A MC-CDMA ITERATIVE SOLUTION FOR BROADBAND OVER POWERLINE COMMUNICATIONS

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ABSTRACT

Power Line Communication (PLC) is foreseen as a potential solution for increasing the throughput of future wireline communication systems. Indeed, the existing infrastructure allows the development of Broadband over Power Lines (BPL) to provide a competing high-speed Internet 'to-the-home' alternative. The frequency selectivity and the impulsive noise of the PLC channel call for advanced signal processing techniques. Multi-Carrier Code Division Multiple Access (MC-CDMA) is a promising transmission procedure to mitigate these unfavorable properties, along with a linear iterative receiver to remove Multiple Access Interference (MAI) and Inter Symbol Interference (ISI). This paper focuses on the full description of a MC-CDMA transceiver on a block by block basis over realistic PLC channel models and adequate simulation parameters including spreading, interleaving, Orthogonal Frequency Division Multiplex (OFDM) modulation, linear Minimum Mean Square Error (MMSE) equalizer, Soft Output Viterbi Algorithm (SOVA) and iterative decoding.

1. INTRODUCTION

The telecommunication industry faces the growing demand for voice calls, file sharing, video on demand, online gaming etc. Wireless and wireline technologies have to provide more bandwidth to the end user. Power Line Communication (PLC) uses the Low Voltage (LV) cables to carry data information on the standard 50 or 60 Hz Alternating Current (AC) power supply. Either Indoor PLC (household Local Area Networks) or Broadband over Power Lines (BPL) are foreseen as a complement of existing wireline technologies such as cable, Digital Subscriber Lines (x-DSL), Fiber-To-The-Home (FTTH) or Sattelite Communications to provide high-speed Internet 'to-the-home'. Recently, Homeplug AV was chosen as a standard for BPL, which uses Orthogonal Frequency Division Multiplexing (OFDM). Extensive measurements showed that the PLC channel is rather unfavorable, exhibiting frequency selectivity, abrupt time selectivity due to the impedance unmatching of plugging or unplugging devices, and numerous synchronous and asynchronous impulse noises [1]. This channel calls for advanced signal processing techniques, namely OFDM or Multi-Carrier Code Division Multiple Access (MC-CDMA) techniques along with iterative receivers as proposed in [2].

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The combination of OFDM multi-carrier modulation and CDMA has been presented for the first time in [3, 4]. This MC-CDMA technique operates data spreading in the frequency domain using Walsh-Hadamard codes and achieves great performance in a downlink transmission. 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 [8] opened a new field leading to numerous iterative receivers combining equalization and channel decoding in order to reach the optimal performance which otherwise is obtained only with a significantly more complex joint Maximum Likelihood (ML) receivers. The decoded data is used to reconstruct the Multiple Access Interference (MAI) and Inter Symbol Interference (ISI) which are subtracted from the received signal, allowing the next stage to decode the data with better reliability.

The goal of this paper is to propose a full description of a MC-CDMA transceiver over PLC on a block by block basis including spreading, interleaving, OFDM modulation, linear Minimum Mean Square Error (MMSE) equalizer, Soft Output Viterbi Algorithm (SOVA) and iterative decoding. Realistic channel models based on measurements are used in the communication chain along with adequate simulation parameters. Simulation results will compare the performance between the non-iterative and the iterative receiver over these channels and impulsive noise. This paper is mainly intended for a downlink MC-CDMA transmission over PLC, but the framework can also be applied to an uplink SS-MC-MA system or any access technique using a spreading operation and an OFDM modulation.

The paper is organised as follows: Section II describes the MC-CDMA transmitter and the iterative receiver. The transmitter basically consists of a channel coding, bit interleaving, spreading, symbol interleaving, and an OFDM modulator. The receiver consists of the reverse operations, and can be updated by an iterative loop between the channel decoding and an interference canceller. The proposed receiver has a low complexity owing to the use of a linear Minimum Mean Square Error (MMSE) equalizer and a Soft Output Viterbi Algorithm (SOVA). Section III presents the PLC channel model. Section IV gives the results of the proposed scheme over two reference channel models using re-

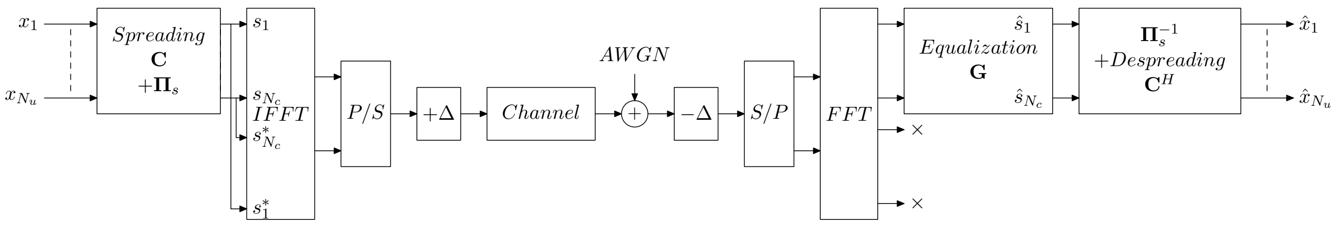

Figure 1: Modulator and demodulator of a MC-CDMA system in a PLC transmission

alistic parameters. These channel models are adopted from [1].

2. TRANSMITTER/RECEIVER

The transmitter on Figure 1 is explained as follows. First, a coded vector $\mathbf{x}$ of length NN_u 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 $\mathbf{s} = \mathbf{C}\mathbf{x}$. This spread signal is then applied to a symbol interleaver $\mathbf{\Pi}_s$ of size $NL_c \times NL_c$ and an OFDM modulator. Practically, this modulation is performed by an Inverse Fast Fourier Transform (IFFT) operation $\mathbf{F}^H$ of the spreaded 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. The definition of MC-CDMA sets up $N_c = L_c$, however for the SS-MC-MA technique $N_c > L_c$ and it is also possible to imagine other access techniques with $N_c < L_c$. 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. Subscript $[.]^H$ denotes the transpose conjugate. The baseband signal is then transmitted into the PLC channel which is represented by a Toeplitz matrix $\mathbf{H}$ and an Additive White Gaussian Noise $\mathbf{n}$'. At the receiver side, orthogonality between subcarriers has to be restored by an OFDM demodulator. The first stage consists of the removal of the guard interval. This guard interval has to be longer than the impulse response of the channel to guarantee the absence of intersymbol interference. Therefore, the channel matrix $\mathbf{H}$ is transformed into an equivalent circulant matrix $\tilde{\mathbf{H}}$. Then, an FFT operation $\mathbf{F}$ is applied on the receiving sequence leading to a diagonal channel matrix of independent frequency responses. The received vector $\mathbf{r}'$ of length $2N_c$ is given by:

$$\mathbf{r}' = \mathbf{F}\tilde{\mathbf{H}}\mathbf{F}^H\mathbf{s}' + \mathbf{n}' \tag{1}$$

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:

$$\mathbf{r} = \mathbf{\Lambda}\mathbf{\Pi}_s\mathbf{C}\mathbf{x} + \mathbf{n} \tag{2}$$

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. For 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. The receiver consists of an iterative process represented on Figure 2 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:
    $LLR_i^{pri} = log\left(\frac{Pr(b_i=-1|\hat{x})}{Pr(b_i=+1|\hat{x})}\right)$
  - Bit deinterleaving $\mathbf{\Pi}_b^{-1}$
  - A posteriori LLR calculation (channel decoding):
    $LLR_i^{post} = log\left(\frac{Pr(b_i=-1|decoding)}{Pr(b_i=+1|decoding)}\right)$
  - 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

First, an MMSE equalizer $\mathbf{G}$ is applied which is a diagonal matrix containing the equalization coefficients g_k correcting the amplitude and phase variations of the channel frequency responses. The equalization coefficients are expressed as:

$$g_k = \frac{\lambda_k^*}{|\lambda_k|^2 + \frac{1}{\gamma}} \tag{3}$$

where $\lambda_k = [\mathbf{\Lambda}]_{kk}$ and γ is the Signal to Noise Ratio (SNR) at the receiver. Then, the symbol deinterleaving and the despreading operation are carried out on the resulting 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) which are probabilities on the coded bits. Using a QPSK modulation with Gray mapping, this formula can be approximated as:

$$LLR_0^{Pri} = log\left(\frac{Pr(b_0=-1|\hat{x})}{Pr(b_0=+1|\hat{x})}\right) \approx Re(\hat{x}) \tag{4}$$

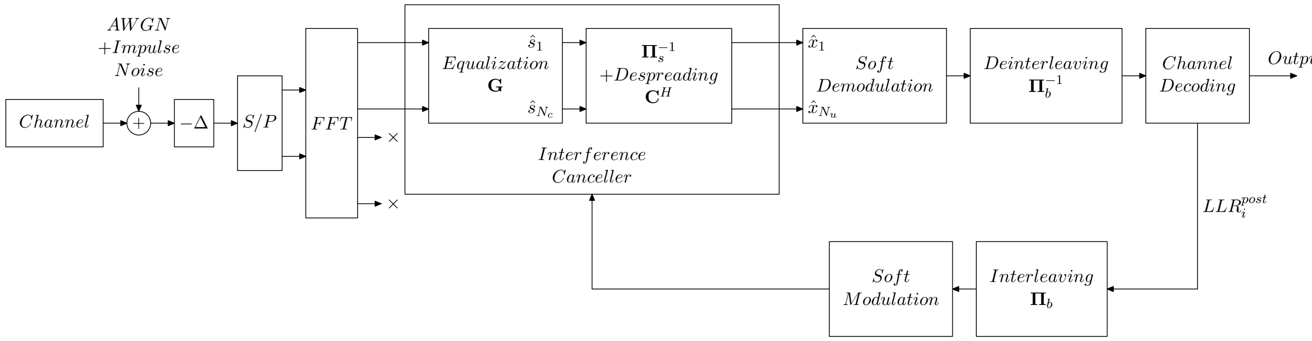

Figure 2: Iterative receiver of a MC-CDMA system in a PLC transmission

and

$$LLR_1^{Pri} = log\left(\frac{Pr(b_1 = -1|\hat{x})}{Pr(b_1 = +1|\hat{x})}\right) \approx Im(\hat{x}) \tag{5}$$

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 [8] 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. Using a QPSK modulation with Gray mapping, the soft modulation can be expressed as:

$$Re(\tilde{x}) = tanh(LLR_0^{post}) \tag{6}$$

and

$$Im(\tilde{x}) = tanh(LLR_1^{post}) \tag{7}$$

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:

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

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. Several iterations can be used depending on the channel. Usually four iterations should be enough to converge.

3. THE PLC CHANNEL

The PLC channel is described in the frequency domain by [6]:

$$H(f) = \sum_{i=1}^{N_p} g_i.e^{-(a_0+a_1f^k)d_i}.e^{-j2\pi f(d_i/v_p)} \tag{9}$$

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. The channel impulse response is obtained by the inverse DFT of the frequency response.

Intensive channel studies are carried out in [1] where the authors propose four channels which reflect the main characteristics of typical PLC transfer functions. These frequency

Bandwidth	25 MHz
Sampling Rate	50 MHz
Modulation	QPSK
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 1: Simulation Parameters

RC1 attenuation term:			RC4 attenuation term:		
k=1	a_0=0	a_1= 1.5 10^{-9}	k=1	a_0=0	a_1= 4.5 10^{-9}
RC1 path parameter:			RC4 path parameter:		
i	g_i	d_i	i	g_i	d_i
1	0.6	100	1	0.26	300
2	-0.08	130	2	0.05	350
3	0.08	160	3	-0.3	370
4	-0.08	190	4	0.25	450
5	0.15	300	5	-0.35	510

Table 2: Reference Channel 1 and 4

selective channels can also change abruptly in time due to the plugging or unplugging of devices in the network. In this paper, we assume that the channel is constant over the time period of the simulation.

The noise in powerline channels is a mixture of colored noise, narrow band noise, asynchronous and synchronous impulsive noises [7]. 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.

4. RESULTS

The simulation parameters are given in Table 1. Simulations are carried out on two reference channels adopted from [1], namely the Reference Channel 1 (RC1) and RC4, which are representation of a good and a poor channel. Their parameters are given in Table 2. RC1 gives a channel impulse response with maximum delay spread 2μs (with $v_p = 0.5c$).

RC4 gives a channel impulse response with maximum delay spread 3.4μs. We choose a cyclic prefix length of 256 and FFT size 4096 given the sampling rate of 50 MHz (8% loss of spectral efficiency). A half rate convolutional code with $K = 7$ is used for channel coding and the spreading codes belong to the Fourier matrix. Simultations 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 a MC-CDMA system with the parameters given in Table 1 and the RC1 channel whose parameters are given in Table 2. The difference between the performance of the non-iterative receiver and the performance of the iterative receiver is small because the RC1 channel is representative of a good powerline channel with only few reflection points. Therefore, no frequency diversity can be exploited through the iterative receiver by enabling symbol interleaving and spreading.

RC4 represents a bad channel for powerline communications. The link has numerous branches and exhibits frequency selectivity. Figure 4 shows that the iterative receiver leads to a gain of 2.3 dB at $BER = 10^{-3}$ compared to the non-iterative receiver. In this case spreading and symbol interleaving enables the exploitation of the frequency selectivity through the iterative receveiver.

Fig. 5 shows the Bit Error Rate (BER) performance of an iterative MC-CDMA system with the parameters given in 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.

Fig. 6 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 approximately 7 dB for QPSK, 16QAM and 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 approximately 15 dB is attained for the different modulations.

5. CONCLUSION

Powerline channel properties call for advanced signal processing techniques to counteract the frequency selectivity and the noise. In this paper, a MC-CDMA transmission with a low complexity iterative receiver 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 iterative receiver may be inefficient in the case of

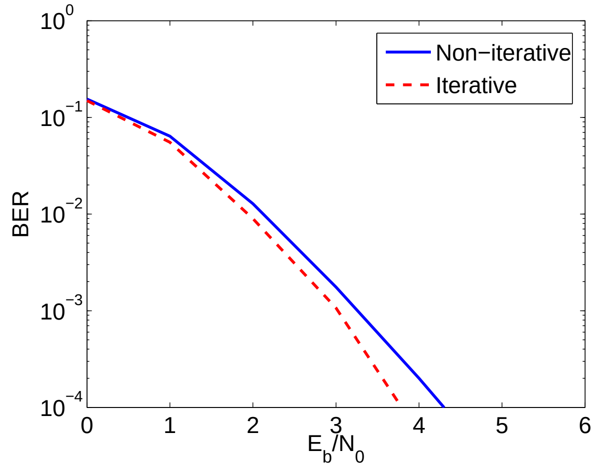

Figure 3: Performance of QPSK non iterative and iterative MC-CDMA receiver on reference channel 1

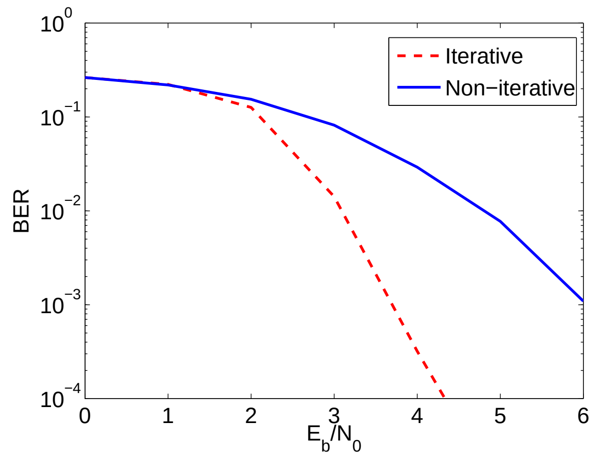

Figure 4: Performance of QPSK non iterative and iterative MC-CDMA receiver on reference channel 4

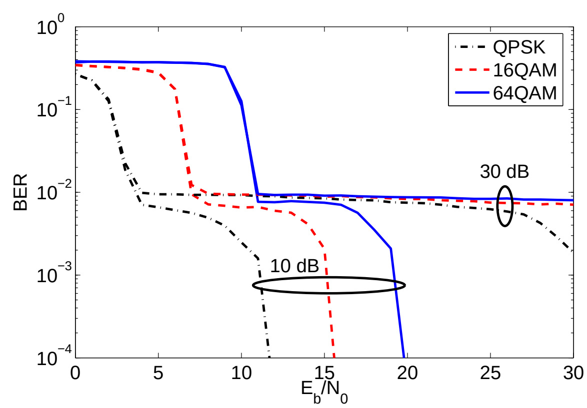

Figure 5: Performance of QPSK, 16QAM and 64QAM iterative MC-CDMA receiver on reference channel 4 with 1% impulse noise 10 dB and 30 dB higher than AWGN without interleaving

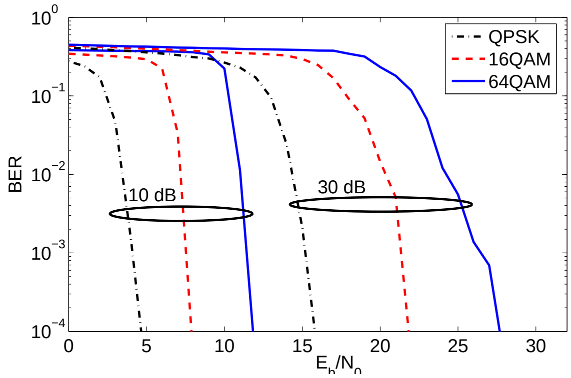

Figure 6: Performance of QPSK, 16QAM and 64QAM iterative MC-CDMA receiver on reference channel 4 with 1% impulse noise 10 dB and 30 dB higher than AWGN with interleaving

good powerline channels, a significant performance gain is observed for poor powerline channels. 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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