On the mitigation of impulse noise using a MC-CDMA iterative solution for Broadband over Powerline Communications

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***Abstract*— Power Line Communication (PLC) is predicted as a prospective solution for indoor and outdoor communications over power supplies. Broadband over Power Lines (BPL) uses a large bandwidth to provide high-speed Internet services to the end user. However, the channel exhibits high frequency selectivity and impulse noise, requesting modern signal processing methods. Orthogonal Frequency Division Multiplex (OFDM) modulation and spreading techniques are known to mitigate these negative properties when combined with iterative receivers. This paper gives the full characterization of a Multi-Carrier Code Division Multiple Access (MC-CDMA) transceiver associating high-order modulations, OFDM, spreading, interleaving and channel decoding with an iterative process. Then, the simulation results will focus on the impulse noise palliation by means of symbol interleaving between spreading and OFDM modulation.**

I. Introduction

The growing demand for high-speed Internet services on the last mile access calls for new paradigms having an increased capacity and better performance using existing or ongoing infrastructures such as copper loops for Digital Subscriber Line (x-DSL), cable or Fiber-To-The-Home (FTTH). Service providers begin to use the Low Voltage (LV) cables as an alternative technology for digital communications to offer more bandwidth to the end user. Power Line Communication (PLC) allows indoor (household Local Area Networks) and outdoor Broadband over Power Lines (BPL) communications over the 50 or 60 Hz power supplies. The numerous devices plugged in the PLC architecture leads to a high frequency selective channel with impulse noise, requesting modern signal processing methods [1]. Recent standards for PLC use Orthogonal Frequency Division Multiplex (OFDM) modulation which are known to mitigate Inter-Symbol Interference (ISI). The recent paper [2] proposes an iterative receiver with Multi-Carrier Code Division Multiple Access (MC-CDMA) to remove Multiple Access Interference (MAI) and ISI along with erasure decoding techniques to counteract the detrimental effect of impulse noise.

MC-CDMA operates data spreading in the frequency domain using unitary matrices to provide the set of spreading codes [3], [4]. While the original definition of MC-CDMA states that the N_u users spread their data using spreading codes of length L_c which are equal to the number of subcarrier N_c, a larger definition of MC-CDMA allows $N_c \neq L_c$ using a mixture of TDMA, FDMA and CDMA by means of spreading and OFDM modulation, even including the Spread-Spectrum-Multi-Carrier Multiple Access (SS-MC-MA) technique combining spreading with Frequency Division Multiple Access (FDMA) where the data is spread on a user by user basis [5]. In 1993, the original work of [9] opened a new field leading to numerous iterative receivers combining equalization and channel decoding with lower complexity than joint Maximum Likelihood (ML) receivers. For a MC-CDMA iterative receiver, MAI and ISI are cancelled from the received signal to allow a better reliability on the decoded data for the next iteration.

Firsly, the goal of this paper is to give the full characterization of a MC-CDMA transceiver associating high-order modulations, OFDM, spreading, interleaving and channel decoding with an iterative process over realistic PLC channels. Then, this article will focus on the impulse noise palliation by means of symbol interleaving between spreading and OFDM modulation contrary to the previous literature which uses erasure decoding techniques for impulse noise mitigation.

The intensive measurements over the PLC channel are used as input to a tapped delay line channel along with adequate parameter setup. The performance of the iterative receiver is analysed through simulation results with and without symbol interleaving over realistic channels with impulse noise. The proposed transceiver is mainly intended to a downlink MC-CDMA transmission but can also be applied to an uplink SS-MC-MA or another access scheme using a mixture of FDMA, TDMA, CDMA associating OFDM and a spreading operation over PLC.

The paper is organised as follows: Section II describes the PLC channel model and the impulsive noise. Section III presents the MC-CDMA transceiver. The transceiver basically consists of a channel coding, bit interleaving, mapping, spreading, symbol interleaving, OFDM modulator, PLC channel, OFDM demodulator, channel equalization, symbol deinterleaving, despreading, soft demapping, bit deinterleaving, channel decoding, interference canceller. The channel equalization and the interference canceller are based on linear Minimum Mean Square Error (MMSE) while channel decoding uses Soft Output Viterbi Algorithm (SOVA). Simulation results with impulse noise over a realsitic PLC channel and adequate parameters are given Section IV.

II. The PLC channel and impulse noise

The PLC architecture consists of a shared bus containing numerous connections that cause reflections leading to a frequency selective channel. Moreover, in Broadband over Power Lines (BPL), two classes of noise is harmful to the transmission [7]. The first class of noise is the background noise which usually remains stationary over minutes or hours. The second class of noise is impulsive noise which leads to a higher Power Spectral Density (PSD) over microseconds or milliseconds causing burst errors. The mathematical description of the PLC channel in the frequency domain proposed in [6] is:

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

where g_i are the weighting factors, a_o, a_1 the attenuation factors, k is the exponent of the attenuation factor, N_p the number of paths and d_i the length of these paths, v_p is the propagation velocity of the cable. An inverse DFT of this frequency response gives the channel impulse response.

In [1], complete parameters of four channel models are proposed which reflect typical channel characteristics observed in measurements. These channels can change abruptly during the day depending on the connections joints enabled or disabled, but they are slowly time-varying channels. Therefore, we assume a constant channel through the time of simulation.

As seen in the previous paragraph, the noise in powerline channels is a mixture of background noise and impulsive noise. Because impulse noise can appear in long bursts, it is necessary to include interleaving in our communication chain to allow spreading and channel coding to lower its impact.

III. Iterative MC-CDMA Transceiver

The transmitter is explained as follows. First, input bits feed a convolutional encoder. Then, a symbol mapping transforms the output into a Quadrature Amplitude Modulation (QAM) coded vector $\mathbf{x}$ of length NN_u. This vector is spread by a matrix $\mathbf{C} = \mathbf{I}_N \otimes \mathbb{C}$ with $\mathbb{C}$ of size $L_c \times N_u$, where N_u is the number of users and L_c the length of the spreading codes, resulting in $\mathbf{s} = \mathbf{Cx}$. For the original MC-CDMA, the spreading matrix is an orthogonal Walsh-Hadamard matrix. However, other real or complex valued unitary matrices can be used, for instance Fourier matrices or Vandermonde matrices. A symbol interleaver $\mathbf{\Pi}_s$ of size $NL_c \times NL_c$ is then applied to the spread signal. The interleaved data go through an OFDM modulator which performs an Inverse Fast Fourier Transform (IFFT) operation $\mathbf{F}^H$ on the spread data concatenated with its mirrored conjugate $\mathbf{s}' = [s_1 \dots s_{N_c} s^*_{N_c} \dots s^*_1]$, where N_c is the number of subcarriers (subscript $[.]^H$ denotes the transpose conjugate). The IFFT operation is followed by a guard interval insertion, i.e. the last $L-1$ symbols of a block are prepended at the beginning of the block, where L is length of the cyclic prefix. The baseband signal is then transmitted into the PLC channel which is represented by a Toeplitz matrix $\mathbf{H}$, Additive White Gaussian Noise (AWGN) and impulse noise $\mathbf{n}$'. The impulse noise PSD is significantly higher than the PSD of AWGN. At the receive side, orthogonality between subcarriers is restored by an OFDM demodulator. The first stage consists of the removal of the guard interval which is longer than the impulse response of the channel to guarantee the absence of intersymbol interference. The channel matrix $\mathbf{H}$ is therefore transformed into an equivalent circulant matrix $\tilde{\mathbf{H}}$. Finally, an FFT operation $\mathbf{F}$ is applied on the resulting sequence leading to a diagonal channel matrix of independent frequency responses. The received vector $\mathbf{r}'$ of length $2N_c$ is given by:

$$\mathbf{r}' = \mathbf{F}\tilde{\mathbf{H}}\mathbf{F}^H \mathbf{s}' + \mathbf{n}' \qquad (2)$$

The last N_c symbols of $\mathbf{r}'$ are discarded. The OFDM component of the MC-CDMA signal converts the frequency selective fading channel into multiple parallel flat fading subchannels. The equivalent received vector $\mathbf{r}$ of length NL_c is equal to:

$$\mathbf{r} = \mathbf{\Lambda}\mathbf{\Pi}_s \mathbf{C}\mathbf{x} + \mathbf{n} \qquad (3)$$

where $\mathbf{n}$ is the AWGN vector of length NL_c. $\mathbf{\Lambda}$ is a diagonal matrix of size $NL_c \times NL_c$, where each diagonal element of the matrix corresponds to the frequency response of the channel for the corresponding subcarrier. The receiver consists of an iterative process represented on Figure 1 and can be written as follows:

Iterative Receiver Algorithm

- MMSE equalization:
  $\hat{\mathbf{s}} = \mathbf{G}\mathbf{r}$ with $\mathbf{G} = (\mathbf{\Lambda}^H\mathbf{\Lambda} + \frac{1}{\gamma}\mathbf{I})^{-1}\mathbf{\Lambda}^H$
- Symbol deinterleaving $\mathbf{\Pi}_s^{-1}$
- Despreading:
  $\hat{\mathbf{x}} = \mathbf{C}^H \hat{\mathbf{s}}$
- BEGIN LOOP
  - Soft demodulation:
    $LLR_i^{pri} = log\left(\frac{Pr(b_i=0|\hat{x})}{Pr(b_i=1|\hat{x})}\right)$
  - Bit deinterleaving $\mathbf{\Pi}_b^{-1}$
  - A posteriori LLR calculation (channel decoding):
    $LLR_i^{post} = log\left(\frac{Pr(b_i=0|decoding)}{Pr(b_i=1|decoding)}\right)$
  - Bit interleaving $\mathbf{\Pi}_b$
  - Soft Modulation:
    $Re(\tilde{x}) = f(LLR_i^{post})$
    $Im(\tilde{x}) = g(LLR_i^{post})$
    where f and g are non linear functions.
  - Iterative Canceller
    $\hat{\mathbf{x}} = (diag\Gamma + \frac{1}{\gamma}\mathbf{I})^{-1}(\mathbf{C}^H\mathbf{\Pi}_s^{-1}\mathbf{\Lambda}^H\mathbf{r} - (\Gamma - diag\Gamma)\tilde{\mathbf{x}})$
    with $\Gamma = \mathbf{C}^H\mathbf{\Pi}_s^{-1}\mathbf{\Lambda}^H\mathbf{\Lambda}\mathbf{\Pi}_s\mathbf{C}$
- END LOOP

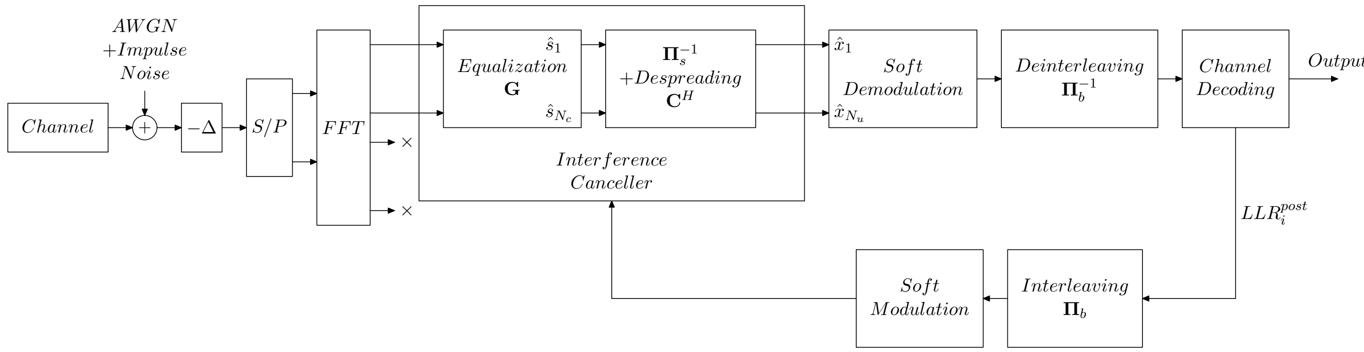

Fig. 1. Iterative receiver of a MC-CDMA system in a PLC transmission

First, an MMSE equalizer $\mathbf{G}$ is applied which is a diagonal matrix containing the equalization coefficients correcting the amplitude and phase variations of the channel frequency responses where γ is the Signal to Noise Ratio (SNR) at the receiver. Then, the symbol deinterleaving and the despreading operation are carried out on the output vector to produce an estimated vector $\hat{\mathbf{x}}$ of length NN_u. Then a soft demodulation is applied assuming equally likely transmitted bits. The soft demodulation calculates the a priori Log Likelihood Ratios (LLRs). For instance, assuming a rectangular QAM with gray mapping and following the reference [8], the QAM modulation is represented by two Pulse Amplitude Modulation (PAM), one in-phase an the other in quadrature. For a 64-QAM, the associated PAM is represented by:

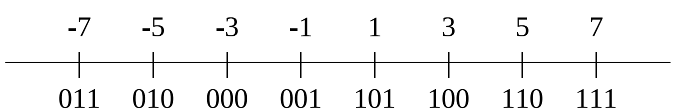

Fig. 2. Gray Mapping for the corresponding PAM of a rectangular 64-QAM modulation

This formula can be approximated for the in-phase bits of a 64-QAM as:

$$\begin{aligned} LLR_1^{Pri} &= log\left(\frac{Pr(b_1=0|\hat{x})}{Pr(b_1=1|\hat{x})}\right) \approx Re(\hat{x}) \\ LLR_2^{Pri} &= log\left(\frac{Pr(b_2=0|\hat{x})}{Pr(b_2=1|\hat{x})}\right) \approx |\,Re(\hat{x})| - 4 \\ LLR_3^{Pri} &= log\left(\frac{Pr(b_3=0|\hat{x})}{Pr(b_3=1|\hat{x})}\right) \approx ||\,Re(\hat{x})| - 4| - 2 \end{aligned} \quad (4)$$

For the quadrature bits of the 64-QAM, the a priori probabilities are expresssed as:

$$\begin{aligned} LLR_4^{Pri} &= log\left(\frac{Pr(b_4=0|\hat{x})}{Pr(b_4=1|\hat{x})}\right) \approx Im(\hat{x}) \\ LLR_5^{Pri} &= log\left(\frac{Pr(b_5=0|\hat{x})}{Pr(b_5=1|\hat{x})}\right) \approx |\,Im(\hat{x})| - 4 \\ LLR_6^{Pri} &= log\left(\frac{Pr(b_6=0|\hat{x})}{Pr(b_6=1|\hat{x})}\right) \approx ||\,Im(\hat{x})| - 4| - 2 \end{aligned} \quad (5)$$

After deinterleaving, the channel decoding processes the soft information and computes the a posteriori LLR on coded bits. A forward-backward Bahl-Cocke-Jelinek-Raviv (BCJR) algorithm or a SOVA as described in [9] can be implemented. Then, the a posteriori LLRs are reinterleaved and a soft binary to M-ary conversion is applied in order to estimate the transmitted symbols. For the 64-QAM, the soft modulation for the in-phase bits can be expressed as:

$$\begin{aligned} Re(\tilde{x}) = \Big[&-7(e^{(LLR_2^{Post}+LLR_3^{Post})}) - 5(e^{LLR_2^{Post}}) \\ &-3 - 1(e^{LLR_3^{Post}}) + 1(e^{(LLR_1^{Post}+LLR_3^{Post})}) \\ &+3(e^{LLR_1^{Post}}) + 5(e^{(LLR_1^{Post}+LLR_2^{Post})}) \\ &+7(e^{(LLR_1^{Post}+LLR_2^{Post}+LLR_3^{Post})})\Big] \\ / \Big[&(e^{LLR_1^{Post}}+1)(e^{LLR_2^{Post}}+1)(e^{LLR_3^{Post}}+1)\Big] \end{aligned} \quad (6)$$

For the quadrature bits the soft modulation is expressed as:

$$\begin{aligned} Im(\tilde{x}) = \Big[&-7(e^{(LLR_5^{Post}+LLR_6^{Post})}) - 5(e^{LLR_5^{Post}}) \\ &-3 - 1(e^{LLR_6^{Post}}) + 1(e^{(LLR_4^{Post}+LLR_6^{Post})}) \\ &+3(e^{LLR_4^{Post}}) + 5(e^{(LLR_4^{Post}+LLR_5^{Post})}) \\ &+7(e^{(LLR_4^{Post}+LLR_5^{Post}+LLR_6^{Post})})\Big] \\ / \Big[&(e^{LLR_4^{Post}}+1)(e^{LLR_5^{Post}}+1)(e^{LLR_6^{Post}}+1)\Big] \end{aligned} \quad (7)$$

Finally, an Interference Canceller (IC) is applied to the resulting vector which reconstructs the transmitted signal with the estimated version of the transmitted symbols. The MMSE-IC formula takes into account the channel in the frequency domain, the symbol interleaving and the spreading codes:

$$\hat{\mathbf{x}} = (diag\Gamma + \frac{1}{\gamma}\mathbf{I})^{-1}(\mathbf{C}^H\mathbf{\Pi}_s^{-1}\mathbf{\Lambda}^H\mathbf{r} - (\Gamma - diag\Gamma)\tilde{\mathbf{x}}) \quad (8)$$

with $\Gamma = \mathbf{C}^H\mathbf{\Pi}_s^{-1}\mathbf{\Lambda}^H\mathbf{\Lambda}\mathbf{\Pi}_s\mathbf{C}$. This MMSE-IC allows the MAI and the ISI to be suppressed iteratively.

Considering Channel State Information (CSI) at the transmit side, an adaptive MC-CDMA system can be build. Depending on the channel conditions, power-loading and bit-loading techniques can be used to transmit more bits on advantageous frequencies. However, for an adaptive MC-CDMA scheme, the spread data should belong to the same order of modulation which is determined by the Shannon's equation $C_i = log_2(1 + SNR.|h_i|^2)$ for each subcarrier. Therefore, the spectrum is divided into block of frequencies having the same order of modulation, the high-order modulations being favourable to low frequencies because of the frequency attenuation of the cable. In the following simulation results, several order of

Bandwidth	25 MHz
Sampling Rate	50 MHz
Modulation	QPSK, 16QAM, 64QAM
FFT size $2N_c$	4096
Cyclic Prefix	256
Channel Coding	Convolutional Code $(133, 171)_o$
Spreading type	Fourier matrix
Spreading length L_c	2048
Bit interleaver	2048
Symbol interleaver	2048, 204800
Channel decoding	SOVA
Number of iterations	4

TABLE I
SIMULATION PARAMETERS

RC4 attenuation term:		
k=1	a_0=0	a_1= 4.5 10^{-9}
RC4 path parameter:		
i	g_i	d_i
1	0.26	300
2	0.05	350
3	-0.3	370
4	0.25	450
5	-0.35	510

TABLE II
REFERENCE CHANNEL 4

modulations are studied for a particular channel with impulse noise assuming CSI only at the receive side. This work can be applied to an adaptive MC-CDMA scheme if CSI is known at the transmit side.

IV. RESULTS

The simulation parameters are given in Table 1. Simulations are carried out on the worst channel adopted from [1], namely the Reference Channel 4 (RC4), which are representation of a PLC channel with multiple reflections. The parameters of the RC4 channel are given in Table 2. RC4 gives a channel impulse response with maximum delay spread 3.4μs (with $v_p = 0.5c$). We choose a cyclic prefix length of 256 and FFT size 4096 given the sampling rate of 50 MHz (8% loss of spectral efficiency). The OFDM symbol period is 81.92 μs.

The impulse noise is modelled as a random complex noise 10 or 30 dB higher than the AWGN. The probability that an impulse noise occurs is 1% of the number of OFDM symbols lasting 100 μs. A half rate convolutional code with $K = 7$ is used for channel coding and the spreading codes belong to the Fourier matrix. Simulations are provided for a downlink transmission at full load (no loss in spectral efficiency due to spreading), meaning that either the number of users N_u equals the spreading length L_c or $N_u \leq L_c$ where then several spreading codes are assigned to a particular user. For the simulations, it is assumed that the reference channels represent an average channel for all users, therefore each user experiences the same channel.

Figure 3 shows the Bit Error Rate (BER) performance of an iterative MC-CDMA system with the parameters given in

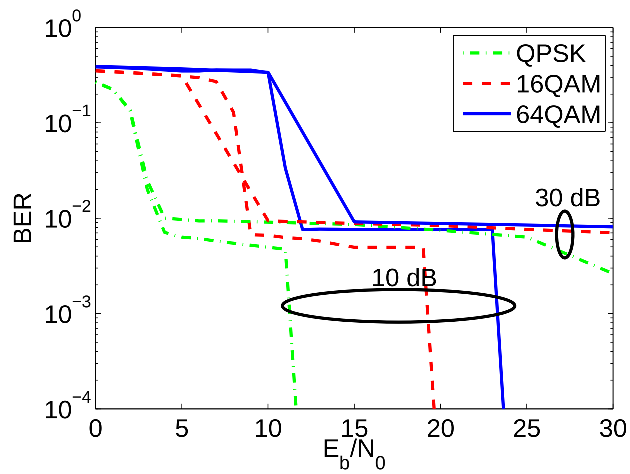

Fig. 3. Performance of QPSK, 16QAM and 64QAM iterative MC-CDMA receiver on a PLC channel with 1% impulse noise 10 dB and 30 dB higher than AWGN without interleaving

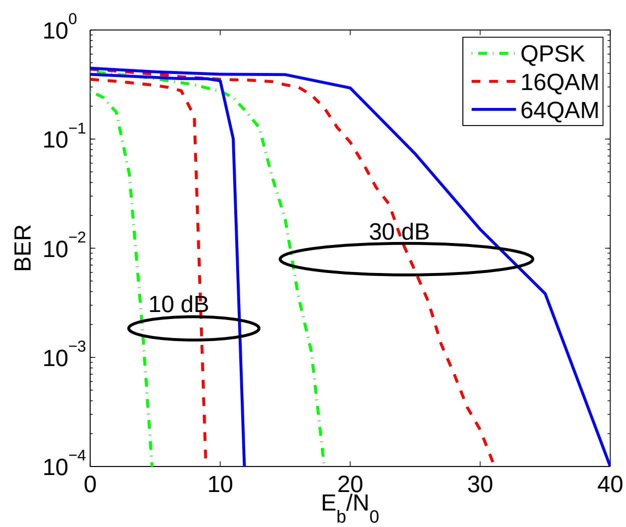

Fig. 4. Performance of QPSK, 16QAM and 64QAM iterative MC-CDMA receiver on a PLC channel with 1% impulse noise 10 dB and 30 dB higher than AWGN with interleaving

Table 1 and the RC4 channel whose parameters are given in Table 2. Several order of modulations are simulated, which are QPSK, 16QAM and 64QAM. The impulse noise is 10 dB or 30 dB higher than the AWGN. Impulsive noise has a detrimental effect on the transmission, leading to a high BER treshold (around 10^{-2}) even for high SNR in the case of 30 dB impulsive noise. This treshold is approximately 10 dB and 30 dB long depending on the modulation for impulsive noise of 10 dB and 30 dB respectively.

Figure 4 shows the BER of the same iterative MC-CDMA receiver and impulsive noise with an increased size of symbol interleaving (100 OFDM symbols). For low power impulsive noise (10 dB) the MC-CDMA iterative receiver can recover the data of the different users reaching the performance of a system without impulsive noise. In this case the treshold of 10 dB long is totally cancelled, leading to a gain of 7 dB for QPSK, 11 dB for 16QAM and 13 dB for 64QAM. For high power impulsive noise (30 dB), the symbol interleaving allows the receiver to reach low BER for significantly lower SNR values than without symbol interleaving. Compared to the case without interleaving, a gain of at least 10 dB is attained for a QPSK modulation.

V. Conclusion

Powerline channel properties call for advanced signal processing techniques to counteract the frequency selectivity and the noise. In this paper, an iterative receiver for MC-CDMA with several order of modulation is proposed for the PLC channel, which can also be extended to other access schemes including a spreading operation and an OFDM modulation. While the impulsive noise have a prejudicial effect on the link transmission, it can be counteracted by means of symbol interleaving due to the spreading operation which collects the data under different channel and noise conditions. A significant performance gain is observed for a realistic powerline channel and high power impulsive noise.

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