A Review of MC-CDMA Based Broadband Power Line Communications Systems

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Abstract— **A number of MC-CDMA-based BPLC systems have been proposed-differing in terms of complexity and performance. This work comprehensively reviews MC-CDMA-based BPLC solutions, indicating similarities, differences, advantages and disadvantages of each. The solutions have been classified into two: conventional MC-CDMA-based BPLC solutions and MC-CDMA-based BPLC solutions with MAI reduction techniques. A total of 5 solutions have been summarized.**

Keywords-MC-CDMA; Broadband Power Line Communications; Last Mile Connectivity; Access Networks; Outdoor Power Line Communications

I. INTRODUCTION

Ubiquitous existence of power lines provides an excellent opportunity to redress rural communication infrastructure constraints. Power lines were not meant to carry data, but electricity. Power lines' characteristics such as frequency selective fading, high attenuation at high frequencies and impulsive noise are hostile to communications[1]. To achieve Broadband Power Line Communication (BPLC), the characteristics call for sophisticated modulation schemes to be used.

Orthogonal Frequency Division Multiplexing (OFDM) has been used in a number of works to investigate viability of BPLC. However, recently, Multi-carrier Code Division Multiple Access (MC-CDMA) has been gaining popularity as it combines the best features of OFDM and Code Division Multiple Access (CDMA) to attain spectral efficiency, support multiple users and attain high data rates. MC-CDMA is robust against frequency selective fading and Inter-symbol Interference (ISI)[2]. However, MC-CDMA is affected by Multiple Access Interference (MAI) in frequency selective fading channels[3].

MC-CDMA-based BPLC is capable of transmitting data through low and medium voltage power line networks and therefore extend the reach of telecommunication services to remote areas at a relatively low cost. This work reviews various studies regarding MC-CDMA-based BPLC systems, identifying similarities and differences, also advantages and disadvantages. The rest of the work is organized as follows: Section II presents the characteristics of the Power Line Communication (PLC) channel and its standardization efforts. Section III presents an MC-CDMA-based BPLC system, how it works, categories, similarities, differences, advantages and disadvantages of various solutions. Finally, Section IV provides some conclusions.

II. PLC CHANNEL

A. Standardization

At high frequencies, a PLC channel acts as an antenna emitting electromagnetic waves and can therefore interfere with other nearby communication services. PLC must therefore be standardized if they are to be used to offer broadband communication services. A draft standard with Physical and Media Access Control Layers specification for BPLC has already been ratified (in 2010) by IEEE. The standard (IEEE1901-2010) indicates data rates of up 500Mbps for transmission frequencies below 100MHz[4]. However, the standard is yet to be adopted by most countries' regulatory authorities.

B. Topology of Power Line Networks

The electrical power supply system can be broadly categorized into three network levels, namely: high-voltage, medium-voltage, and, low-voltage that can be employed as transmission medium for implementation of PLC technology. Fig. 1 illustrates the topology of the power-line network**.**

Among the three categories, low voltage network is of interest as it can be used as "last mile" access network. The access network can be connected to the backbone network through conventional communication links such as fiber-optic, radio relay links, or even, the medium voltage network. The connection is normally done at the secondary substation (transformer). It can also be done anywhere else in the network. All customers are connected to the access network through a distribution cable and so the low-voltage network is a shared medium (logical bus topology).

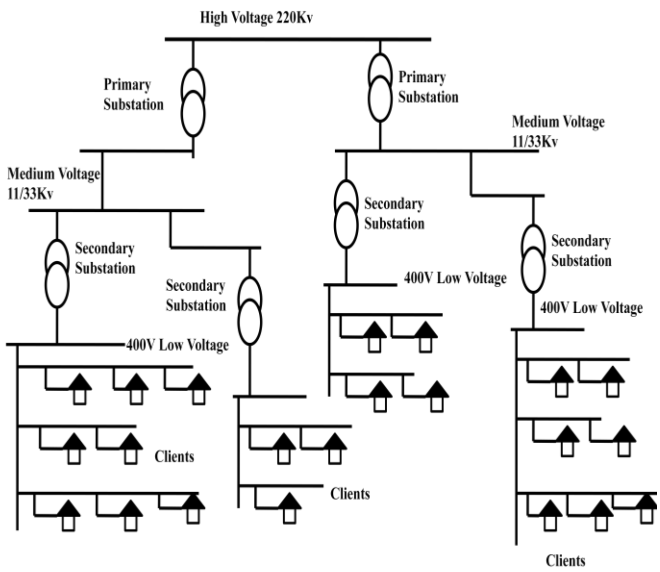

Figure 1: Topology of Power Line Network

C. PLC Channel Model

Development of communication systems requires suitable models that describe the transfer characteristics of the channels (media). The first low voltage power-line channel model proposed in [5] was simple and straight-forward, with attenuation increasing with frequency. The model did not take into consideration the multipath phenomenon which is characteristic of power-line networks.

The multipath phenomenon was addressed in the second model in [6], the model is expressed by (1), where out of N possible signal flow paths, each path delayed by τ_i multiplied by a complex factor ρ_i (product of transmission and reflection factors).

$$H(f) = \sum_{i=1}^{N} \rho_i^{-j2\pi f \tau_i} . \qquad (1)$$

A famous low voltage power-line channel model based on multipath signal propagation and cable losses was presented by [7]. The model (given by (2)) is an extension to that of [6]. Each path is characterized by weighing factor g_i (product of reflection and transmission factors) and path length d_i. The attenuation factor is modeled by the parameters a_0, a_1 and k which are obtained from measurements.

$$H(f) = \sum_{i=1}^{N} g_i e^{-(a_0 + a_1 f^k) d_i} e^{-j2\pi f \frac{d_i}{v_p}} . \qquad (2)$$

The model by [7] was extended in [8] to account for physical characteristics and termination loading of indoor power line networks. It enables derivation of important communication parameters such as root-mean-square delay spread and characterization of the efficiency of sub-channels based on frequency selectivity and their sensitivity to loading variations by estimating the multipath signal. This approach does not scale well with power-line network size[9].

In general, the discussed models do not indicate precisely the contribution of each parameter (in their proposed transfer function) to the stochastic behavior of channel responses. For example, by how much the number of branches contribute to the signal response[10]. In [11], a low voltage PLC model based on the TLT, has been proposed. The model takes into account the loads, interconnection of nodes and distances between nodes. However, it has many parameters.

Most characterizations of the PLC channel are based on Low voltage power lines. If comprehensive 'last mile' connectivity over power lines is to be achieved, more studies will have to be directed to Medium voltage power lines.

D. Noise in Power line Networks

With no electromagnetic shielding, power-line cables are very prone to interference from radio devices and other electromechanical equipments. A number of assessments and measurements have been done in order to characterize noise in the PLC environment [12-14]. The noise in power-line channels can be categorized into two: generalized background noise and impulsive noise.

The generalized background noise is considered to be a superposition of the coloured background noise and narrowband disturbances. As for the impulsive noise, it is composed of the periodic impulses that are synchronous with the main frequency and the asynchronous impulsive noise. The impulsive noise is the fundamental cause of error bursts that occur on the PLC channel. Assuming an unspecified number of independent noise sources transmitting at random in time and space, Middleton's Class A noise model was found to be an appropriate statistical model for modeling electromagnetic noise encountered in the PLC environment [15, 16].

According to the model, impulsive and background noises forms a sequence of independent and identically distributed complex random variables with the Probability Density Function (pdf) of Class A noise given by:

$$p_z(z) = \sum_{m=0}^{\propto} \frac{\alpha_m}{\sqrt{2\pi\sigma}} . \qquad (3)$$

In Equation 3, m is the number of impulsive noise sources and is characterized by Poisson distribution with mean parameter A called the impulsive index (the product of the average rate of impulsive noise and the mean duration of a typical impulse as per (4)).

In (5), Γ represents the Gauss Impulsive Power Ratio (GIR) which is the ratio between the variance of Gaussian noise components σ^2_g and the variance of impulse components σ^2_m . σ^2_z is the variance of noise as per expression (6).

$$\propto_m = e^{-A} \frac{A^m}{m!} . \qquad (4)$$

$$\sigma_m^2 = \sigma_g^2 \frac{\left(\frac{m}{A}\right) + \Gamma}{\Gamma} . \qquad (5)$$

$$\sigma_z^2 = E\{z^2\} = \frac{e^{-A}\sigma_g^2}{\Gamma}\sum_{m=0}^{\infty}\frac{A^m}{m!}\left(\frac{m}{A}+\Gamma\right). \qquad (6)$$

III. BPLC SYSTEMS

BPLC systems provide considerably higher data rates (re n 2 Mbps) compared to narrowband PLC systems that can only realize a small number of voice channels and data transmission with very low bit rates. The BPLC systems can realize more sophisticated communication services such as multiple voice connections, higher data rates, and transfer of video signals.

There are typically two types of BPLC solutions: Indoor PLC Network and PLC Access Network. The indoor PLC network makes use of internal electrical wirings in residences to connect devices such as Computer, Telephone, Printer, etc. PLC Access networks are realized through power-line network's low voltage network which spans from the transformer unit to customer residences.

A. Description of MC-CDMA-based BPLC System

Combination of OFDM and CDMA results in three kinds of multiple access schemes: Multicarrier Direct Sequence Code Division Multiple Access (MC-DS-CDMA), Multi-tone Code Division Multiple Access (MT-CDMA), and MC-CDMA. Using spreading codes, both MC-DS-CDMA and MT-CDMA spreads data streams in time domain in order to satisfy orthogonality condition of subcarriers with minimum frequency separation.

MC-CDMA spreads data streams in the frequency domain, mapping different chip of a spreading to an individual subcarrier. Spreading in the frequency domain gives an edge to MC-CDMA as it means the receiver can always use all received signal energy scattered in the frequency domain. Performance comparisons indicate that MC-CDMA is better than MC-DS-CDMA and MT-CDMA [17, 18].

The block diagram of an MC-CDMA system over power lines is indicated in Figure 2. At the transmitter side, high speed binary data is first encoded into coded bits using various coding techniques (block and/or convolutional codes). To address burst noise associated with power lines, coded bits are interleaved and then baseband modulated. The modulated signal is converted to several parallel sequences and each is spread in the frequency domain using specific codes (Walsh Hadamard, Gold codes, etc).

The spread symbols are again modulated into multicarrier stream using Inverse Fast Fourier (IFFT) and converted back to serial stream, before transmission on the power line channel. The serial stream is then converted into blocks and a Guard Interval (GI) is added to each block so as to counter Inter-symbol Interference (ISI) and Inter-channel Interference (ICI). For GI to work, guard symbol length must be at least equal to the maximum delay spread of the power line channel[17, 18]. The resulting signal is passed to the power line channel and the opposite of transmitter's processing happening at the receiver.

Since MC-CDMA systems tend to suffer from MAI when the channel is frequency selective fading, the design of MC-CDMA-based BPLC system is a compromise between transceiver complexity and system performance. As such, MC-CDMA-based BPLC systems can be categorized into two: conventional MC-CDMA-based BPLC systems (without MAI reduction schemes) and MC-CDMA-based BPLC systems with MAI reduction algorithms. Subsequent Sections groups various solutions into the two categories while pointing out their key differences.

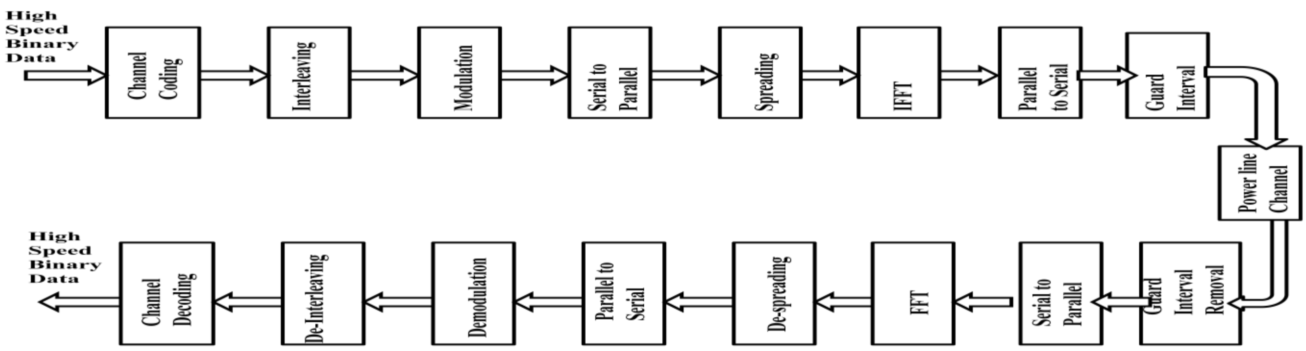

Figure 2: MC-CDMA Communication System over Power Line Channel

B. Conventional MC-CDMA-based BPLC Solutions

Conventional MC-CDMA-based BPLC Systems seeks to achieve high data rates while avoiding complexity associated with addressing MAI. Examples of the conventional system implementation are as follows:

- MC-CDMA-BASED BPLC SYSTEM BY KATSIS, PAPADOPOULOS AND PAVLIDOU (2003)
  Authors consider a low voltage power line network spanning from a transformer unit to customer residence. Performance of coded MC-CDMA-based BPLC is evaluated using a measurement-based channel model. The work indicates the impact of block codes, convolutional codes and Interleaving in the system. Moreover, performance variation of subcarrier modulation schemes with different bandwidth efficiency is established. Subcarriers are modulated by Binary Phase Shift Keying (BPSK) and 16-Quadrature Amplitude Modulation (16-QAM). It is observed that although 16-QAM transmits more bits than BPSK, its performance is poorer than that of BPSK, for both coded and un-coded systems. This is attributed to the fact that 16-QAM is a multilevel modulation scheme; so the fading nature of the power line channel leads to deterioration of performance[19].
  Channel coding by Hamming (7,4), Cyclic Golay(23,12) and Convolutional code (3,1) using hard-decision Viterbi for decoding was applied to the system. Performance with Convolutional codes was the best, while that with Hamming code was the poorest. Interleaving (16 depth for Hamming, and 11 depth for both Cyclic Golay and Convolutional codes) improved performance of each coding scheme, but again, convolutional codes with interleaving were the best followed by interleaved Cyclic Golay and Interleaved Hamming codes[19].
  The work builds a solid foundation for understanding the impact of block codes (e.g. Hamming and Cyclic Golay), Convolutional codes and Interleaving on system performance. However, there is an opportunity to further improve performance using more sophisticate coding schemes such as concatenated codes (e.g. combining block and convolutional codes), and LDPC codes. Also, rate-adaptive modulation can be employed so as to make the most of the channel when transmission conditions are favorable.

- MC-CDMA-BASED BPLC SYSTEM BY VAL AND CASAJUS-QUIROS (2009)
  An indoor power line channel with impulsive noise has been considered for asynchronous un-coded MC-CDMA based BPLC-comparing binary and complex valued long sequences. Subcarriers are modulated using Quadrature Phase Shift Keying (QPSK), spreading is done using Walsh Hadamard Codes, Gold Codes, and Song-Park(SP) codes. Results indicate that long sequences result in good performance of MC-CDMA, especially with SP codes. Only the performance of un-coded MC-CDMA-based BPLC with long sequences has been considered[20]. It would be interesting to establish if the long sequence spreading codes results in better performance of the coded system. Moreover, the channel model used has not been explicitly indicated.

C. MC-CDMA-based BPLC Solutions with MAI Reduction Algorithms

- MC-CDMA-BASED BPLC SYSTEM BY DAI AND POOR (2003)
  Both Indoor and Outdoor low voltage power line networks have been studied for MC-CDMA-based BPLC using a multipath channel model by [7]**.** The authors make use of multicarrier techniques, Multiuser detection and Turbo decoding to curb adverse channel characteristics of power lines.MC-CDMA is used as a multicarrier scheme with BPSK modulated subcarriers. For data detection, Optimum Maximum Likelihood and Suboptimal MMSE parallel interference cancellation Multiuser Detection schemes have been used. Data detection was also done using Convolutional (2,1) with different interleavers of length 2000 for each user. The proposed Turbo multiuser detector successfully combats MAI and Impulsive noise[21]. Although employed coding and multiuser detection techniques result in much improved performance of MC-CDMA-based BPLC system, erasure decoding plus multiuser detection means more receiver complexity.
- MC-CDMA-BASED BPLC SYSTEM BY LE NIR AND MOONEN (2006)
  In this work, a low voltage power line network has been studied for downlink MC-CDMA based BPLC. The PLC channel is modeled using model in [7]. The work seeks to make the PLC channel more favorable to communication by enhancing data detection.
  QPSK, 16-QAM and 64-QAM is used for modulation of subcarriers, spreading is done using Walsh-Hadamard Codes. The study illustrates impulsive noise and MAI mitigation, impact of iterative decoding and Interleaving. Results indicate that in a channel with impulsive noise, the iterative receive can recover data at a rate comparable a channel without impulsive noise. Moreover, the three modulation schemes indicate significant improvement in performance when there is interleaving[1].
  It can be noted that with MMSE and iterative decoding, high throughout subcarrier modulation schemes are possible. However, compared to the conventional MC-CDMA-based BPLC, transceiver

complexity has increased because of sophisticated data detection and correction mechanisms.

- MC-CDMA-BASED BPLC SYSTEM BY HUANG, TAN, CHENG AND WANG (2008)
  BPSK modulated subcarriers for un-coded MC-CDMA-based BPLC system has been considered. The channel is modeled as a random process characterized by complex baseband representation of impulse response. To study the impact of MAI, both orthogonal Wash Hadamard Codes and non-orthogonal gold codes were used for spreading purposes. The paper seeks to reduce MAI associated with MC-CDMA systems using a proposed five stage Partial Parallel Interference Cancelation (PPIC) multiuser detector. It was observed that the proposed scheme attains superior performance than the conventional Parallel Interference Cancellation (PIC)[3].
  The five stage PPIC MUD results in more complex receiver compared to the conventional MC-CDMA receiver and may be unsuitable for time-sensitive applications. Moreover, the work does not indicate the power line network for which the MUD was targeted.

IV. CONCLUSIONS

In this paper, works regarding MC-CDMA-based BPLC system have been studied. To identify similarities and differences, the solutions have conveniently been categorized into two groups based on transceiver complexity and performance. Future studies can be conducted to analyze performance of systems that combine best features of key solutions.

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