

# Advanced Signal Processing for Powerline Communications<sup>\*</sup>

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*Invited Paper*

## Abstract

In this paper, signal processing techniques to combat the adverse communications environment on power lines are addressed, so as to enable reliable high speed data communications over low-voltage (LV) power distribution networks for Internet access and in-home/office networking. It is seen that multicarrier code division multiple access (MC-CDMA), multiuser detection (MUD), and turbo decoding, having demonstrated their limit-approaching capacity in digital subscriber line (DSL) and wireless communication systems, are readily applied to powerline communications (PLC). In particular, it is argued that these methods can successfully mitigate the influence of the principal impairments in PLC channels, namely time-varying channel attenuation, multipath frequency-selective fading, multiple-access interference, and background noise. Strategies to deal with the most unfavorable noise source, the impulse noise, are also discussed.

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# I. Introduction

The increasing ubiquity of the Internet is creating a rapidly growing demand for larger bandwidth to the home. Currently the narrowband twisted-pair access network from an optical network unit or a central office to a customer's premises, the so-called "last dirty mile", is the bottleneck for Internet traffic. The increasing demand for home/office networks further necessitates a flexible broadband network access.

Currently, among others, there are two major approaches to the high-speed data transmission on this last mile. One is digital transmission over phone lines through digital subscriber line (DSL) technology or over cable networks through cable modems (CATV). The other is wireless access exemplified by wireless local loop (WLL) or wireless local area network (wireless LAN). Electric power lines, which can be found in essentially all buildings and residences, naturally exhibit potential as a convenient and cheap communication alternative. Also, in rural areas where services from telephone companies or cable companies do not reach, and where radio coverage is poor or very expensive through one-way satellite access, communication through power lines may be the only feasible solution. As to in-home networking, the powerline is inherently the most attractive medium due to its universal existence in homes, the ubiquity of outlets, and the simplicity of the power plug. In comparison, the phone line/cable suffers from too few connection points, and wireless suffers from congestion and interference in the unlicensed bands.

Even though powerline communications is an attractive alternative for broadband Internet access for the last mile and in-home/office networking, many difficulties and challenges exist. The characteristics of the powerline that need to be contended with are time-varying frequency-dependent channel attenuation of up to 60 dB, reflections from non-terminated points resulting in

multipath fading, and various types of noise [16], [17]. Originally designed for power delivery rather than for signal transmission, the powerline has many less-than-ideal properties as a communications medium. Various loads connected to and disconnected from the powerline randomly make the rapidly changing channel condition even more unpredictable. The reflections are caused by impedance mismatches at joints or points where equipment is connected to the mains network. In contrast to many other communication channels, the noise in a powerline environment cannot be described by an additive white Gaussian noise (AWGN) model. According to [16], five types of noise can be found on power lines, among which the most unfavorable one is perhaps the asynchronous impulse noise, caused by switching transients in the network. These impulses have durations of some microseconds up to a few milliseconds with random occurrences. The power spectral density (PSD) of this type of noise may reach values of more than 50 dB above the background noise and may cause bit or burst errors especially in high-speed data transmissions during its occurrence. In addition, only a low transmitting power density will be possible for future broadband PLC, due to strict emission regulations for electromagnetic (EM) compatibility. Thus, the signal-to-noise ratio (SNR) at the receiver can be very low if the transmitter is far away while a large noise source can be nearby.

Furthermore, multiple-access interference is another important source of performance degradation due to the inherent multiuser communication nature over low-voltage (LV) power distribution networks, beginning at a pole or pad transformer “substation” and ending at the associated residences, a configuration that is of particular interest nowadays for subscriber access applications. The network topology is such that a line termination (LT) is installed at each distribution transformer, serving to connect to a wide area network (WAN), via fiber, fixed wireless, or the public switched telephone network (PSTN). Network terminations (NTs), like

user modems, are located at the associated residences and connected to the LT through distribution cables in a star or bus topology. Downlink transmission refers to transmission from LT to NTs, and uplink the reverse.

To facilitate reliable high-speed communications over LV power distribution networks, advanced signal processing techniques should be pursued to combat the adverse environment described above. Preferably, signal processing should be implemented in the receiver side, as a feedback channel to the transmitter may not be feasible due to the time varying nature of the channel, or may be inappropriate for applications that require low latency. In addition, signal processing at the transmitter side has limitations for broadcast/multicast applications, e.g., in-home/office networking, as channel characteristics vary greatly for different cables, transmission lengths, network structures, and locations. In this paper, we discuss signal processing techniques that are of interest in this context.

## **II. Related Problems and Corresponding Techniques in DSL and Wireless Communications**

As discussed in the previous section, the dominant sources of impairment for powerline communications are time-varying channel attenuation, multipath frequency-selective fading, multiple-access interference, and impulse noise. These phenomena naturally remind us of the similar impairments and corresponding mitigating techniques used in DSL and wireless communications. In this section, we describe these latter issues.

### ***1. Modulation Schemes for Multipath Fading Channels***

For narrowband applications on power lines, single carrier modulation has been adopted for its simplicity, employing frequency-shift keying (FSK), quadrature phase-shift keying (QPSK), or

other modulation methods [6]. However, in broadband applications on powerline channels, these techniques have been shown to be inadequate for high-speed communications. The principal problem is the frequency-selective fading, which places deep notches in the frequency response, whose locations vary from cable to cable, time to time, and location to location. If the signaling band contains such an unfavorable notch, very poor system performance can be expected. Another problem arises when trying to use the rest of the spectrum: usually the channel attenuation increases with frequency and many bands are not flat enough to accommodate high rate communications with narrowband modulation. Also, the signal is easy to localize in frequency and to disturb deliberately [12]. Similar considerations in wireless and DSL communications have given rise to two powerful techniques for combating multipath fading and intersymbol interference (ISI): spread-spectrum and multicarrier modulation (MCM).

As a wideband modulation approach, spread spectrum techniques can exploit spectral diversity (e.g., through a RAKE receiver for direct-sequence spread spectrum) to effectively combat the multipath fading, resulting in its widespread use in mobile radio communications. Furthermore, spread spectrum is well known for its ability to suppress the effects of narrowband and other types of interference. Of course, spread spectrum comes in several varieties: direct-sequence, frequency hopping, time hopping, chirp and hybrid methods. The direct sequence (DS) spread spectrum techniques have the ability to realize a multiple access structure in a simple way by choosing suitable spreading sequences, i.e., code-division multiple-access (CDMA), and hence is widely used in practical communication systems.

Multicarrier modulation, following Shannon's optimum transmission suggestion, achieves the highest performance in channels with frequency-selective fading and severe ISI [2]. The underlying rationale of MCM is to divide-and-conquer: a channel is divided into many

independent ISI-free subchannels in the frequency domain, and power and bits are allocated adaptively according to the channel characteristics. The advantages of using MCM for communications over frequency-selective fading and ISI channels include optimality for data transmission, adaptivity to changing environments and flexibility in bandwidth management. Furthermore, the demodulation and modulation processes have very low complexity when the fast Fourier Transform (FFT) and its inverse, the IFFT, are used. There are many different names for this technique. In DSL applications it is often called discrete multitone (DMT), while in wireless applications it is better known as orthogonal frequency division multiplexing (OFDM). Generally the performance of MCM systems is limited by the subchannels with the worst SNRs in a frequency-selective fading channel, and adaptive bit loading and power allocation is almost a necessity for efficient MCM transmission in practice. However, this adaptation is a complication in the transmission protocol and is sometimes not even appropriate (as in point to multipoint broadcast applications or time-varying mobile channels). The common approach to MCM over unknown channels, such as wireless channels (see, e.g., the IEEE 802.11a wireless LAN standard), is to use the same allocation to all frequencies and use advanced signal processing to improve the performance at the frequencies which are found to be attenuated at the receiver. MCM is also robust to narrowband interference and impulse noise.

There are several approaches to multiple access using MCM. One such technique is to assign different groups of subcarriers to different users. The drawback of this scheme is that some users may be stuck in a null in the spectrum and thus achieve very poor performance. This problem can be overcome by frequency hopping the carriers, at the cost of increasing the complexity of the transmitter and receiver. A more effective multiple-access scheme for MCM is to combine MCM and CDMA to form a *multicarrier CDMA* (MC-CDMA) system. There are several forms

of MC-CDMA, among which we focus here on a form in which each user's data is spread over all the subcarriers through a unique spreading code, with each sub carrier modulated by a single chip [8]. It can be seen that MC-CDMA is a frequency-domain dual of DS-CDMA, which will be further illustrated in the next section (see also [9]).

## **2. Advanced Signal Processing at the Receiver**

*Multiuser detection* (MUD) is well known to be an effective technique for dealing with the multiple-access interference [13]. It exploits the well-defined structure of the multiuser interference, distinct from that of ambient noise, in order to improve the system performance. Multiuser detection can be applied naturally in CDMA systems that use nonorthogonal spreading codes. It also can be employed in wireless time-division multiple-access (TDMA) or frequency-division multiple-access (FDMA) systems to ameliorate the effects of non-ideal channelization or multipath, or to combat co-channel interference from adjacent cells. Multiuser detection techniques include optimum maximum-likelihood (ML) joint detection and various suboptimum linear and non-linear methods. Linear multiuser detection, including decorrelating (zero-forcing) MUD and minimum-mean-square-error (MMSE) MUD, is relatively simple and effective, but its performance is limited in overloaded (more users than degrees of freedom) systems. Non-linear multiuser detection such as decision feedback (DF) MUD and successive interference cancellation (IC) MUD, often provides a favorable tradeoff between performance and complexity.

Error control coding is a common way of approaching the capacity of communication channels and is a fundamental element in the design of modern digital communication systems. Recent trends in coding favor parallel and/or serially concatenated coding and probabilistic, soft-decision, iterative (turbo-style) decoding techniques, which exhibit near-Shannon-limit

performance with reasonable complexities in many cases [1]. This technique, *turbo decoding*, is of significant interest for communications applications that require moderate error rates and can tolerate a certain amount of decoding delay.

As a specific application of the turbo principle, by introducing an interleaver between coding and modulation to form a serially concatenated coding system at the transmitter, and the associated turbo decoding between the multiuser detector and channel decoder at the receiver, one has *turbo multiuser detection* which has drawn much attention recently [10]. Turbo multiuser detection has demonstrated its limit-approaching capacity in DSL [4] and wireless [15] communication systems with Gaussian background noise.

### **3. Combating Impulse Noise**

As in powerline communications, short time-duration and high magnitude impulse noise over copper twisted pairs or wireless communication channels can potentially be the limiting impairment on performance in many high-speed data transmission applications. While spread spectrum or multicarrier modulation is inherently more robust to this form of impairment, in the sense that they have a higher error threshold than a single-carrier system, effective error control schemes are still required to ensure reliable system performance. Impulse noise is typically combated with forward error correction (FEC) [18]. To enable the correction of long bursts of errors, interleaving can be used to spread the burst over many codewords. An applied FEC scheme can be made more effective if channel state information is available at the decoder. Then *erasure decoding* techniques can be employed to mitigate the influence of impulse noise. Erasure decoding is fairly easy to implement for MCM systems, where individual tones can be zeroed without affecting other tones [4].

Given the similarities among DSL, wireless and PL channels, techniques developed for the first two types of channels are natural candidates for application in powerline communications. In this study we consider such application. We adopt DS-CDMA and MC-CDMA as modulation and multiple-access methods, based on which communication models of power lines are under consideration (see Section III). On forming a serially concatenated system at the transmitter through introducing an interleaver between coding and modulation modules, multiuser detection and turbo decoding are used at the receiver for data detection and decoding, further details of which are given in Section IV. Some numerical results are given in Section V to demonstrate the performance of the proposed signal processing techniques, in comparison with traditional ones. Finally, Section VI concludes the paper and discusses some interesting signal processing topics that have been left out.

### **III. Powerline Communication Model**

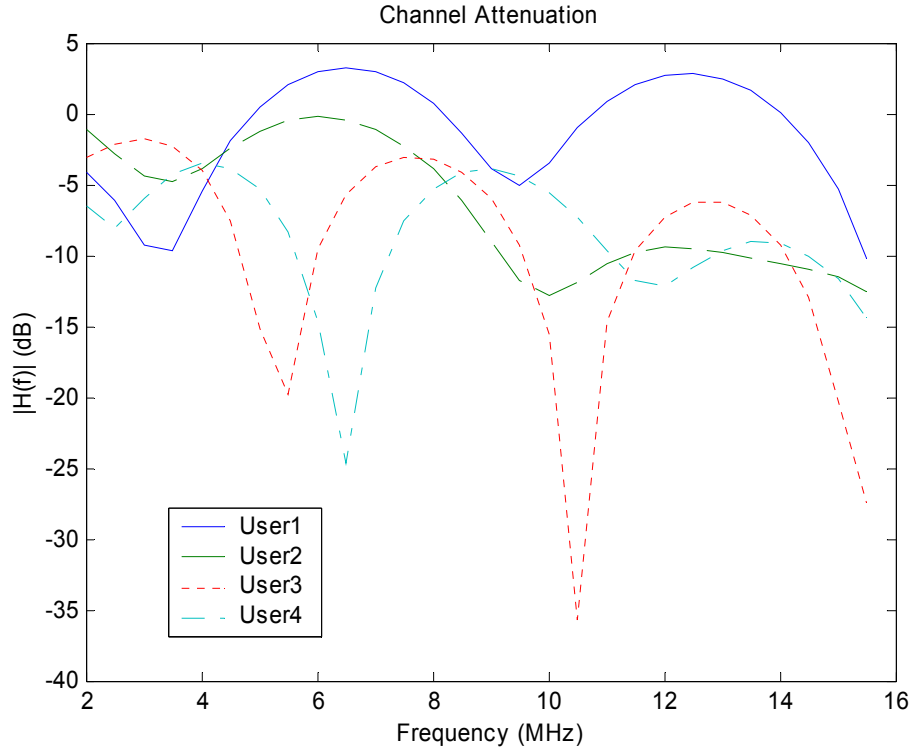
As powerline communication is still a rather new area, few standards have been established, especially for broadband applications. European standard EN 50065 specifies a frequency band of 3 kHz to 148.5 kHz for low voltage mains signaling, which is clearly not adequate for high speed Internet access. As with its counterpart on twisted-pair phone lines, high speed communications over power lines requires much larger bandwidth than their normal usage, which should be well separated from the lower frequency band where normal services are provided. To support envisioned services such as video on demand, audio or video streaming, multimedia communications with varying quality of service (QoS) requirements, and high speed Internet access, data transmission rates of 1-10M bits/s are needed, which may require use of up to several tens of MHz of bandwidth. As part 15 of the FCC rules restricts powerline communications in the AM frequency band (535 to 1705 kHz), a reasonable range of frequencies

for broadband application on power lines would be from 2 MHz to 30 MHz, or even up to 60 MHz, depending on the nature of specific LV distribution networks and the requirements of potential services. But one should bear in mind that attenuation on power lines increases substantially with increasing frequency.

A mathematical multipath propagation model for the transfer function of powerline channels has been proposed in [17]:

$$H(f) = \sum_{i=1}^{N_p} g_i \cdot e^{-(a_0 + a_1 f^\kappa) d_i} \cdot e^{-j2\pi f (d_i / v_p)} . \quad (1)$$

This model is based on physical signal propagation effects in mains networks including numerous branches and impedance mismatching. Besides multipath propagation accompanied by frequency selective fading, signal attenuation of typical power cables increasing with length and frequency is considered. The principal advantage of this model is the comparatively small set of parameters needed. These are the weighting factor  $g_i$ , the length  $d_i$  of path  $i$  with total number of paths  $N_p$ , and general parameters of  $a_0$ ,  $a_1$  and  $\kappa$  for signal attenuation with respect to length and frequency. The propagation speed,  $v_p$ , is a constant depending on the cable's insulation material. It has been verified that this model allows an accurate reproduction of powerline channel behavior and will be used here as a basis for channel emulation [7]. In Fig. 1, simulated channel frequency responses of four users are shown, where the frequency-dependent attenuation and the frequency selective fading can easily be seen.



**Fig. 1 Simulated channel frequency responses of four users**

Consider a direct-sequence CDMA communication system of  $K$  users, employing normalized spreading waveforms  $s_1, \dots, s_K$  with spreading gain  $N$ . User  $k$  (for  $1 \leq k \leq K$ ) transmits a frame of  $M$  independent equiprobable binary phase shift keying (BPSK) symbols<sup>1</sup>  $b_k(i) \in \{+1, -1\}$ ,  $0 \leq i \leq M-1$ ; and the symbol sequences from different users are assumed to be mutually independent. The  $k$ th user's signal  $x_k(t)$  propagates through a multipath channel with impulse response  $h_k(t)$ , whose transfer function  $H_k(f)$  is in the form of (1). The signal at the receiver is the superposition of the  $K$  users' signals plus the ambient noise.

Usually it is convenient to deal with a discrete-time sufficient statistic, which is derived by passing the received signal  $r(t)$  through a chip-matched filter and then sampling at the chip rate. For such an asynchronous multiuser multipath channel, a vector  $\mathbf{r}$  containing sufficient numbers

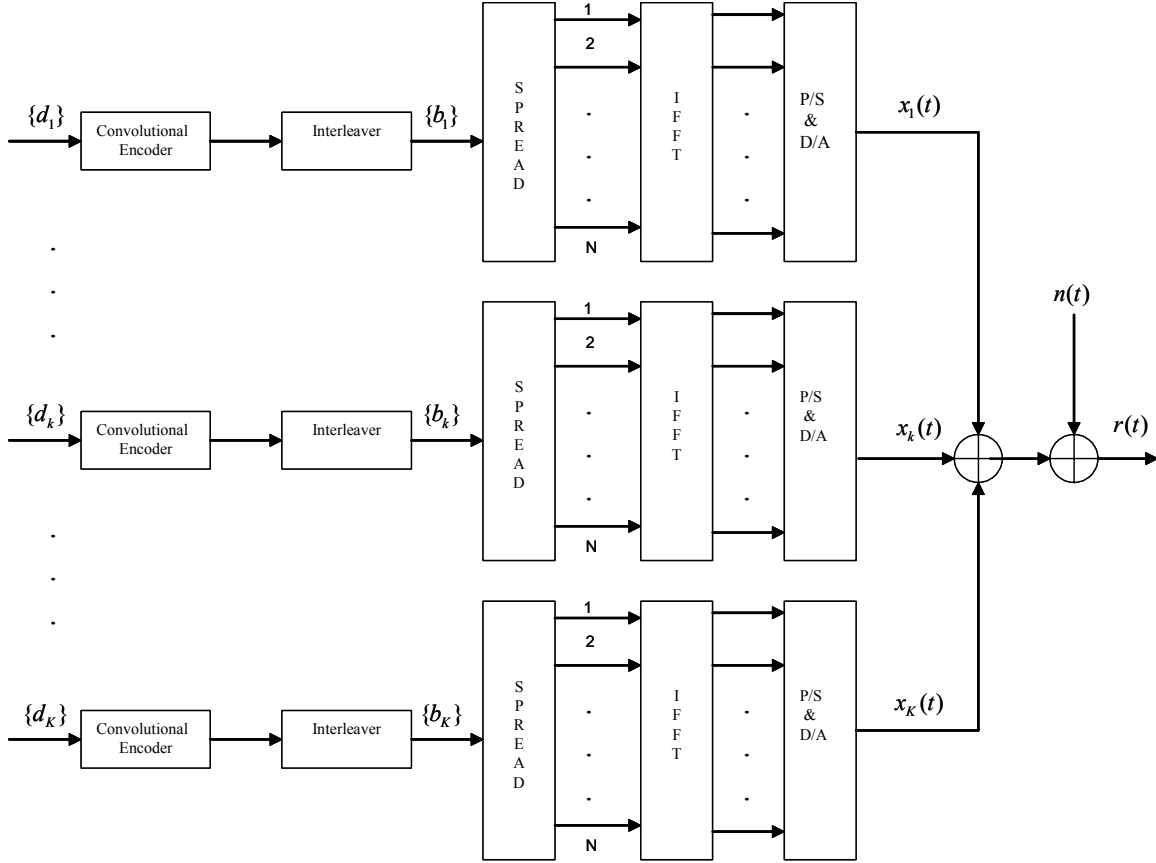
<sup>1</sup>  $\{b_k(i)\}$  may be encoded streams derived from underlying information symbols.

of samples should be collected without incurring loss of information, which after some analysis can be expressed in a succinct form

$$\mathbf{r} = \mathbf{F}\mathbf{b} + \mathbf{n}, \quad (2)$$

where  $\mathbf{b}$  and  $\mathbf{n}$  are the corresponding data and noise vector, respectively, and  $\mathbf{F}$  is a matrix capturing the cross-correlations between different symbols and different users.

MC-CDMA systems are the frequency-domain duals of DS-CDMA systems, in which the spreading is carried out in the frequency domain instead of the time domain. The effects of a frequency-selective channel can be analyzed in the frequency domain as convolution is replaced by multiplication. Let us assume for simplicity that the total bandwidth is divided into  $N$  subchannels with the center frequency of each subchannel given by  $f_{c,i} = \frac{i}{T} = \frac{i}{NT_c} = \frac{i}{N}B_T$ ,  $i = 1, \dots, N$ , where as before  $N$  is the processing gain,  $T$  is the symbol interval,  $T_c$  is the notional chip duration, and  $B_T$  is the total bandwidth. Each user assumes a transmitted signal in a form analogous DS-CDMA, but in the frequency domain. We assume that the subchannel bandwidth is less than the channel coherence bandwidth so that each subchannel experiences frequency-flat fading represented by a corresponding gain. It is straightforward to show that the received signal in the frequency domain is given by a same form as (2), where  $\mathbf{r}$  collects the discrete received spectrum in the  $N$  subcarriers,  $\mathbf{b}$  and  $\mathbf{n}$  are again the corresponding data and noise vector, respectively, and  $\mathbf{F}$  captures the compound channel characteristics in the frequency domain.



**Fig. 2 A coded multiuser MC-CDMA system**

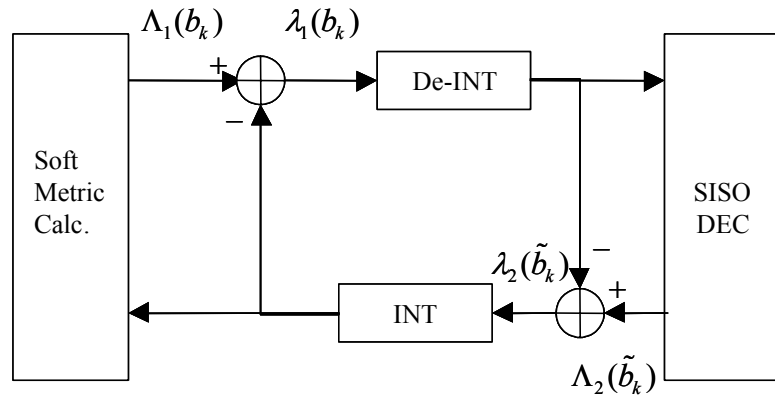
Since the received signals in DS-CDMA and MC-CDMA can be expressed in the same form, the receiver signal processing described below can be applied to either system. Consequently in the following, for simplicity, we will illustrate only MC-CDMA systems.

#### **IV. Turbo Multiuser Detection for Powerline Communications**

In Fig. 2, a convolutionally encoded multiuser MC-CDMA system is shown. For each user  $k$ ,  $1 \leq k \leq K$ , the information bits  $\{d_k\}$  are first encoded into coded bits with a standard binary convolutional encoder with code rate  $R$ . A code-bit interleaver is used to decorrelate the noise on the coded bits at the input of the channel decoder. The interleaved coded bits  $\{b_k\}$  are spread

across the  $N$  subchannels and mapped to quadrature amplitude modulation (QAM) signals. Then the conjugate-symmetric vector of length  $\bar{N} = 2N$  is transformed using the IFFT to get a real time-domain vector. After parallel-to-serial and digital-to-analog conversion, the signal of the  $k$ th user  $x_k(t)$  is transmitted into the channel, where it is corrupted by additive multiple-access signals and background noise. At the receiver end, after analog-to-digital and serial-to-parallel conversion, the received signal is transformed back to the frequency domain using an FFT, where it can be written as in (2).

Figure 3 shows the turbo structure for turbo multiuser detection and decoding. It consists of iteration between two stages: a soft metric calculator (the demodulation stage) and a soft-input soft-output (SISO) channel decoder (the decoding stage). The two stages are separated by an interleaver and a de-interleaver. A channel log-likelihood ratio (LLR) for the interleaved coded bit of the  $k$ th user is calculated as follows:



**Fig. 3 Turbo structure for iterative demodulation and decoding**

$$\Lambda_1(b_k) = \log \underbrace{\frac{p(\{r(t)\} | b_k = 1)}{p(\{r(t)\} | b_k = -1)}}_{\lambda_1(b_k)} + \log \underbrace{\frac{P(b_k = 1)}{P(b_k = -1)}}_{\lambda_2^p(b_k)},$$

where the second term  $\lambda_2^p(b_k)$  represents the *a priori* LLR delivered from the decoding stage in the previous iteration. For the first iteration, this term is set to zero if we assume equally likely coded bits. The first term  $\lambda_1(b_k)$ , denoting the extrinsic information obtained from the demodulation stage about the bit  $b_k$ , is then de-interleaved and sent to the channel decoder as its *a priori* information. Similarly, the SISO channel decoder computes the *a posteriori* LLR of each coded bit and then excludes the influence of *a priori* knowledge to get extrinsic information from the decoding stage about the bit  $\tilde{b}_k$  as

$$\lambda_2(\tilde{b}_k) = \Lambda_2(\tilde{b}_k) - \lambda_1^p(\tilde{b}_k) = \log \frac{P(\tilde{b}_k = 1 | \text{decoding})}{P(\tilde{b}_k = -1 | \text{decoding})} - \lambda_1^p(\tilde{b}_k),$$

where  $\tilde{b}_k$  is the de-interleaved version of  $b_k$ , alternatively the coded bits before the interleaver in Fig. 1. Again, this extrinsic information is interleaved and fed back to the demodulation stage as *a priori* knowledge for the next iteration. At the last iteration, the SISO decoder also computes the *a posteriori* LLRs for information bits, which are used to make final decisions.

In the demodulation stage, either optimum ML multiuser detection or sub-optimum MMSE parallel interference cancellation (PIC) can be used. We will show in Section V that these two schemes achieve the same performance, owing to the turbo processing. For the SISO decoding, either the optimum maximum *a posteriori* probability (MAP) algorithm or suboptimum Max-log-MAP or SOVA algorithms can be used. The reader is referred to [3] and [15] for details.

## V. Numerical Results

In this section, we simulate a multiple-access high-speed powerline communication channel with  $K = 4$  users, with which the proposed advanced signal processing techniques are tested and compared with some traditional detection techniques. The users are ordered by their distance to the line termination, with user 1 being the closest. For each user, the multipath weighting factors are independent normalized complex Gaussian random variables, and the lengths of paths are uniformly distributed within a certain range. The simulated channel frequency responses are shown in Fig. 1.

First we examine the immunity of single-carrier and MC-CDMA systems to frequency-selective fading channels and impulse noise. The single carrier system employs the carrier frequency of 3.5 MHz with a bandwidth of 0.5 MHz, with BPSK modulation. The MC-CDMA system occupies from 2 to 16 MHz with  $N = 28$  subchannels, the center frequencies (MHz) of which are given by  $f_n = 2 + 0.5(n-1)$ ,  $1 \leq n \leq 28$ . For each subchannel, BPSK modulation is used for simplicity. For ease of comparison, we assume a single-user uncoded system. The user of interest is user 1.

To simulate the influence of impulse noise, we adopt the commonly used two-term Gaussian mixture model as proposed in [5], [14]. The first-order probability density function of this noise model has the form  $(1-\varepsilon)\mathcal{N}(0, \sigma^2) + \varepsilon\mathcal{N}(0, \kappa\sigma^2)$  with  $\sigma > 0$ ,  $0 \leq \varepsilon \leq 1$ , and  $\kappa \geq 1$ . Here, the  $\mathcal{N}(0, \sigma^2)$  term represents the nominal background noise (Gaussian with zero mean and variance  $\sigma^2$ ), and the  $\mathcal{N}(0, \kappa\sigma^2)$  term represents an impulse component (Gaussian with zero mean and variance  $\kappa\sigma^2$ ), with  $\varepsilon$  representing the probability that impulses occur. In our simulation we choose parameters  $\varepsilon = 0.01$ , which means impulses occur with a 1% disturbance ratio [16].

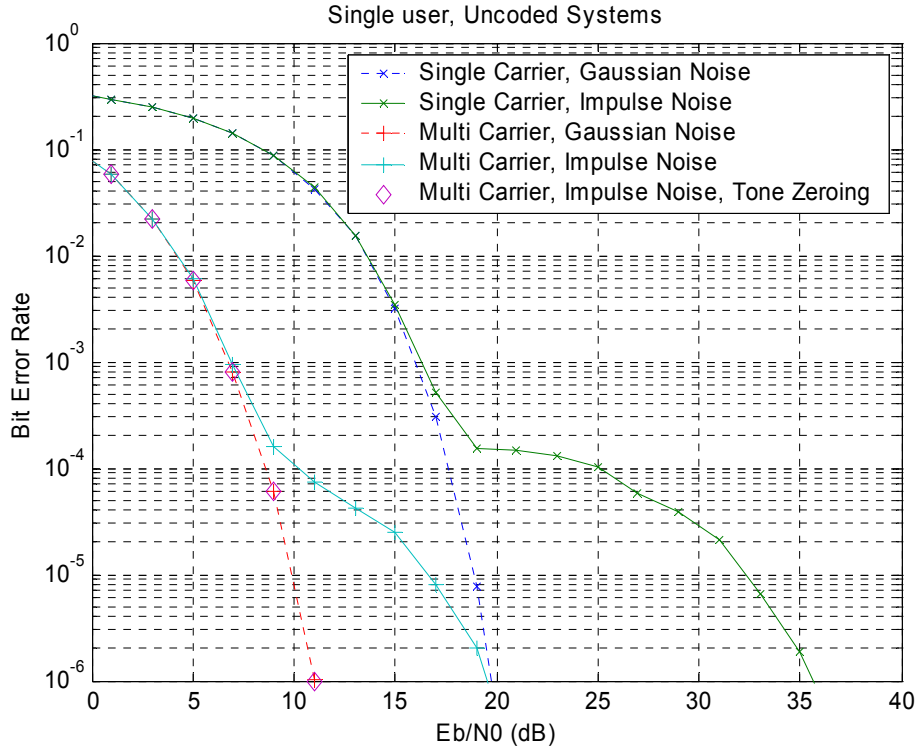
According to the observation in [16], when an impulse occurs, the noise PSD is colored and the overall power level is raised. Usually the spectral power of the impulse noise is concentrated in particular frequency ranges, due to the oscillating behavior of the impulse noise. In our simulation, we increase the noise PSD to 20dB higher for the frequency range of 3-6 MHz when an impulse occurs, and we set the impulse width to be of  $100 \mu s$ , lasting as long as 50 symbol intervals<sup>2</sup>.

From Fig. 4, we can see that, with the Gaussian background noise, MC-CDMA offers almost 10dB gain over the single carrier system at a bit-error-rate (BER) of  $10^{-6}$ . We have normalized the transmitted power of the parallel subchannels of the MC-CDMA system, so that they are compared for the same  $E_b / N_0$ . From Fig. 3 we see that there is a fading notch in the band of 3.5 MHz for user 1, which results in the poor performance of the single carrier system, while the inherent spectral diversity of the MC-CDMA system significantly improves the system performance. The MC-CDMA system is also more robust to the influence of the impulse noise, as we can see from the Fig. 4, for the same reasons. Furthermore, for the MC-CDMA system, the infected tones can be easily zeroed, resulting in almost no loss in system performance in the presence of impulse noise. The main challenge of tone zeroing<sup>3</sup> is in finding practical methods of obtaining fairly reliable channel state information. One may argue that the single carrier system can choose a favorable band for data communication, but this will add complexity to the transmitter and the protocols, and even may not be possible due to the rapid time-varying nature of powerline channels.

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<sup>2</sup> In our simulation, the symbol duration is  $2 \mu s$ .

<sup>3</sup> A form of erasure decoding.

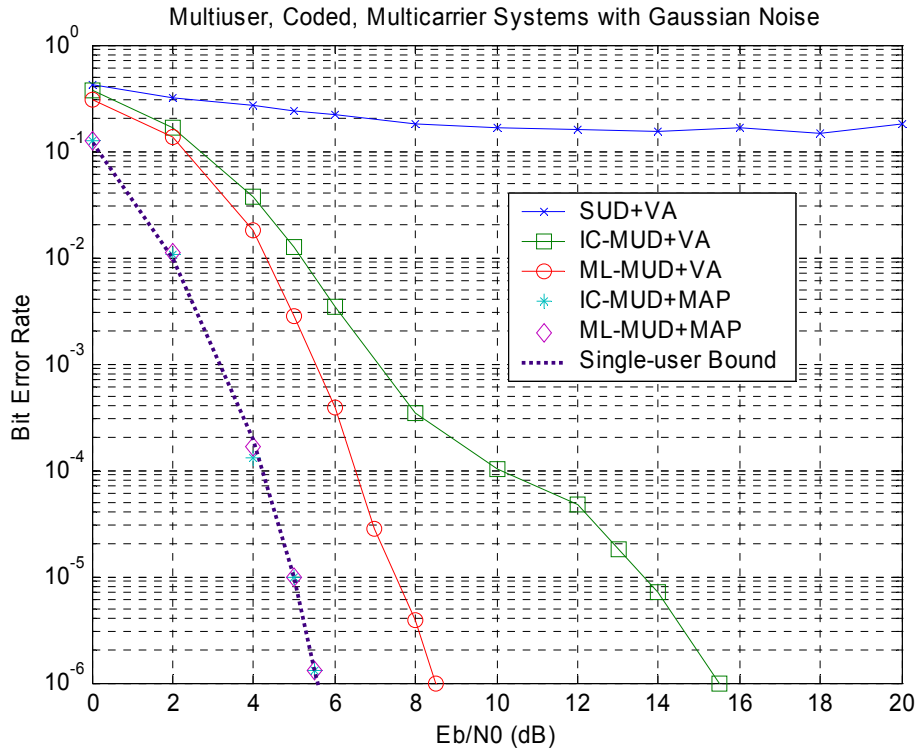


**Fig. 4 Performance comparison of single-carrier and MC-CDMA systems with Gaussian and impulse noise**

In Fig. 5, our proposed turbo multiuser detectors are tested with a coded multiuser MC-CDMA system as shown in Fig. 2, with the Gaussian background noise. A rate-1/2 convolutional code with constraint length 5 and generator polynomials  $[23, 35]_8$  is used for channel coding. The number of information bits per block per user is set as 996. Each user uses a different random interleaver of length 2000 for interleaving and de-interleaving. For simplicity, the spreading gain is set as  $N = 8$ , and the subchannels used are  $\{2, 3.5, 5, 6.5, 8, 9.5, 11, 12.5\}$  MHz<sup>4</sup>. The spreading code for each user is independently and randomly generated. The channel responses of the four users are given in Fig. 1. The user of interest is user 4, the weakest one<sup>5</sup>.

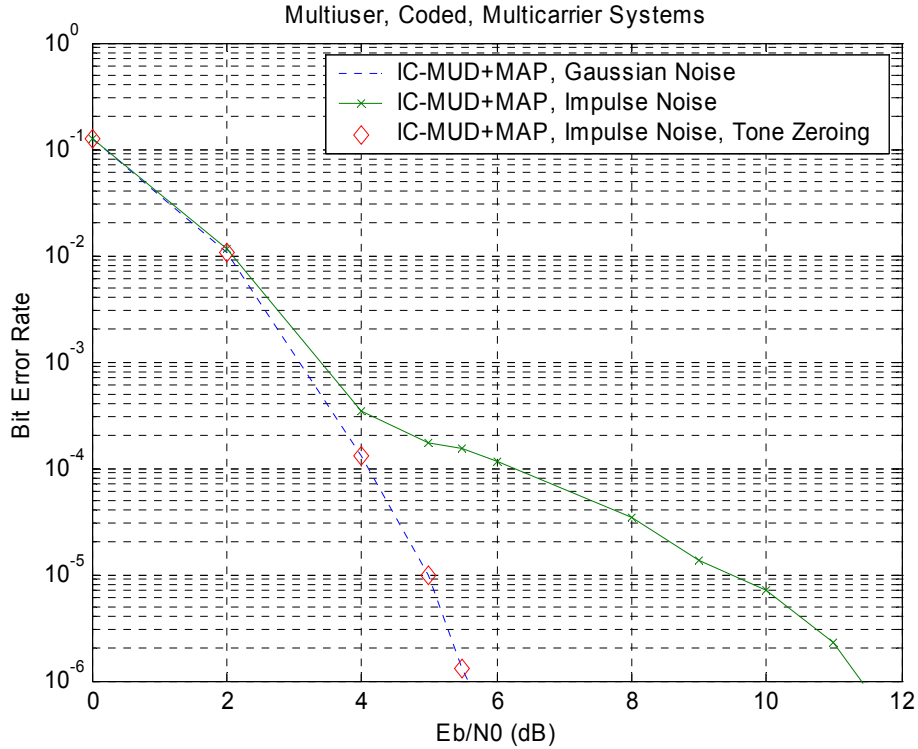
<sup>4</sup> These so-called comb spread carriers are commonly used for multiple access purposes to improve the frequency diversity.

<sup>5</sup> For ease of comparison and reference, the channel of user 4 has been normalized, and the other channels have been adjusted accordingly.



**Fig. 5 Performance Comparison of various detectors for coded MC-CDMA systems with multiple users and Gaussian noise**

There are six detectors of interest in Fig. 5. IC-MUD+MAP and ML-MUD+MAP are our proposed turbo multiuser receivers, with MMSE parallel interference cancellation or maximum likelihood demodulation stages, respectively, and a MAP decoding stage. IC-MUD+VA and ML-MUD+VA are their non-iterative counterparts: after multiuser detection, hard decisions are made on coded bits, then the Viterbi algorithm (VA) is used for decoding. Also shown in the figure is the traditional detection method, SUD+VA, which ignores the multiple-access interference and uses the classical single-user detector (SUD) followed by the VA, and the single user bound, which assumes no multiple-access interference.



**Fig. 6 Performance comparison of a proposed turbo multiuser receiver with Gaussian and impulse noise**

From Fig. 5 we can see that there is a substantial performance gap between the traditional single user detector and the single user bound. Optimum ML multiuser detection significantly narrows this gap down to 3dB at a BER of  $10^{-6}$ , but it suffers from a complexity exponentially increasing with the number of users. The suboptimum interference cancellation method, even though a good tradeoff between performance and complexity, suffers an extra 7dB loss. Both of our proposed turbo multiuser receivers, however, approach the single user bound. It is worth noting that IC-MUD+MAP achieves this excellent performance with reasonable computational complexity, making it very appealing for practical systems.

When the same impulse noise setting used in Fig. 4 is introduced, the performance of IC-MUD+MAP deteriorates about 5dB at a BER of  $10^{-6}$ , which is easily recovered by tone zeroing or erasure decoding, as seen in Fig. 6.

## VI. Conclusions and Discussions

In this paper, advanced signal processing techniques previously developed for DSL and wireless communications have been applied to high speed powerline communications and have been seen to achieved satisfactory results therein. To be specific, coded MC-CDMA systems have been employed for data transmission, and multiuser detection and turbo decoding have been used for data detection. The proposed communication systems achieve obvious advantages over single carrier systems with respect to time varying channel attenuation, multipath frequency-selective fading, and impulse noise. The proposed turbo multiuser receivers effectively mitigate the multiple-access interference and approach the single user bound. The detrimental effects of impulse noise to the proposed scheme are remedied through erasure decoding techniques.

Even though we adopt identical transmission schemes for all subcarriers of MCM systems in our study, for the reason given in Section II.1, adaptive transmission techniques are also of great interest in practice. For appropriate environment and applications, adapting code rate, power, or constellation size to the different conditions of subchannels is foreseen to substantially improve the system performance.

It is also noted that the proposed turbo multiuser receivers may still turn out to be too complex for some applications. For example, if some power lines exhibit quite good conditions (say, short-distance link with few branches), sub-optimum or even traditional receivers may be sufficient, with simpler structure and lower cost. This study is intended to demonstrate how advanced signal processing can potentially improve the communication quality for such an unfriendly channel. In this study, we have assumed that the receiver has knowledge of the channel. In practice, however, channel identification is needed, and the effects of channel estimation errors should be taken into consideration. The problem of detecting impulse spike

positions (for erasure decoding purposes), both in time and frequency, also deserves further study.

As a final comment we note that, besides the erasure decoding techniques considered in this paper, there is another effective scheme to combat impulse noise in conjunction with multiuser detection, based on the  $M$ -estimation method for robust regression. For white Gaussian noise, maximum likelihood detection is the same as least-squares (LS) regression. It is well known from the classic work of Tukey that least-squares estimates are very sensitive to the tail behavior of the probability density of measurement errors (represented here by the additive noise). Its performance depends significantly on the Gaussian assumption, and even a slight deviation of the noise density from the Gaussian distribution can, in principle, cause a substantial degradation of the LS estimate. The LS estimate can be robustified by using the class of  $M$ -estimators proposed by Huber. The reader is referred to [5] and [11], [14] for application of this technique to jointly combat the impulse noise and the multiple-access interference in DSL and wireless communications, respectively.

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