise at the OFDM symbols where there is one single dominant burst, and are disabled for other symbols, but this is a common case. Through the text, u_k is the element k of vector $\mathbf{u}$ for any vector $\mathbf{u}$, and $C_{i,j}$ is the element at line i and column j of matrix $\mathbf{C}$, for any matrix $\mathbf{C}$. Also $|x|$ is the absolute value of x.

2. State of the art

There are many papers dealing with impulsive noise reduction. However, they are not usually targeted to OFDM PLC, and normally deal with short impulses, one sample width, while in PLC these are much wider, more like bursts, sometimes reaching a large fraction of the OFDM symbol as shown in [6,7]. Namely, the impulse noise model used is usually memoryless; for instance the Middleton Class A impulsive noise model, [8,9]. However, note that bursts can be converted to a set of distant impulses by an interleaver.

The simplest methods for impulse noise reduction consist of clipping or nulling the impulses. In [10,11] clipping and nulling are analyzed, and in [12] a practical method for computing the clipping threshold is presented. In [13] Empirical Mode Decomposition (EMD) is used to reduce impulsive noise. They achieved a noise reduction of about 3 dB, but tested the algorithm only in very simple signals. They classified the components after EMD with higher amplitude as noise.

Other methods are iterative. In [14] the noise is estimated after de-mapping and pilot insertion. Then a peak detector is used to find the impulses and the estimated impulsive noise is subtracted from the signal. De-mapping and pilot insertion are done again. This is repeated a predetermined number of times. Improvements

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of about 1 dB in the signal to noise ratio for real noise recorded from a hairdryer are reported. In [15] the signal is coded by applying a simple liner transformation (G) to an input vector. G can be the Discrete Fourier Transform (DFT) as in OFDM modulation. A new iterative decoding algorithm is presented. The time domain received signal and the signal estimate is used to estimate the impulsive noise using a MMSE estimator; then the impulsive noise estimate and the transform domain received signal is used to estimate the signal using a MMSE or MAP estimator, and this is done recursively. A Middleton's Class A noise model is used for the impulsive noise in the time domains, and a Gaussian model for the impulsive noise in the transform domain. Large improvements in the BER are reported. In [16] convex programming techniques were used to determine impulse positions. Then their amplitudes are determined and the impulses are removed from the signal. The pilot and unused carriers are used to determine the impulse positions. Gains of up to 3 bits in the capacity are reported. The results are compared with the Gaussian-erasure channel.

Other methods are modifications to forward error correction (FEC) coding. This can be using convolutional codes with erasure [17,18], turbo codes [19,20] or low density parity check codes [21,22].

3. OFDM MODEM

In Fig. 1 the OFDM MODEM considered in the current work is presented. It is composed of a number of blocks. First the serial bit stream is converted to a parallel stream by the S/P block. Then the bits are combined into groups of $\log_2(K)$ for K-QAM, and modulated by a set of $(N/2 - N_G)$ QAM modulators, where N is the OFDM symbol length minus the circular prefix (CP), and N_G is the number of guard carriers. The guard carriers will be set to zero, and will appear in the lower and upper part of the spectrum. This will result in a vector, $\mathbf{T}(n)$, with $N/2$ complex values. Then the Mi (mirror) block will fill the remaining $N/2$ entries of this vector, with $\mathbf{T}_{N-k}(n) = \mathbf{T}_k^*(n)$ so that Inverse Fast Fourier Transform (IFFT) of $\mathbf{T}(n)$ will result in a real signal. The IFFT block will do a N point IFFT as the name implies, resulting in the vector, $\mathbf{t}(n)$. After the IFFT a circular prefix of length N_P is added, by copying to the beginning of $\mathbf{t}(n)$ the last N_P samples of $\mathbf{t}(n)$. Finally the signal is transmitted through the channel. At the receiver, the circular prefix is removed by the CPR block, resulting in signal $\mathbf{r}(n)$. This includes a noise term $\mathbf{u}(n)$. Then, a N point Fast Fourier Transform (FFT) is applied to the signal, resulting in $\mathbf{R}(n)$. The SL (select) block discards the second half of $\mathbf{R}(n)$ since it is just the conjugate of the first half. The EQ (equalizer) compensates for the frequency response of the channel by multiplying the signal at each carrier by the inverse of the frequency response of the channel. The resulting signal, discarding the guard carriers, will pass through a set of QAM demodulators, resulting in a parallel bit stream. Finally, the bit stream is converted to a serial bit stream by the P/S block.

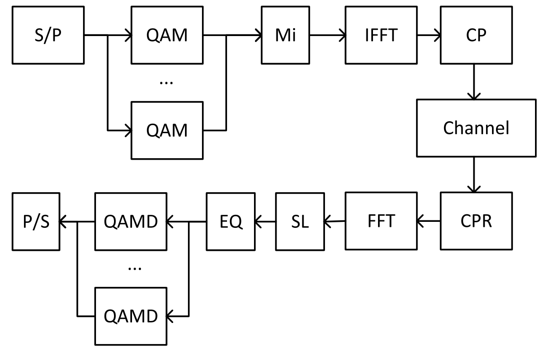

Fig. 1. OFDM MODEM.

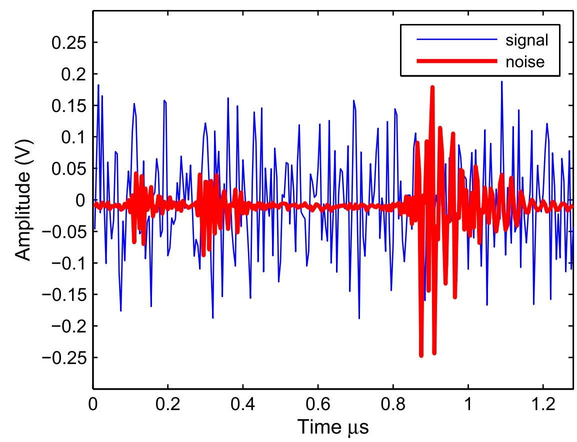

Fig. 2. Plot of typical signal (in blue) and noise (in red) for a SNR of 7 dB and for the duration of one typical OFDM symbol. Sampling rate was 200 MHz. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Power line noise measurements

In a previous paper [7] the authors presented a set of measurements of power line noise. These measurements, along with the work of [6] motivated the work presented in this paper, and are used in the simulations. Fig. 2 presents a typical waveforms for the signal and noise, for a Signal no Noise Ratio (SNR) of about 7 dB, using the noise measured in [7].

In [7] it is shown that shifting the impulses position to the origin in each received OFDM symbol results in high correlation between the noise at different carriers.

Namely, consider the noise of the received OFDM symbol, after circular prefix removal, $\mathbf{u}(n) = [u_0(n) \dots u_{N-1}(n)]^T$, and its DFT, $\mathbf{U}(n) = [U_0(n) \dots U_{N-1}(n)]^T$. Let d be calculated so that the correlation between different elements of $\mathbf{U}_2(n)$ is maximized, with $U_{2k}(n) = U_k \exp(2\pi kd/N\, i)$. If the noise is a single impulse, then d is the impulse position, so this correspond to shifting the impulse to the origin in the time domain. Define the cross-correlation matrix of $\mathbf{U}_2(n)$ by,

$$\boldsymbol{\Sigma} = \mathrm{E}[\mathbf{U}_2(n)\,\mathbf{U}_2^H(n)], \tag{1}$$

and the matrix of correlation coefficients, $\mathbf{C}$ by,

$$C_{i,j} = \Sigma_{i,j}/\sqrt{\Sigma_{i,i}\Sigma_{j,j}}. \tag{2}$$

The values for correlation coefficients, the diagonals of $\mathbf{C}$ are plotted in Fig. 3. It can be seen that the correlation coefficients of adjacent carriers takes large values. The impulse position, d, that maximizes the correlation of the noise between carriers can be calculated from [7],

$$2\pi d/N = \angle\left(\sum_{k=0}^{N-2} (\mathbf{U}[k]\mathbf{U}[k+1]^H\right), \tag{3}$$

where $\angle(x)$ stands for the angle of the complex number x, and gives results in 0 to 2π. Note that if $\mathbf{u}(n)$ is a single impulse at the origin, then $\mathbf{U}(n)$ is constant, so the correlation coefficients between its elements are equal to one.

5. BER improvement techniques

In this section we present three techniques to reduce the BER in PLC with impulsive noise. The first two are based on the frequency domain correlations of the time shifted noise signals, and the last