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Robust multicarrier CDMA receiver for coded power-line communications

Ivan Ku[a)]

Faculty of Engineering, Multimedia University, Jalan Multimedia, 63100 Cyberjaya, Selangor

a) *kccivan@mmu.edu.my*

Abstract: Existing indoor power-line grids are a potential solution to the last mile problem for broadband communication providers. However, power-line communication (PLC) channels suffer from deep frequency notches and severe impulsive noise making powerful signal processing essential if these channels are to be utilized. Broadband communications using Multicarrier Code Division Multiple Access (MC-CDMA) with channel coding is considered. Although resilient to frequency-selective fading, the coding gain from turbo signal processing is substantially compromised in the presence of impulsive noise. To overcome this, we propose a low complexity non-linear matched filter utilizing M-estimation technique. We will show that this matched M-estimate filter is indispensable in providing efficient baseband filtering in impulsive channels.

Keywords: turbo processing, MC-CDMA, power-line, impulsive noise

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

Broadband over power-line (BPL) communications has received considerable research interest recently. This is because power-line grids are readily available in all premises and can be potentially utilized as broadband access to home networking, thus providing an inexpensive and convenient communication medium. However, realizing a reliable high-speed communication over a medium originally designed for electrical energy delivery rather than data communication presents a difficult challenge. The power-lines are modeled as channels afflicted with colored background noise, narrowband interference, frequency-selective fading and impulsive noises caused by switching transients of electrical appliances [1].

The well-known OFDM is seen as the favorite modulation scheme for BPL. By transmitting data in parallel on many orthogonal subcarriers, each narrow subband of the subcarriers has a flat frequency response, transforming the channel into a set of multiple flat-fading subchannels. Thus, intersymbol interference caused by frequency-selective multipath propagation is canceled. On the other hand, CDMA scheme is appealing due to its robustness against interference caused by multiple wireless devices and users simultaneously accessing the home network. Therefore, having the advantages of both technique, multicarrier CDMA or MC-CDMA has been proposed as an attractive multiple access technique in PLC channels. Combined with forward error control coding to provide improved performance, joint mitigation of background noise and multiple access interference is achieved successfully through turbo signal processing [3]. However, the virtues of turbo processing in the presence of strong impulsive noise can be greatly compromised if proper countermeasures are not taken [4].

In this paper, we develop a robust MC-CDMA receiver to overcome the effects of impulsive noise. Specifically, we replace the matched filter of the conventional MC-CDMA receiver with a non-linear filter utilizing M-estimation signal processing technique, an approach used extensively in robust statistics.

2 Transmission model

Consider a coherent, bit and chip synchronized baseband MC-CDMA system using BPSK modulation with K users. Equiprobable M information bits $(b_k^j = \pm 1 : 1 \leq j \leq M)$ of the kth user are encoded into L coded bits $(d_k^i = \pm 1 : 1 \leq i \leq L)$. Following the encoding, random interleaving is employed for the coded bit sequence $\underline{d}_k$ to avoid burst errors due to deep fading. The coded bit d_k^i is then spread by a spreading code of length N and transmitted using MC-CDMA with total number of subcarriers equal to the spreading code length. Therefore, the received N by 1 baseband complex signal matrix, $\mathbf{r}$, at the ith time interval is given by

$$\mathbf{r} = \mathrm{IFFT}\left\{\mathbf{SAd}\right\} + \mathbf{n}, \tag{1}$$

where the N by K normalized spreading code $\mathbf{S} = \frac{1}{\sqrt{N}}(\xi_c^k = \pm 1 : 1 \leq c \leq N, 1 \leq k \leq K)$, the K by K user amplitude $\mathbf{A} = \mathrm{diagonal}(A_1, \cdots, A_K)$,

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the K by 1 transmitted code bits $\mathbf{d} = (d_k^i : 1 \leq k \leq K)$ and the N by 1 zero-mean complex symmetric alpha stable (SαS) random variables $\mathbf{n} = (n_c^i : 1 \leq c \leq N)$. S$\alpha$S distribution accurately models impulsive noise over a wide range of conditions and includes Gaussian noise as one of its limiting cases [4]. The characteristic exponent, α $(0 < \alpha \leq 2)$ and dispersion, γ $(\gamma > 0)$ determines its impulsiveness and scale of distribution respectively. The IFFT$\{\cdot\}$ operation is the inverse fast Fourier transform applied independently to the real and imaginary parts. All multiplication and addition are complex matrix operations.

3 Countermeasures against impulsive noise

A linear matched filter (MF) is usually first used to process the received signal $\mathbf{r}$. The MF does a convolution over the received signal energy, thus averaging out random noise and resulting in a correlation gain. However, impulsive noise causes the performance of the MF to degrade substantially [2]. Impulsive noise possesses infinite variance and therefore integrating directly the contaminated received signal will result in the MF output having infinite noise power, thus violating its SNR optimality criteria. If proper mitigation is not considered, these high power contaminants will permeate into the subsequent iterative signal processing blocks and disrupt the optimality there.

With this as our motivation, we begin by defining the N by 1 complex residual noise vector at the ith time interval as,

$$\left(e_1^i, \cdots, e_N^i\right)^{\mathrm{T}} \quad = \quad \mathbf{r} - \mathrm{IFFT}\left\{\mathbf{Sy}\right\}, \tag{2}$$

where $\mathbf{y} = (y_k^i : 1 \leq k \leq K)$ is the K by 1 estimated code bits and $(\cdot)^{\mathrm{T}}$ is the transpose operator. In ordinary case, the residual noise samples follow a Gaussian distribution. However, under the influence of impulsive noise, it may contain random destructive outliers of high magnitude. Therefore to provide protection against it, we adopt the M-estimation criteria in designing our robust M-estimate filter (MEF). The objective of the MEF is to choose the estimated code bits $\mathbf{y}$ in such a way as to satisfy

$$\hat{\mathbf{y}}_{\mathrm{MEF}} = \arg\min_{\mathbf{y}} \sum_{c=1}^{N} \rho\left(e_c^i\right), \tag{3}$$

where ρ is the cost function applied to every element in the residual noise vector. To solve Eq. (3), we begin by letting $\mathrm{W}^i(\mathbf{y}) = \sum_{c=1}^{N} \rho\left(e_c^i\right)$. Then, its gradient is written as

$$\begin{aligned} \nabla \mathrm{W}^i(\mathbf{y}) &= \left(\frac{\partial \mathrm{W}^i(\mathbf{y})}{\partial y_1^i}, \cdots, \frac{\partial \mathrm{W}^i(\mathbf{y})}{\partial y_K^i}\right)^{\mathrm{T}} \\ &= -\mathbf{S}^{\mathrm{T}}\, \mathrm{FFT}\left\{\psi(\mathbf{r} - \mathrm{IFFT}\left\{\mathbf{Sy}\right\})\right\}, \end{aligned} \tag{4}$$

where the FFT$\{\cdot\}$ operation is the fast Fourier transform and ψ is the derivative of ρ. When $\rho(x) = \frac{1}{2}|x|^2$, the filter becomes the least square (LS) estimator which is not immune to impulsive noise as its Euclidean metric allows

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outliers to past indiscriminately [6]. Instead, we have chosen a hybrid metric known as the Huber cost function defined as,

$$\rho(x) = \begin{cases} \frac{1}{2}\,|x|^2, & |x| \le h, \\ h\,|x| - \frac{1}{2}h^2, & |x| > h, \end{cases} \tag{5}$$

where $h > 0$ is a cutoff for tuning the robustness of the MEF against outliers. The convex cost function in Eq. (5) is practically the LS estimator for small residual noise and becomes the robust slower-than-quadratic least absolute estimator to penalize outliers. Furthermore, the derivative of Eq. (5) is bounded and continuous (bounded influence function) and thus is indeed robust [5].

Using Eq. (4), an iterative solution to Eq. (3) is found, based on gradient descent method, by transforming it to a difference equation given by

$$\mathbf{y}^{u+1} = \mathbf{y}^u + \mu \mathbf{S}^{\mathrm{T}}\,\mathrm{FFT}\,\{\psi(\mathbf{r} - \mathrm{IFFT}\,\{\mathbf{S}\mathbf{y}^u\})\}, \tag{6}$$

where $\mathbf{y}^u$ is the uth iteration estimated code bits and μ is the step size. Initially, elements in $\mathbf{y}$ are set to zero at $u = 0$. At the last iteration, the MEF output is taken as the estimate $\hat{\mathbf{y}}_{\mathrm{MEF}}$ and is passed into the receiver's subsequent multiuser detector and decoder for further processing [3].

4 Simulation results and discussion

Recursive systematic convolution code with code rate $\frac{1}{2}$, constraint length 3 and octal generator polynomial $[7,5]_8$ is used as the channel code. Gold spreading codes of length $N = 7$ is used with a half loaded system of $K = 4$ and $\mu = 1$. Perfect power control is assumed so that the algorithm can be studied under controlled conditions as the focus is on impulsive noise suppression, after which existing methods can only be effective against near-far and multi-path problems in more realistic BPL communications. Smaller α simulates more impulsive noise while $\alpha = 2$ gives the Gaussian noise. Since α-stable processes have infinite variance at $\alpha < 2$, we use the geometric signal-to-noise ratio, $\mathrm{E_b/N_0} = \frac{1}{2C_g}\left(\frac{A_k}{S_0}\right)^2$. Here, S_0 and $C_g \approx 1.78$ are the geometric power and exponential of the Euler constant respectively [7].

The performance of the MF and MEF in impulsive noise can be illustrated clearly from the eye diagrams of Fig. 1(a), obtained by plotting the magnitudes of 800 BPSK symbols at the output of the filters. The narrow eye opening of the MF indicates a high degree of signal waveform distortion. This is expected as the structure of the MF is not designed to cope with the presence of outliers, thus resulting in a less reliable signal to work with. On the contrary, the wide eye opening of the MEF demonstrates its robustness against the destructive outliers, giving a good reconstruction of the signal waveform with a more reasonable amplitude range, as shown in Fig. 1(b).

Unsuppressed impulsive noise inhibits the iterative structure of the MC-CDMA receiver from reaching its full performance. This can be seen in Fig. 2. Because the MF allows impulsive noise to permeate through it, these outliers

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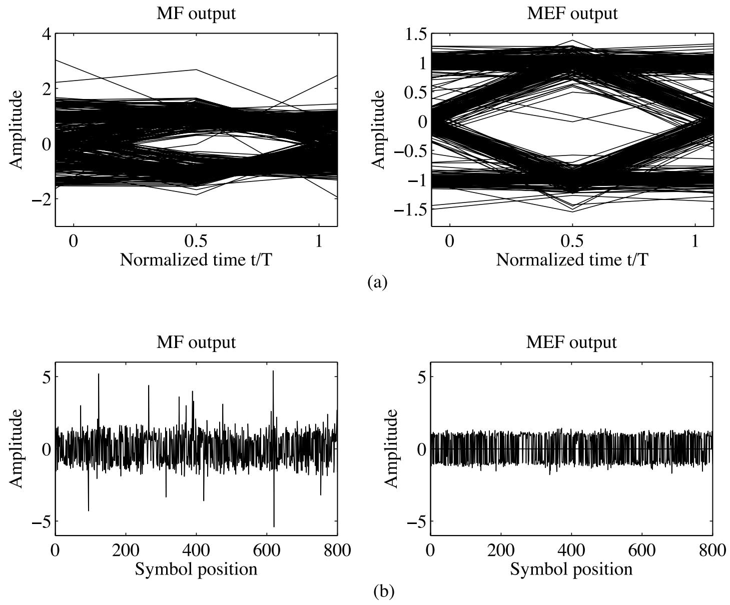

Fig. 1. (a) Eye diagrams for the MF and MEF outputs and (b) their impulsive noise suppression capabilities ($\alpha = 1.5$, $E_b/N_0 = 25$ dB).

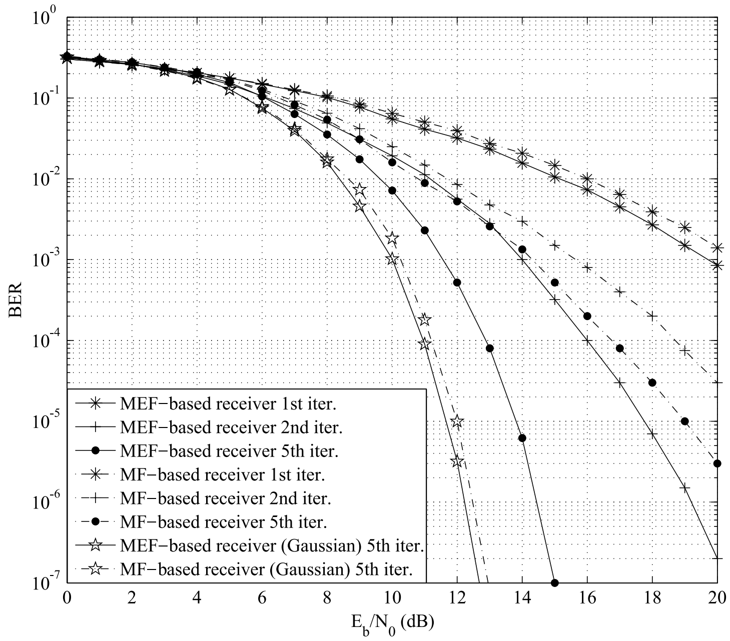

Fig. 2. BER performance of MF-based and MEF-based receivers ($\alpha = 1.7$).

introduce harmful errors that partially paralyze the mechanism for delivering improved bit error rate (BER) at each iteration between the multiuser detector and decoder bank. Consequently, the MF-based receiver is rendered defenceless against the presence of outliers. On the other hand, the virtue of turbo signal processing in the MEF-based receiver is preserved. While their performances are comparable at Gaussian noise ($\alpha = 2$), coding gains of up to 4 dB at BER $= 10^{-4}$ is observed after the fifth iteration of the MEF-based

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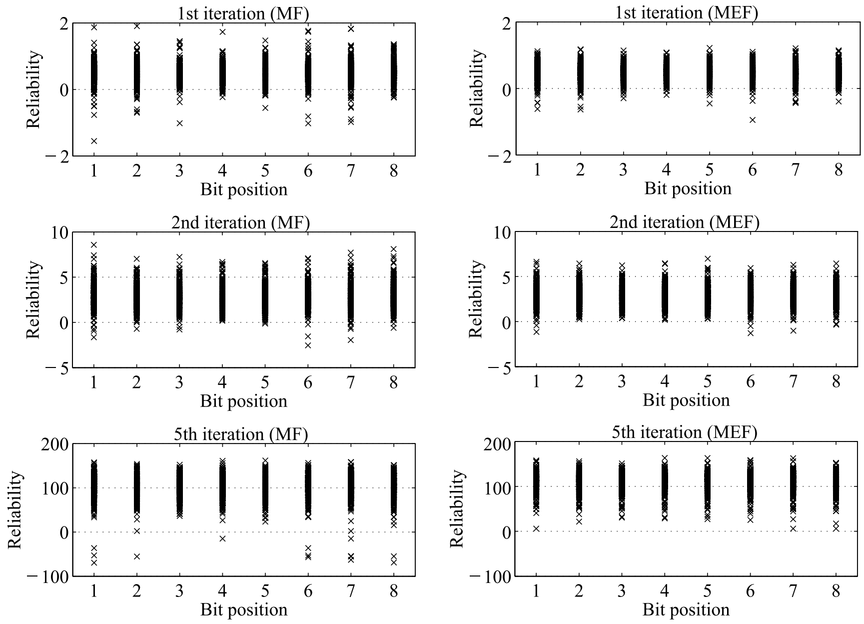

Fig. 3. Reliability plots of MF-based and MEF-based receivers ($\alpha = 1.7$, $E_b/N_0 = 12\,dB$).

receiver.

To further demonstrate this, reliability plots are examined in Fig. 3. The reliability is calculated as the product of the decoder's *a-posteriori* log-likelihood ratio output and the transmitted information bits. A large positive reliability constitutes a high confidence of correct estimation while a negative reliability represents a wrong decision. After the first iteration, the decoder of the MF-based receiver produces an appreciable amount of low-confidence and erroneous decision estimates. In fact, even after the fifth iteration there is no noticeable decrease in the negative reliability values. The outliers initially appearing at the MF's output have traveled unhindered through the multiuser detector. Due to its quadratic metric, it is expected that the multiuser detector is unable to stop the outliers from propagating to the input of the decoder. In turn, this drastically interrupts its trellis decoding process. Thus, the decoder also fails to prevent the outliers from reaching its output. The circulation of outliers back to the multiuser detector and subsequently the decoder again continues to dominate the succeeding iterations. Therefore, this error propagation in the MF-based receiver prevents it from achieving large incremental of performance improvement. Conversely, even though the MEF-based receiver started out having a handful of negative reliability values, its number quickly lessens as the iteration proceeds and by the fifth iteration, all of the bits have been correctly estimated. The MEF filtering mechanism successfully prevents outliers from propagating forward. This allows the multiuser detector and decoder to cooperatively correct more errors by iteratively exchanging higher quality a-priori information.

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5 Conclusion

A robust M-estimate filter is proposed for coded MC-CDMA power-line transmission channel. The results demonstrate that the MEF-based MC-CDMA receiver is more robust against heavily tailed outliers. It is shown to effectively mitigate impulsive noise, thus preventing error propagation which is the main cause of performance degradation in iterative systems.

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