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Performance Analysis of Asynchronous MC-CDMA Long Sequences for PLC Systems with Impulsive Noise

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Abstract

In this letter, the performance of two asynchronous multi–access MC-CDMA systems with binary and complex valued long sequences is compared. An indoor multipath powerline network is used under narrowband interferences from RF couplings and impulsive noise from switching power–electronics devices. A complete analytical performance study is provided for asynchronous MC-CDMA with cyclic prefix and long sequences, which provides a better channel coding than short sequences. The performance of MC-CDMA under impulsive noise is also analyzed. Monte Carlo simulation and analytical results are reported, based on a complete powerline channel model with impulsive noise.

Index Terms

MC-CDMA, Powerline, Long sequences.

I. INTRODUCTION

THE indoor low–voltage (LV) powerline communication (PLC) system is a low–cost network solution which takes advantage of existing LV power wires to transmit data between different kinds of devices connected to home outlets.

This letter focuses on indoor PLC systems where the media is accessed simultaneously by all the users for medium data rate domestic appliances, music or HDTV broadcasting [1]. Data is carried asynchronously without any knowledge or cooperation between the users. The multipath effect [2] combined with the coloured noise sources makes the powerline channel one of the most unpleasant channels for mitigating adverse effects. Powerline noise can be classified in coloured background noise caused mainly by the composition of several low power noise sources, narrowband noise from RF emissions coupled to the power wires, and impulsive noise as single and burst pulses [3]. Multicarrier code division multiple access (MC-CDMA) [4] has been widely researched in PLC and takes advantage of orthogonal frequency division multiplexing (OFDM), which has shown very good performance in wireless and powerline communications [1]. Synchronous MC-CDMA systems are evaluated in [5-9] using short spreading codes in a powerline channel without impulsive noise. Analytical approaches for synchronous MC-CDMA systems have been proposed in [8] and [10]. However, a zero–mean Gaussian model is used for impulsive noise in [10], and [9] models impulsive noise with a middlestone class A filter. In [11], long Gold sequences have been used instead of short codes for synchronous system without impulsive noise model. In [12], an asynchronous MC-CDMA system is proposed without cyclic prefix (CP), which is used to improve the OFDM system performance avoiding inter–symbolic interference (ISI) caused by the multipath effect. In [13], the background plus impulsive noise is modeled as zero–mean Gaussian noise for the performance analysis under impulsive noise of a OFDM system with CP, whereas the additive white Gaussian noise (AWGN) was considered as background noise. The present work shows the closed–form bit error rate (BER) for asynchronous MC-CDMA with CP under coloured narrowband and impulsive noise, using long spreading sequences for better channel coding, although it can be generalized to short spreading codes.

II. SYSTEM MODEL AND PERFORMANCE ANALYSIS

An asynchronous MC-CDMA system is considered with a spreading gain factor of N, which is the number of OFDM subcarriers. The independent and identically distributed random data symbols of the kth user are mapped on a QPSK constellation of the vth data multiplex for the mth symbol $a_m^{v,k}$ with $|a_m^{v,k}|=1$. The multiple access scheme is based on joint utilization of short Walsh–Hadamard orthogonal and long sequences. The data is multiplexed using a set of N length orthogonal Walsh codes $\{\boldsymbol{b}^{1,k},\boldsymbol{b}^{2,k},\ldots,\boldsymbol{b}^{Vk,k}\}$ for each kth user. Transmitted MC-CDMA signal of kth user can be written as

$$x_k(t) = \sum_{m=-\infty}^{\infty} \frac{1}{N} p(t - mT_s) \sum_{v=1}^{V_k} \sqrt{P_{k,v}}\, a_m^{v,k} \sum_{p=0}^{N-1} b_p^{v,k} \cdot c_{k,\langle p+mN \rangle} \cdot e^{j2\pi f_p d(t)} \tag{1}$$

where $P_{k,v}$ is the signal power, $p(t)$ is the rectangular pulse shape in the interval $[-T_G,T)$, T is the OFDM symbol length, $f_p=p/T$ is the frequency of the pth subcarrier, T_G is the guard interval of the symbol which is longer than the maximum multipath channel delay T_{MAX}, and $T_S=T_G+T$ is the complete symbol length. The interval guard in the form of CP is expressed as

$$d(t) = \begin{cases} (t+T) - mT_S & mT_S - T_G \le t < mT_S \\ t - mT_S & mT_S \le t < mT_S + T \end{cases} \tag{2}$$

The system uses a set of $N_u \le Q$ sequences $\{\boldsymbol{c}_0, \boldsymbol{c}_1, \ldots, \boldsymbol{c}_{Q-1}\}$, and each user has a sequence $\boldsymbol{c}_l = \{c_{l,0}, c_{l,1}, \ldots, c_{l,Lc-1}\}$ of length L_c. The user symbol data rate is V_k/T_s. We consider an uplink asynchronous system with N_u users transmitting simultaneously over the powerline network. The user delays with respect to the user of interest are assumed to be i.i.d. and uniformly distributed in $[0, (1+T_G/T)L_c)$. Therefore, received MC-CDMA baseband equivalent signal $r(t)$ at receiver input is given by

$$r(t) = \sum_{l=0}^{L-1} h_l^0 \cdot x_0(t - \tau_l) + \sum_{k=1}^{N_u-1} \sum_{l=0}^{L-1} h_l^k \cdot x_k(t - \tau_l - \Lambda_k) + n(t) \tag{3}$$

where h_k is the lossless channel impulse response for L paths and Λ_k is the time delay of the kth user with respect to the user of interest ($\Lambda_1=0$). The signal comprises the signal of the user of interest (k=0), the MAI term, and the powerline noise $n(t)$. The asynchronous MC-CDMA analysis is carried out in absence of impulsive noise. To simplify the mathematical analysis, noting that the user data is i.i.d., the long spreading sequences are reordered to enable delays in the range $[0,T_s)$ without any loss of generality. User delay is split in two terms

$$\Lambda_k = T_s \lfloor \Lambda_k / T_s \rfloor + \Delta_k \tag{4}$$

where $\lfloor \cdot \rfloor$ is the floor operation and Δ_k is the new user delay for a given kth user, as shown in Figure 1.

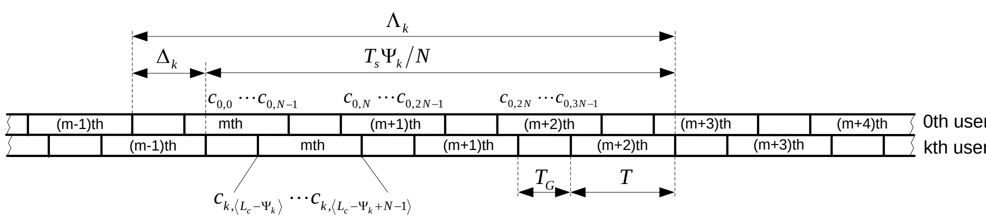

Figure 1 Long sequence reordering for MC-CDMA interference users

From (1) and (3), after the sequence reordering, the signal at the receiver without impulsive noise is given as

$$r(t) = \sum_{k=0}^{N_u-1} \sum_{m=-\infty}^{\infty} \sum_{v=1}^{V_k} \sqrt{\frac{P_{k,v}}{N^2}}\, a_m^{v,k} \sum_{l=0}^{L-1} h_l^k \cdot p(t - \tau_l - \Delta_k - mT_s) \sum_{p=0}^{N-1} b_p^{v,k} \cdot c_{k,\langle p-\Psi_k+mN \rangle} \cdot e^{j2\pi f_p d(t-\tau_l-\Delta_k)} + n(t) \tag{5}$$

where the code delay $\Psi_k = N \lfloor \Lambda_k / T_s \rfloor$. The MRC output sampled at $1/T_c=N/T$ for the mth symbol in perfect time synchronization with the user of interest (k=0) and xth multiplex is given by

$$Z_0^x(m) = \sum_{i=0}^{N-1} H_{0.i}^* \left(b_i^{x,0} \cdot c_{0,\langle i+mN \rangle}\right)^* \cdot \sum_{n=mN_S}^{N-1+mN_s} r(n) \cdot e^{-j2\pi \frac{ni}{N}} = D_{0.x}(m) + D_{I,x}(m) + MAI(m) + \eta(m) \tag{6}$$

Where $H_{k,p}$ is the cannel pth harmonic, $D_{0,x}$ is the desired output xth data multiplex, $D_{I,x}$ is the interference from the user of interest data multiplexes, MAI is the interference term from other users, and η is assumed to be zero mean–valued complex Gaussian noise. The received multi–access interference MAI, as shown in Figure 2, can be broken down into

$$MAI(m) = MAI_1^0(m) + MAI_2^0(m) + MAI^{-1}(m) \tag{7}$$

where MAI^{-1} is the ISI from the previous symbol, MAI_1^0 and MAI_2^0 are the ICI from the same symbol, expressed as

$$MAI_1^0(m) = \sum_{k=1}^{N_u-1} \sum_{i=0}^{N-1} H_{0.i}^* \left(b_i^{x,0} \cdot c_{0,\langle i+mN \rangle}\right)^* \sum_{v=1}^{V_k} \sqrt{\frac{P_{k,v}}{N^2}}\, a_m^{v,k} \sum_{l=0}^{l_k-1} h_l^k \sum_{n=mN_S}^{N-1+mN_S} \sum_{p=0}^{N-1} b_p^{v,k} \cdot c_{k,\langle p+mN \rangle} \cdot e^{j2\pi\left(\frac{p}{NT_c} d(nT_c-\tau_l-\Delta_k) - \frac{ni}{N}\right)} \tag{8}$$

$$MAI_2^0(m) = \sum_{k=1}^{N_u-1} \sum_{i=0}^{N-1} H_{0.i}^* \left(b_i^{x,0} \cdot c_{0,\langle i+mN \rangle}\right)^* \sum_{v=1}^{V_k} \sqrt{\frac{P_{k,v}}{N^2}}\, a_m^{v,k} \sum_{l=l_k}^{L-1} h_l^k \sum_{n=n_k(l)+mN_S}^{N-1+mN_S} \sum_{p=0}^{N-1} b_p^{v,k} \cdot c_{k,\langle p+mN \rangle} \cdot e^{j2\pi\left(\frac{p}{NT_c} d(nT_c-\tau_l-\Delta_k) - \frac{ni}{N}\right)} \tag{9}$$

$$MAI^{-1}(m) = \sum_{k=1}^{N_u-1} \sum_{i=0}^{N-1} H_{0.i}^* \left(b_i^{x,0} \cdot c_{0,\langle i+mN \rangle}\right)^* \sum_{v=1}^{V_k} \sqrt{\frac{P_{k,v}}{N^2}}\, a_{m-1}^{v,k} \sum_{l=l_k}^{L-1} h_l^k \sum_{n=mN_S}^{n_k(l)-1+mN_S} \sum_{p=0}^{N-1} b_p^{v,k} \cdot c_{k,\langle p+(m-1)N \rangle} \cdot e^{j2\pi\left(\frac{p}{NT_c} d(nT_c-\tau_l-\Delta_k+T_s) - \frac{ni}{N}\right)} \tag{10}$$

where l_k is the channel path that starts creating ISI, defined as

$$l_k = \begin{cases} L & T_G - \Delta_k > T_{MAX} \\ \lfloor N_G - \Delta_k / T_c \rfloor + 1 & 0 \le T_G - \Delta_k \le T_{MAX} \\ 0 & T_G - \Delta_k < 0 \end{cases} \quad (11)$$

where T_{MAX} is the maximum channel delay defined as $T_{\mathrm{MAX}}=\max(\zeta_l^k)$, N_G is the number of points for the OFDM interval guard expressed as $N_G=T_G/T_c$ and $n_k(l)$ is the point where there is no more ISI defined as $n_k(l) = \lceil (\tau_l + \Delta_k)/T_c - N_G \rceil$, with $\lceil \cdot \rceil$ as the ceil operation.

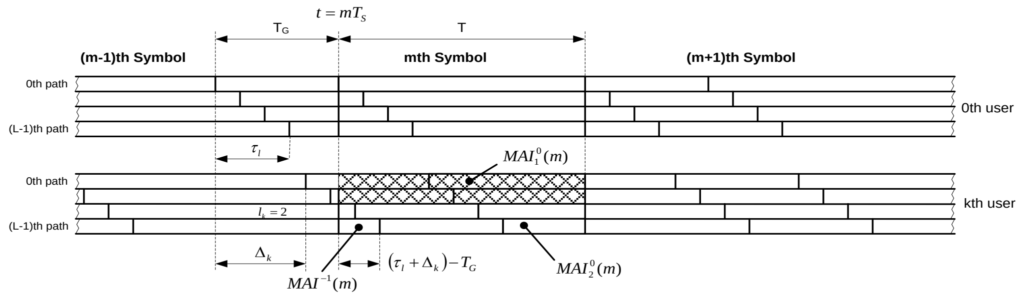

Figure 2 Multi–access interference for asynchronous MC-CDMA

The variance of the MAI term is given as

$$Var[MAI] = \sum_{k=1}^{N_u-1} \sum_{k=0}^{N-1} \sum_{i=0}^{N-1} \left(M_k^{-1}(k) M_k^{-1^*}(i) + M_k^0(k) M_k^{0^*}(i) + M_k^1(k) M_k^{1^*}(i) \right) \quad (12)$$

Standard Gaussian approximation (SGA) is used to assess the BER performance, which relies on the observation that MAI is caused by the sum of a large number of signals, thus the MAI term can be seen as zero mean–valued Gaussian noise. The signal–to–interference plus noise ratio ($SINR_0$) at the receiver output is expressed as

$$SINR_0 = Var[D_0] / (Var[MAI] + Var[D_I] + Var[\eta]) \quad (13)$$

III. IMPULSIVE NOISE EFFECT

During impulsive noise peaks, information symbols get damaged, so that proper coding and interleaving schemes are needed in order to avoid performance loss. In this work, only uncoded systems are taken into account. The probability of occurrence of impulsive noise p_{imp} is expressed as

$$p_{imp} = E[T_{imp}] / E[T_{IAT}] \quad (14)$$

where $E[T_{\mathrm{imp}}]$ and $E[T_{\mathrm{IAT}}]$ are the average length time and inter arrival time of pulse events. It is reasonable to assume that the user signal PSD is much lower than impulsive noise PSD [3, 14]. Under the worst case, each pulse event will destroy at least two symbols. Thus, this constraint sets an upper bound to the bit error rate and the new length mean value $E[T_{imp}] = E[T'_{imp}] + 2T_S$. The probability of bit error is given as

$$P_e = P(e \mid no\, impulse\ event) \cdot (1 - P_{imp}) + P(e \mid impulse\ event) \cdot P_{imp} \quad (15)$$

where *P(e|no impulse event)* is the system probability error in absence of impulsive noise, and *P(e|impulse event)* is the system probability for impulsive noise, which in the worst case, is equal to one half. From (13) and (15), the probability bit error for a MC-CDMA system under impulsive noise is defined as

$$P_e = E\left[Q\left(\sqrt{SINR_0}\right)\right] \cdot (1 - P_{imp}) + \frac{1}{2} \cdot P_{imp} \quad (16)$$

IV. RESULTS

In order to assess the performance of the analyzed system, several simulations have been carried out under a powerline channel model with impulsive noise, where the carrier frequency f_c has been selected randomly for each simulation (6-16MHz). The MC-CDMA system uses 64 subcarriers for a bandwidth of 4,096MHz, and an interval guard of 16 samples (i.e. 3.9 microseconds), which is smaller than the maximum spreading delay of the multipath channel. The background and narrowband noise spectrums are defined for a residential environment in [15]. From the impulse noise measurements carried out in [14], the average length time $E[T'_{\mathrm{imp}}]=9.2938 \cdot 10^{-4}$, and inter arrival time of pulse events $E[T_{\mathrm{IAT}}] =0.0558$. The performance of MC-CDMA receiver is evaluated in terms of BER averaged over Monte Carlo simulations against E_b/N_0 at the receiver input, where N_0 is the equivalent mean noise power density of the coloured background noise. The media is interfered by 10 users transmitting asynchronously, assuming $P_1=P_n$ $(2 \le n \le N_u)$ and perfect timing and frequency synchronization at the receiver of the user of interest. In combination with these receivers, Walsh, Gold, and Song–Park (SP) [16]sequences are tested with lengths 64, 2047 and 2047, respectively. Figure 3 validates the MC-CDMA analytical model described in section II for short and long sequences, such as Walsh, Gold and SP codes. The theoretical curves match the Monte Carlo simulation results under impulsive noise, except for polyphase sequences where a small error due to SGA approximation can be seen. Moreover, in order to evaluate the BER upper bound for a MC-CDMA system under impulsive noise estimation, simulation without interferer users were carried out (i.e. an OFDM system). Figure 3 shows how the BER upper bound nearly matches the Monte Carlo result.

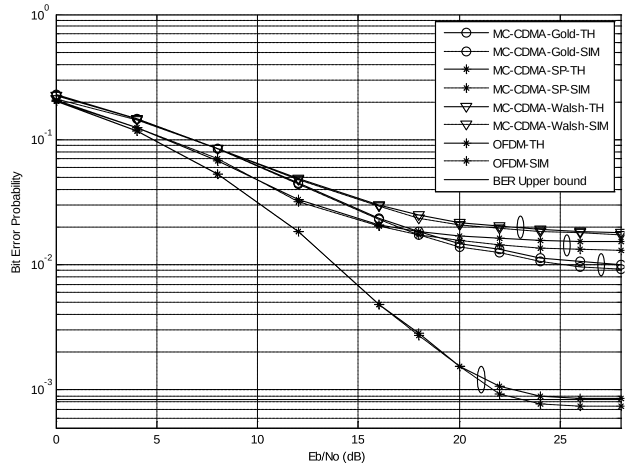

Figure 3 BER performance for asynchronous MC-CDMA (simulation and theoretical)

V. CONCLUSION

High data rate OFDM systems have shown successful performance under multipath channels, whereas its multi–access extension MC-CDMA has probed good results under synchronous PLC environments. In this letter, the performance of asynchronous MC-CDMA system employing an interval guard in the form of a CP has been analyzed, for an indoor powerline channel under impulsive noise. The performance study has been done for binary and complex–valued long sequences, but it can be generalized for short codes. Monte Carlo simulations show the good performance of long sequences for MC-CDMA systems and the BER bound because of the impulsive noise.

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