Advanced Signal Processing for Power Line Communications

Huaiyu Dai, North Carolina State University
H. Vincent Poor, Princeton University

ABSTRACT

In this article, 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 power distribution networks for Internet access and in-home/office networking. It is seen that multicarrier code-division multiple access, multiuser detection, and turbo decoding, having demonstrated their limit-approaching capacity in DSL and wireless communication systems, are readily applied to power line communications. In particular, it is argued that these methods can successfully mitigate the influence of the principal impairments in PLC channels: 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.

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 mile, is the bottleneck for Internet traffic. The increasing demand for home/office networks further necessitates flexible broadband network access.

Currently, among others, there are two major approaches to 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 for in-home networking, the power line is inherently the most attractive medium due to its almost 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 power line communications (PLC) 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 power line that need to be contended with are time-varying frequency-dependent channel attenuation of up to 60 dB, reflections from nonterminated points resulting in multipath fading, and various types of noise [1, 2]. Originally designed for power delivery rather than signal transmission, the power line has many less than ideal properties as a communications medium. Various loads connected to and disconnected from the power line 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 power line environment cannot be described by an additive white Gaussian noise (AWGN) model. According to [1], five types of noise can be found on power lines, among which the most unfavorable is perhaps 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 it may cause bit or burst errors, especially in high-speed data transmissions, during its occurrence. In addi-

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tion, 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 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 article we discuss signal processing techniques that are of interest in this context.

RELATED PROBLEMS AND CORRESPONDING TECHNIQUES IN DSL AND WIRELESS COMMUNICATIONS

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

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 [3]. However, in broadband applications on power line channels, these techniques have been shown to be inadequate for high-speed communications. The principal problem is 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 [4]. 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 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, that is, code-division multiple access (CDMA), and hence is widely used in practical communication systems.

MCM, following Shannon's optimum transmission suggestion, achieves the highest performance in channels with frequency-selective fading and severe ISI [5]. 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, 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

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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 that 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 subcarrier modulated by a single chip [6]. It can be seen that MC-CDMA is a frequency-domain dual of DS-CDMA, which will be further illustrated in the next section [7].

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.

ADVANCED SIGNAL PROCESSING AT THE RECEIVER

Multiuser detection (MUD) is well known to be an effective technique for dealing with multiple access interference [8]. It exploits the well-defined structure of multiuser interference, distinct from that of ambient noise, in order to improve system performance. MUD 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 nonideal channelization or multipath, or to combat co-channel interference from adjacent cells. MUD techniques include optimum maximum likelihood (ML) joint detection and various suboptimum linear and nonlinear methods. Linear MUD, 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. Nonlinear MUD, such as decision feedback (DF) MUD and successive interference cancellation (IC) MUD, often provides a favorable trade-off 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 [9]. 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 MUD*, which has drawn much attention recently [10]. Turbo MUD has demonstrated its limit-approaching capacity in DSL [11] and wireless [12] communication systems with Gaussian background noise.

COMBATING IMPULSE NOISE

As in PLC, short-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 and MCM are 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) [12]. 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 [11].

Given the similarities among DSL, wireless, and PL channels, techniques developed for the first two types of channels are natural candidates for application in PLC. 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. On forming a serially concatenated system at the transmitter through introducing an interleaver between coding and modulation modules, MUD and turbo decoding are used at the receiver for data detection and decoding, further details of which are given later. Some numerical results are given to demonstrate the performance of the proposed signal processing techniques, in comparison with traditional ones. Finally, we conclude the article and discuss some further interesting signal processing topics arising in this context.

POWER LINE COMMUNICATIONS MODEL

As PLC is still a rather new area, few standards have been established, especially for broadband applications. European standard EN 50065 specifies a frequency band of 3–148.5 kHz for LV mains signaling, which is clearly inadequate 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 1–10 Mb/s are needed, which may require use of up to several tens of megahertz of bandwidth. As part 15 of the FCC rules restricts PLC in the AM frequency band (535–1705 kHz), a reasonable range of frequencies for broadband application on power lines would be from 2 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 [2]:

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

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 k 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 accurate reproduction of power line channel behavior and will be used here as a basis for channel emulation [14]. In Fig. 1, simulated channel frequency responses of four users are shown, where the frequency-dependent attenuation and frequency selective fading can easily be seen.

Consider a direct sequence CDMA communication system of K users, employing normalized spreading waveforms $s_1, \ldots s_K$ with spreading gain N. User k (for $1 \le k \le K$) transmits a frame of M independent equiprobable binary phase shift keying (BPSK) symbols,[1] $b_k(i) \in \{+1,-1\}$, $0 \le i \le M-1$; and the symbol sequences from different users are assumed to be mutually independent. The kth 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 Eq. 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 of samples should be collected without incurring loss of information, which after some analysis can be expressed in a succinct form,

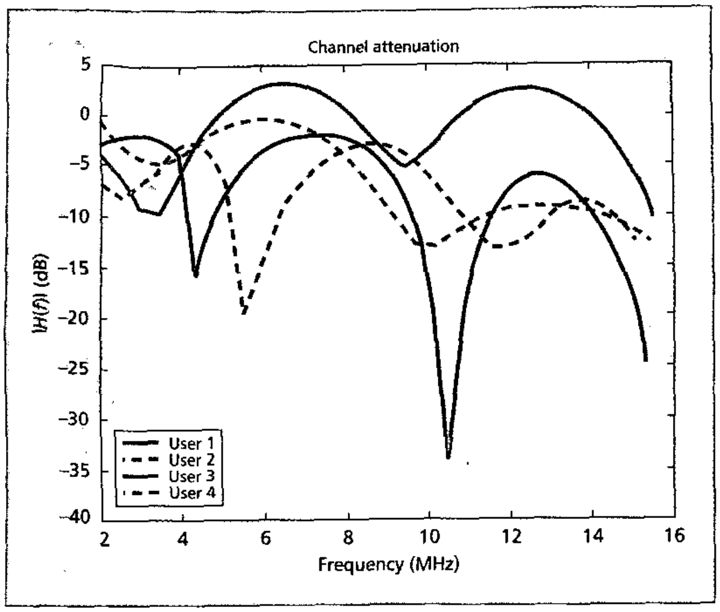

Figure 1. *Simulated channel frequency responses of four users.*

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

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

$$f_{c,i} = \frac{i}{T} = \frac{i}{NT_c} = \frac{i}{N} B_T, i = 1, \ldots N,$$

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 to 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 in the same form as Eq. 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.

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.

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[1] $\{b_k(i)\}$ *may be encoded streams derived from underlying information symbols.*

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 is in finding practical methods of obtaining fairly reliable channel state information.

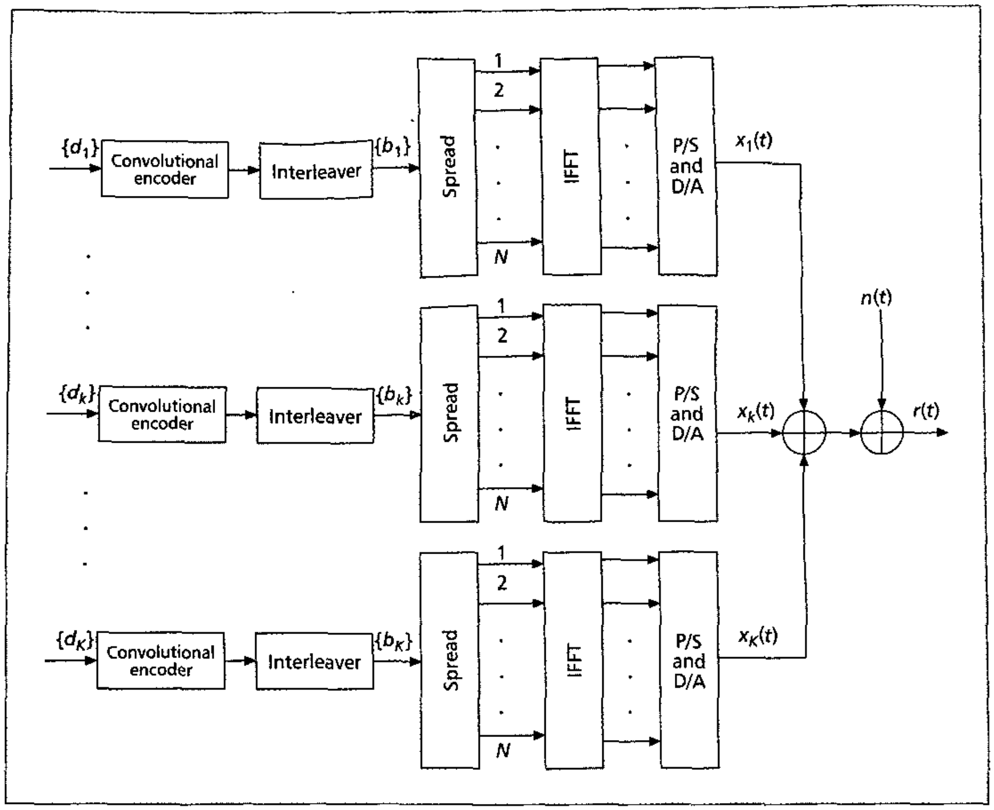


Figure 2. *A coded multiuser MC-CDMA system.*

TURBO MULTIUSER DETECTION FOR POWERLINE COMMUNICATIONS

In Fig. 2, a convolutionally encoded multiuser MC-CDMA system is shown. For each user k, $l \leq k \leq K$, 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 $\overline{N} = 2N$ 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 kth user is $x_k(t)$ 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 Eq. 2.

Figure 3 shows the turbo structure for turbo MUD 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 deinterleaver. A channel log-likelihood ratio (LLR) for the interleaved coded bit of the kth user is calculated as follows:

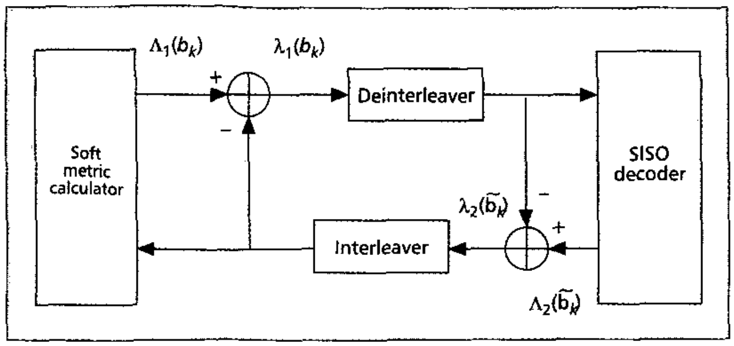
$$\Lambda_1(b_k) = \underbrace{\log\frac{p(\{r(t)\}\,|\,b_k=1)}{p(\{r(t)\}\,|\,b_k=-1)}}_{\lambda_1(b_k)} + \underbrace{\log\frac{P(b_k=1)}{Pb_k=-1)}}_{\lambda_2^p(b_k)},$$

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 deinterleaved 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

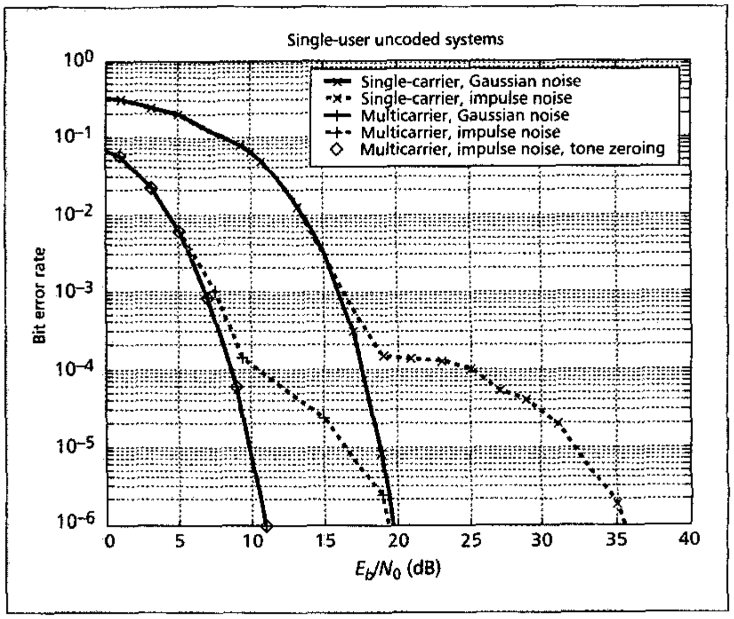
$$\lambda_2(\tilde{b}_k) = \Lambda_2(\tilde{b}_k) - \lambda_2^p(\tilde{b}_k) = \log\frac{P(\tilde{b}_k=1\,|\,\text{decoding})}{P(\tilde{b}_k=-1\,|\,\text{decoding})} - \lambda_1^p(\tilde{b}_k),$$

where $\tilde{b}_k$ is the deinterleaved 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 MUD or suboptimum MMSE parallel interference cancellation (PIC) can be used. We will show later that these two schemes achieve the same performance, due 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 [12, 15] for details.



■ **Figure 3.** *Turbo structure for iterative demodulation and decoding.*



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

NUMERICAL RESULTS

In this section we simulate a multiple access high-speed PLC 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 [16, 17]. 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 σ^2), and the $\mathcal{N}(0,\kappa\sigma^2)$ term represents an impulse component (Gaussian with zero mean and variance $\kappa\sigma^2$), with ε representing the probability that impulses occur. In our simulation we choose $\varepsilon = 0.01$, which means impulses occur with a 1 percent disturbance ratio [1]. According to the observation in [1], 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 oscillatory behavior of the impulse noise. In our simulation, we increase the noise PSD to 20 dB higher for the frequency range of 3–6 MHz when an impulse occurs, and we set the impulse width to be 100 μs, lasting as long as 50 symbol intervals.[2]

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 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[3] 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.

In Fig. 5, our proposed turbo multiuser detectors are tested with a coded multiuser MC-CDMA system as shown in Fig. 2, with 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

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[2] *In our simulation, the symbol duration is 2 μs.*

[3] *A form of erasure decoding.*

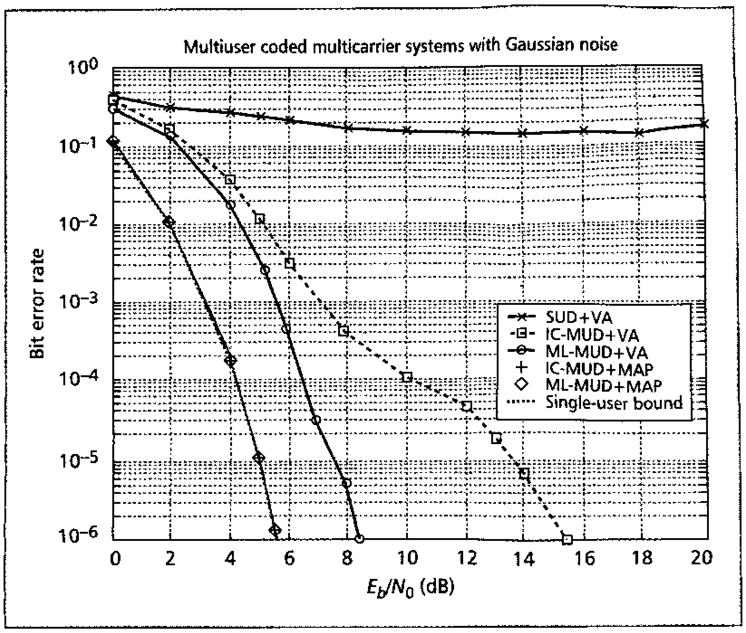

Figure 5. *Performance comparison of various detectors for coded MC-CDMA systems with multiple users and Gaussian noise.*

deinterleaving. 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.[4] 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.[5]

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 noniterative counterparts: after MUD, 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.

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 MUD significantly narrows this gap to 3 dB at a BER of 10^{-6}, but it suffers from a complexity exponentially increasing with the number of users. The suboptimum interference cancellation method, although a good trade-off between performance and complexity, suffers an extra 7 dB 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 5 dB at a BER of 10^{-6}, which is easily recovered by tone zeroing or erasure decoding, as seen in Fig. 6.

CONCLUSIONS AND DISCUSSIONS

In this article advanced signal processing techniques previously developed for DSL and wireless communications are applied to high-speed power line communications and are seen to achieve satisfactory results therein. To be specific, coded MC-CDMA systems are employed for data transmission, and multiuser detection and turbo decoding are 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 earlier, adaptive transmission techniques are also of great interest in practice. For the appropriate environment and applications, adapting code rate, power, or constellation size to the different conditions of subchannels is foreseen to substantially improve 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, a short-distance link with few branches), suboptimum 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), in both time and frequency, also deserves further study.

As a final comment we note that, besides the erasure decoding techniques considered in this article, there is another effective scheme to combat impulse noise in conjunction with MUD, 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 substantial degradation of the LS estimate. The LS estimate can be made more robust by using the class of M-estimators proposed by Huber. The reader is referred to

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[4] *These so-called comb spread carriers are commonly used for multiple access purposes to improve frequency diversity.*

[5] *For ease of comparison and reference, the channel of user 4 has been normalized, and the other channels have been adjusted accordingly.*

[16–18] for application of this technique to jointly combat the impulse noise and multiple access interference in DSL and wireless communications.

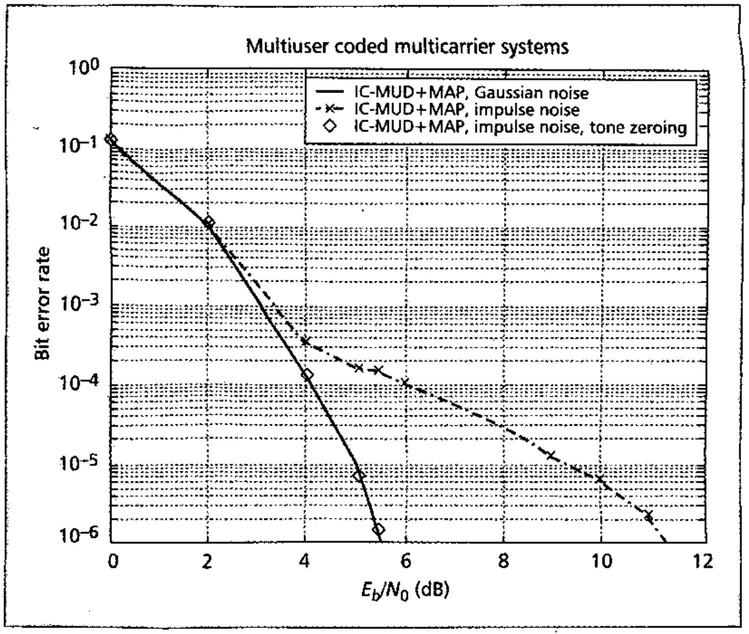

Figure 6. *Performance comparison of a proposed turbo multiuser receiver with Gaussian and impulse noise.*

REFERENCES

[1] M. Zimmermann and K. Dostert, "Analysis and Modeling of Impulse Noise in Broadband Powerline Communications," *IEEE Trans. Electromagnetic Compatibility*, vol. 44, no. 1, Feb. 2002, pp. 249–58.

[2] M. Zimmermann and K. Dostert, "A Multipath Model for the Powerline Channel," *IEEE Trans. Commun.*, vol. 50, no. 4, Apr. 2002, pp. 553–59.

[3] H. C. Ferreira *et al.*, "Power Line Communications: An Overview," *Proc. IEEE 4th AFRICON*, vol. 2, Stellenbosch, South Africa, Sept. 1996, pp. 558–63.

[4] D. Raphaeli and E. Bassin, "A Comparison Between OFDM, Single Carrier, and Spread Spectrum for High Data Rate PLC," *Proc. 1999 Int'l. Symp. Power Line Commun. and Its Apps.*, Lancaster, U.K., Mar. 1999.

[5] J. A. C. Bingham, "Multicarrier Modulation for Data Transmission: An Idea Whose Time Has Come," *IEEE Commun. Mag.*, vol. 28, no. 5, May 1990, pp. 5–14.

[6] A. C. McCormick and E. A. Al-Susa, "Multicarrier CDMA for Future Generation Mobile Communication," *Elec. and Commun. J.*, Apr. 2002, pp. 52–60.

[7] W. Nabhane and H. V. Poor, "Blind Joint Equalization and Multiuser Detection in Dispersive MC-CDMA/MC-DS-CDMA/MT-CDMA Channels," *Proc. 2002 IEEE Military Commun. Conf.*, Anaheim, CA, Oct. 7–10, 2002.

[8] S. Verdú, *Multiuser Detection*, Cambridge Univ. Press, 1998.

[9] C. Berrou *et al.*, "Near Shannon Limit Error-Correction Coding and Decoding: Turbo Codes," *Proc. 1993 IEEE ICC*, Geneva, Switzerland, May 1993, pp. 1064–70.

[10] H. V. Poor, "Turbo Multiuser Detection: A Primer," *J. Commun. and Networks*, vol. 3, no. 3, pp. 196–201, Sept. 2001.

[11] H. Dai and H. V. Poor, "Turbo Multiuser Detection for Coded DMT VDSL Systems," *IEEE JSAC*, vol. 20, no.2, Feb. 2002, pp. 351–62.

[12] X. Wang and H. V. Poor, "Iterative (Turbo) Soft Interference Cancellation and Decoding for Coded CDMA," *IEEE Trans. Commun.*, vol. 47, no. 7, July 1999, pp. 1046–61.

[13] T. N. Zoagakis *et al.*, "Impulse Noise Mitigation Strategies for Multicarrier Modulation," *Proc. 1993 IEEE ICC*, vol. 2, Geneva, Switzerland, May 1993, pp. 784–83.

[14] M. Götz and K. Dostert, "A Universal High Speed Powerline Channel Emulation System," *Proc. 2002 Int'l. Zurich Sem. Broadband Commun.: Access, Transmission, Networking*, Zurich, Switzerland, Feb. 2002, pp. 24-1–6.

[15] H. Dai and A. F. Molisch, "Multiuser Detection for Interference-Limited MIMO Systems," *Proc. 2002 Spring IEEE VTC*, Birmingham, AL, May 2002, CDROM.

[16] H. Dai and H. V. Poor, "Crosstalk Mitigation in DMT VDSL with Impulse Noise," *IEEE Trans. Circuits and Sys. I: Fundamental Theory and Apps.*, vol. 48, no. 10, Oct. 2001, pp. 1205–13.

[17] X. Wang and H. V. Poor, "Robust Multiuser Detection in Non-Gaussian Channels," *IEEE Trans. Commun.*, vol. 47, no. 2, Feb. 1999, pp. 289–305.

[18] H. V. Poor and M. Tanda, "Multiuser Detection in Flat Fading Non-Gaussian Channels," *IEEE Trans. Commun.*, vol. 50, no. 11, Nov. 2002, pp. 1769–77.

BIOGRAPHIES

HUAIYU DAI [M] (Huaiyu_Dai@ncsu.edu) received his B.E. and M.S. degrees in electrical engineering from Tsinghua University, Beijing, China, in 1996 and 1998, respectively, and his Ph.D. degree in electrical engineering from Princeton University, New Jersey, in 2002. He worked at Bell Labs, Lucent Technologies, Holmdel, New Jersey, during summer 2000, and at AT&T Labs-Research, Middletown, New Jersey, during summer 2001. Currently he is an assistant professor of electrical and computer engineering at North Carolina State University, Raleigh. His research interests are in the general areas of communication systems and networks, advanced signal processing for digital communications, and communication theory and information theory. He has worked in the areas of digital communication system design, speech coding and enhancement, and DSL transmission. His current research focuses on space-time processing, the turbo principle and its applications, multiuser detection, and the information-theoretic aspects of multiuser communications and networks.

H. VINCENT POOR [F] (poor@princeton.edu) received his Ph.D. degree in EECS in 1977 from Princeton University, where he is currently a professor of electrical engineering. He is also affiliated with Princeton's Department of Operations Research and Financial Engineering, and with its Program in Applied and Computational Mathematics. From 1977 until he joined the Princeton faculty in 1990, he was a faculty member at the University of Illinois at Urbana-Champaign. He has also held visiting and summer appointments at several universities and research organizations in the United States, Britain, and Australia. His research interests are primarily in the area of statistical signal processing, with applications in wireless communications and related areas. Among his publications in this area is the forthcoming book, *Wireless Communication Systems: Advanced Techniques for Signal Reception*. He is a member of the National Academy of Engineering, and is a Fellow of the Acoustical Society of America, the American Association for the Advancement of Science, the Institute of Mathematical Statistics, and the Optical Society of America. His IEEE activities include serving as President of the IEEE Information Theory Society in 1990, and as a member of the IEEE Board of Directors, 1991–1992. Among his recent honors are an IEEE Third Millennium Medal (2000), the IEEE Graduate Teaching Award (2001), the Joint Paper Award of the IEEE Communications and Information Theory Societies (2001), the NSF Director's Award for Distinguished Teaching Scholars (2002), and a Guggenheim Fellowship (2002–2003).