High Speed Powerline Communications: State of the Art and Beyond

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ABSTRACT

This paper describes the unique challenges associated with high speed digital communication over existing in-building powerlines. The solutions provided by the 14 Mbps HomePlug 1.0 protocol are described, then an overview of the 200 Mbps HomePlug AV protocol and the frame of Multi-Input Multi-Output (MIMO) Power Line Communication system are given. The last two are providing higher throughput than the HomePlug 1.0.

KeyWords: HomePlug 1.0, HomePlug AV, MIMO, Power Line Communcarion .

1. INTRODUCTION

1) Interest in Powerline Communications

There has been a great deal of recent interest in leveraging the existing electrical wiring within and connected to buildings for high speed digital communications[1]. In-home LANs using powerline communication (PLC) are now a reality with products based on the HomePlug 1.0 standard in use worldwide since 2000. [2,3]. PLC LANs using the 14 Mbps HomePlug 1.0 chipsets, provide full house coverage at typical TCP data rates of 5-7 Mbps, and exhibit greater stability than competing wireless LAN solutions [4,10].

In addition there is current activity in the deployment of Broadband Powerline (BPL) for Internet access [5, 6, 7]. BPL and WiFi (IEEE 802.11x) are seriously considered as two other possible offering to complement such broadband services as Digital Subscriber Lines (DSL) and Cable TV Modems. BPL has the advantage of ease of installation with literal ‘plug and play’ and greater penetration inside the home. Thus the powerline, historically used for the delivery of electrical power, now also provides a high speed digital pipe to the home and a ‘no new wires’ communication network inside.

2) Multimedia In-home Networking

While HomePlug 1.0 provides acceptable data rates and performance for data communication needs in connecting multiple computers and peripherals in a LAN setting, higher data rates and more stringent QoS controls are needed to support digital mulitmedia communication within the home[8]. The HomePlug AV standard expected to be available in the last half of 2005, is optimized for precisely this scenario.

The rest of the paper is structured as follows. Section 2 reviews characteristics of the powerline channel, while Section 3 gives an overview of the HomePlug 1.0 standard from a system perspective. Section 4 provides brief descriptions of both the PHY (Physical Layer) and the MAC (Medium Access Control) protocols of the HomePlug AV specification. Section 5 gives the frame of MIMO-PLC system which offers us better perforamnces in throughput and bandwidth.

2. PLC CHANNEL CHARACTERISTICS

1) Multipath Channel Effects

In-building electrical wiring, designed for carrying electrical power at 50 or 60 Hz, consists of a variety of conductor types and sizes connected almost at random. The resulting terminal impedances vary both with communication signal frequenciy and with time as the load patterns at the consumer premises change. The net result is a multi-path effect that causes delay spread (averaging a few microseconds) and deep notches (from 20 to 70 dB) at certain frequencies within the band used by PLC communications[9]. In North America, HomePlug 1.0 uses a frequency band 4.5-20.7 MHz, while HomePlug AV uses the band from 1.8 to 30 MHz. Regulatory constraints make frequencies above 30 MHz unattractive for PLC applications.

2) PLC Channel Noise Issues

In addition to the inherent fading attenuation and phase characteristics of the PLC channel, high speed communications in this channel must also mitigate a plethora of impairments and noise events which have been historically a major impediment to high speed PLC. Typical noise sources are certain types of halogen and fluorescent lamps, switching power supplies, brush motors, and dimmer switches. Futhermore, the PLC channel is subject to interference from, and without spectral masking would itself adversely impact, other users of the specified spectrum, such as citizen band and amateur radio. Another characteristic of the PLC channel that has an impact on achievable data rates is the cyclic variation of noise with the powerline cycle.

3) Taming the Shrew-like PLC Channel

Several specific techniqiues are used in HomePlug 1.0 and HomePlug AV to conquer the many hurdles posed by the PLC channel; these are Orthogonal Frequency Division Multiplexing (OFDM), Programmable Spectral Masking, Orthogonal Channel Adaptation, Modulation and Coding, Efficient Medium Access Control Framing and ARQ.

3. INTRODUCTION OF HOMEPLUG1.0

The 14 Mbps HomePlug 1.0 standard was released in 2000 by the HomePlug Powerline Alliance to provide a PLC-based in-home LAN solution. HomePlug 1.0 stations use the well known carrier sense multiple access with collision avoidance (CSMA/CA) technique for medium sharing. This mechanism is augmented with an enhanced back-off algorithm along with priority resolution slots. The back-off algorithm enables the HomePlug 1.0 network to operate at high efficicency under varying network loads. The priority resolution slots enable four levels of strictly differentiatited QoS to traffic based on priority level.

1) HomePlug 1.0 Medium Access Control

HomePlug 1.0 uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). Physical Carrier Sense (PCS) is complemented by Virtual Carrier Sense (VCS) information contained in the Frame Control Field indicating whether other stations can contend for the medium or not.

2) Security and Key Management

HomePlug 1.0 uses a password-based cryptography standard (PBCS) for key management to effect cryptographic isolation of logical networks. All stations in a logical network share the same Data Encryption Standard (DES) key, called a Network Encryption Key (NEK). Encyption is enabled by default and cannot be disabled, but for proper protection, the user must select a unique network password.

3) HomePlug 1.0 Performance

Simulations and measurement show that HomePlug 1.0 provides typical throughputs of 5-7 Mbps (TCP), Full house coverage in 99% of the homes tested was observed with a data rate of at least 1.5 Mbps.

4. HIGH SPEED PLC SYSTEM

Though HomePlug 1.0 provides acceptable data rates and performance for data communication needs in connecting multiple computers and peripherals in a LAN setting, higher data rates and more stringent QoS controls are needed to support digital mulitmedia communication within the home[8]. Homeplug AV and MIMO-PLC are two choices. Homeplug AV uses more bandwidth; MIMO-PLC used two or three wires to transmite inforamtion and get much higher throughput. This chapter will give an overview of these two systems.

1) HomePlug AV Bandwidth

HomePlug AV provides an order of magnitude throughput improvement over HomePlug 1.0, while also addressing key QoS issues. The bandwidth used has been extended and subcarrier spacing reduced in AV. Whereas HomePlug 1.0 uses 4.5 to 20.7 MHz quantized into 84 subcarriers, AV operates with 1155 carriers over 1.8 to 30 MHz. While Homplug 1.0 in its default configuration uses 76 active carriers in its bandwidth of operation , Homeplug AV uses 917 in its default mode.

a. HomePlug AV OFDM Symbol

Similar to the HomePlug 1.0 standard, Orthogonal Frequency Division Multiplexing (OFDM) is used for HomePlug AV. However, various OFDM system parameters have been updated in order to maximize spectral mask flexibility and increase system throughput. The OFDM symbol's IFFT interval time in HomePlug AV is approximately eight times that of HomePlug 1.0. One advantage of this is that, in the basic configuration, (5.56μs or 7.56μs guard interval) the overhead due to the guard interval, used to mitigate intersymbol interference (ISI), is much less in HomePlug AV. Another advantage of the longer symbol time is that the OFDM symbols can be (and are) shaped and overlapped in such a way that deep frequency notches can be created simply by turning carriers off, whereas HomePlug1.0 required, either turning off a large number of carriers both in and around the desired notched band, or additional filtering.

b. HomePlug AV Carrier Modulation

Carrier modulation has been improved in HomePlug AV to maximize channel throughput. HomePlug 1.0's differential modulation has been replaced in HomePlug AV with coherent modulation – yielding higher carrier SNRs for a given signal power. Second, whereas HomePlug 1.0 used only DBPSK or DQPSK modulations, individual HomePlug AV carriers can be modulated with BPSK, QPSK, 8-QAM, 16-QAM, 64-QAM, 256-QAM, or 1024-QAM. This allows the system to take full advantage of all possible ranges of SNRs that a particular subcarrier could encounter. Finally, in contrast to HomePlug 1.0 that does not mix modulation types across carriers, HomePlug AV fully supports bit-loading. A mix of modulations is tailored for each channel such that each carrier communicates with the fastest modulation that the carrier's SNR can support.

c. HomePlug AV FEC

Forward error correction (FEC) has also been improved in HomePlug AV. Whereas HomePlug 1.0 uses a concatenated code, HomePlug AV uses a state-of-the-art turbo convolutional code, allowing greater throughput for a given channel SNR, a gain equivalent to about 2.5 dB. While HomePlug 1.0 had a single ROBust mOdulation (ROBO) scheme, HomePlug AV features several additional robust modes of operation in which a repetition code is applied as an outer code to the turbo code for broadcast or for use in harsh channel conditions.

d. HomePlug AV and 1.0 Coexistence

The HomePlug AV technology was designed to be able to coexist with HomePlug 1.0 nodes in a given network. HomePlug AV has the ability to send delimiters recognizable by HomePlug 1.0 nodes in order to communicate protocol information regarding channel access and contention.

e. HomePlug AV Medium Access

In HomePlug AV, medium access is primarily through Time Division Multiple Access (TDMA), with CSMA/CA available for bursty applications. In each network, a Central Coordinator (CCo) transmits a beacon frame that contains schedule information for the other stations. Stations that source steady streams request time allocations from the CCo, and transmit in the assigned regions. This avoids the overhead of contention and collision present in CSMA/CA.

f. Framing and Segmentation

HomePlug AV employs Selective Repeat Automatic Retransmission Request (SR-ARQ). Each PB has its own 32-bit Cyclic Redundancy Check (CRC) to detect errors. The receiver responds with a Selective Acknowledgement (SACK) that pinpoints the PBs requiring retransmission. Only the damaged PBs are retransmitted, and these may be combined in a new MPDU with newer PBs that are being sent for the first time. This approach allows full MPDUs to be sent almost all the time, so that the fixed delimiter overhead remains small relative to the total transmission time.

g. Security and Key Management

While HomePlug 1.0 uses 56-bit DES encryption, HomePlug AV uses 128-bit AES. Both use Cipher Block Chaining (CBC) to increase randomness in similar transmissions. The Initialization Vector (IV) is transmitted explicitly in HomePlug 1.0, whereas in HomePlug AV, it is derived from frame information.

h. QoS in HomePlug AV

To support desired delay, packet loss tolerance, and jitter, HomePlug AV takes several measures. As explained above, access for steady streams (such as multimedia applications generate) is carefully scheduled using TDMA. Allocated times reflect the latency requirements, and provide sufficient time for retransmissions as needed to meet the PLT requirements of the stream. Jitter is managed by timestamping incoming data units with their target delivery time.. Stations execute a time synchroni-zation method to remain in tight synchronism so that the jitter remains below 500 ns.

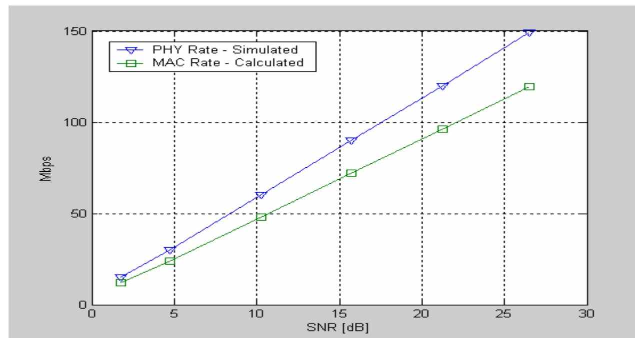

Figure 1 Simulated and Calculated PHY and MAC Data Rates Vs SNR

i. HomePlug AV Performance

The improved design of both PHY and MAC in HomePlug AV render it tremendously efficient. At the PHY level, the data rates achieved are very near the information theoretic limits. MAC framing overhead is minimized and the error correction and retransmission scheme provides an excellent combination of reliability and efficiency. Typical MAC efficiencies are projected to be in the 80% range, depending on the nature of the application and the PHY rate.

5. MIMO-PLC SYSTEM

1) Background of MIMO Communication

MIMO technology had been used by Marconi to mitigate as early as in 1909, but it was not until the 1960's that MIMO was proposed to be used in emerging communications systems. The MIMO approach was introduced for wireless communication systems by AT&T Bell Labs in the 1980s.

Curerntly, MIMO technology is in widespread use in wireless communication as part of the IEEE 802.11n protocol, which is an extension of the the wireless LAN standards that began with 802.11a and was followed by versions b and g. The IEEE formally began work on 802.11n in 2003, and in September 2007, the IEEE ratified

Draft 2.0, which addressed many of the technology's important hardware-related aspects[4].

Multiple-input-multiple-output technology is the main reason 802.11n offers more bandwidth. MIMO wireless systems use spatial multiplexing to divide data streams into multiple pieces, and then send two or more of the streams via different channels simultaneously. A spatial-multiplexing receiver uses complex algorithms to reassemble streams into the original transmissions. The technology also uses algorithms to combine scattered and otherwise useless streams caused by multipath interference resulting from signals bouncing off walls and other objects.

2) MIMO-PLC System Model

The MIMO PLC system may be modeled by a 2×2 MIMO system (with two transmitting terminals and two receiving terminals). The whole system model is showed in Figure 2.

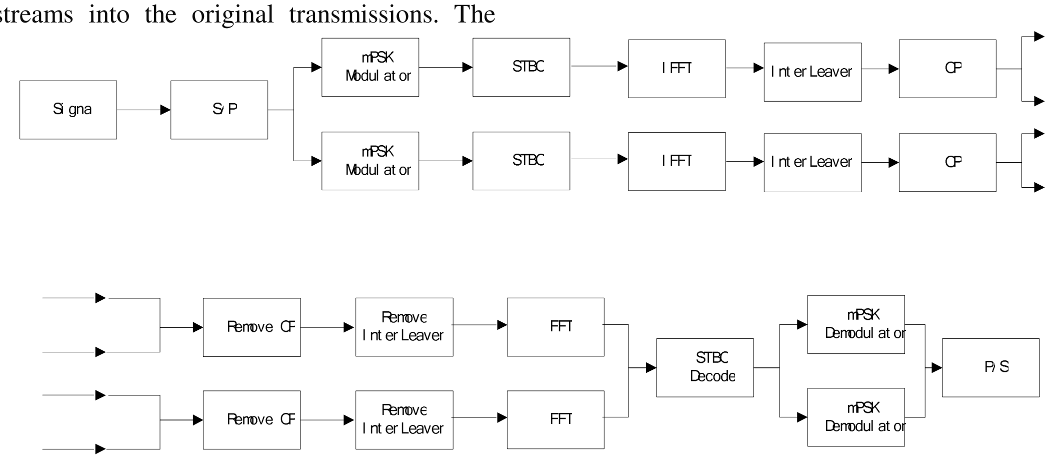

Figure 2. Block diagram of the proposed MIMO system

The signal flow for the transmitter shows a serial to parallel (S/P) conversion typical of OFDM multi-carrier systems, which then feeds a bank of M-ary Phase Shift Keying (M-PSK) modulators, followed by space-time encoders (space time block coders (STBC) are shown. The signal is then processed by an inverse Fast Fourier Transform (IFFT) engine, Interleaving Code parts and a cyclic prefix (CP) insertion block. Then the signal is coupled to the MIMO channel. The process is reversed at the receiver. Each of these elements are discussed the following sections.

a.Modulation/Demodulation Block

Let us conisder the use of an M-PSK modulation scheme, where M is the number of different phases. Figure 3 illustrates the case for a 4-PSK system that uses four different phases. Table 1 shows the relationship between the two bits designated [ab] and the sub-carrier phases.

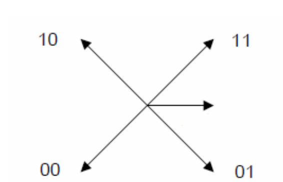

Figure 3. 4-PSK signal vector

b.MIMO Block

To realize the MIMO part of the system, we first consider the standard approaches to space-time/space-frequency (ST/SF) coding. Space-time coding has three main methods: STBC (space-time block coding), STTC (space-time trellis coding) and LST (layered space-time). The STBC method is easy to realize and always has low BER[5]. So, as a first step in the proposed project, we will use STBC to build the 2x2 MIMO block. The STBC encoding can be described by the encoding matrix:

$$S = \begin{pmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{pmatrix}$$

So, every four bits (or every two bits on each channel) forms a block.

c.System Channel Model

The 2x2 MIMO channel character matrix is given by[7]:

$$H = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix}$$

If the transmitted signal matrix is represented by

$$S = \begin{pmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{pmatrix}$$

and the associated signal matrix received from the channel is given by

$$R = H \times S = \begin{pmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{pmatrix}$$

So that we get following received signals

$$r_{11} = h_{11} \times s_1 + h_{12} \times s_2$$
$$r_{12} = h_{11} \times (-s_2^{\ *}) + h_{12} \times s_1^{\ *}$$
$$r_{21} = h_{21} \times s_1 + h_{22} \times s_2$$
$$r_{22} = h_{21} \times (-s_2^{\ *}) + h_{22} \times s_1^{\ *}$$

d.Interleaving/Remove-interleaving Block

Interleaving is frequently used in digital communication and storage systems to improve the performance of forward error correcting codes. Many communication channels are not memoryless: errors typically occur in bursts rather than independently. If the number of errors within a code word exceeds the error-correcting code's capability, it fails to recover the original code word. Interleaving ameliorates this problem by shuffling source symbols across several code words, thereby creating a more uniform distribution of errors [8].

e.IFFT/FFT Block

The IFFT (Inverse Fast Fourier Transform) and FFT (Fast Fourier Transform) provides the required transform signal between the frequency domain and the time domain. Through the N-point IFFT block, the outputs are N points of time domain sample. At the receiving part, the signals go through the FFT block and are transformed into M (which is the number of the signals) plus (N - M) zeros. Removing the (N - M) zeros, the received signals are the M point frequency domain samples.

f.Cyclic Prefix (CP) Block

A CP (Cyclic Prefix) is always added to the N-point signal obtained from the IFFT block. The CP length is Lp, so the actual transmitted signal length is (Lp + N). When the length of CP is greater than the channel memory length, ISI affects only the CP, without affecting the useful data. At the receiver, the CP is removed, and at the same time; the ISI effects are eliminated.

g. performance of MIMO-PLC system

Figure 4, 5 and 6 show that MIMO-PLC has better performance than the SISO-PLC system in several kinds of channel models.

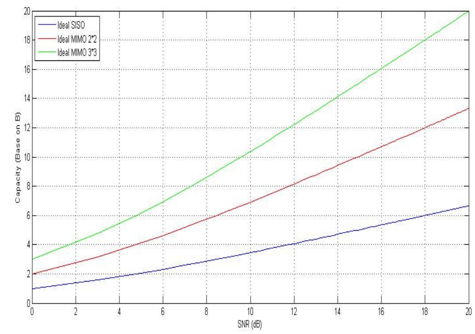

Figure 4 Capcity of SISO/MIMO on Ideal Channel Model with AWGN

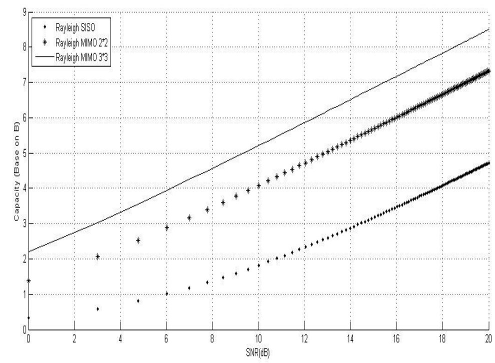

Figure 5 Capcity of SISO/MIMO on Rayleigh Channel Model with AWGN

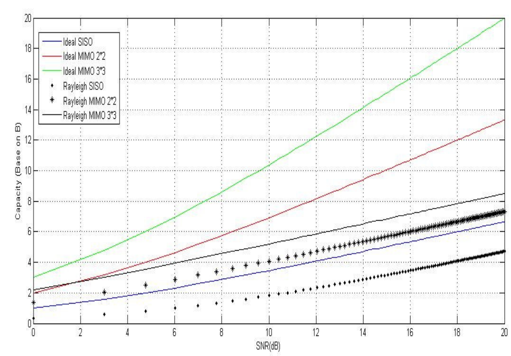

Figure 6 Comparrion Chart

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