HIGH SPEED MULTIMEDIA HOME NETWORKING OVER POWERLINE

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Abstract

This white 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 and an overview of the 200 Mbps HomePlug AV protocol is given. The latter protocol is optimized for multimedia voice and video services, while also providing high speed data communication.

INTRODUCTION

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 curerent 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 digital pipe to the home and a 'no new wires' communication network inside.

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.

A single stream of High Definition Televison (HDTV) may require about 25 Mbps and a typical scenario may require support for a number of simultaneous multimedia streams of voice, audio and video. Moreover multimedia applications also have latency, jitter and packet loss probability (PLP) requirements that must be met for optimal performance (see Table 1)

Application	Bandwidth (Mbps)	Latency (msec)	Jitter (nsec)	PLP (log)
HDTV	25	300	500	-10
SDTV	4	300	500	-10
DVD	6	300	500	-10
VOIP	64	10	10000	-2
Gaming	0.1	10	N/A	-6
Video conf.	1	75	10000	-6

Table 1 – Typical Multimedia QoS Requirements

Although there are several existing in-home communication tech-nologies that appear to be capable of providing the basis for such multimedia communication, a careful examination reveals several possible deficiencies. For example, the popular IEEE 802.x suite of protocols (including the emerging IEEE 802.n standard) does not provide complete house coverage (with a single access point) at adequate data rates and reliability to provide a robust multimedia solution. Although the new Ultra-Wide band (UWB) standard will certainly have adequate bandwith, its reach will likely be confined to a single room rather than the entire home. The recently announced standard from the Multimedia over Coax Alliance (MoCA), while possibly offering a solution for video distribution between video sources and players already connected to the exiting coaxial video cabling, fails to offer whole house coverage for other applications such as audio and VOIP, since video cabling is typically limited. Phoneline networks also have limited phone connections inside the home.

The new 200 Mbps HomePlug AV standard from the HomePlug Alliance, on the other hand, offers whole-house coverage, with an average of 44 outlets per home (in the USA). HomePlug AV will provide roughly a ten fold improvement over HomePlug 1.0, with typical TCP data rates of 50-70 Mbps, and thus it is able to support multiple simultaneous multimedia streams. Futhermore the HomePlug AV standard is specifically designed and optimized for Audio Visual (AV) applications and will provide adaptivity to satisfy relevant QoS requirements. It should also be noted that, compared to the wireless in-home channel, the powerline commun-ication (PLC) channel is relatively static and thus the QoS requirements are much more easily met in the more robust PLC environment.

The rest of the paper is structured as follows. Section II reviews characteristics of the powerline channel, while Section III gives an overview of the HomePlug 1.0 standard from a system perspective. Section IV provides brief descriptions of both the PHY (Physical Layer) and the MAC (Medium Access Control) protocols of the HomePlug AV specification. It describes the HomePlug AV framing structures and unique channel adaptation mechanisms. It also presents the associated network architecture that supports both Time Division Multiple Access (TDMA) as well as Carrier Sense Multiple Access (CSMA), with multiple independent overlapping networks. The paper concludes in Section V with some observations on the efficiency and performance of HomePlug AV and comments on further work in this area.

II. PLC CHANNEL CHARACTERISTICS

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 band. Regulatory constraints make frequencies above 30 MHz unattractive for PLC applications.

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 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. In particular, it has been found that the signal to noise ratios are much better in the vicinity of the zero crossings of the 50/60 Hz powerline cycle.

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 described below.

Orthogonal Frequency Division Multiplexing (OFDM): OFDM is ideal for the frequncey selective PLC channel since it allows the division of the available spectrum into a large number of smaller, independent flat fading channels for each of which appropriate adaptive multi-level modulation schemes can be selected.

Programmable Spectral Masking: In order to meet regulatory constraints and to minimize mutual interference, a fixed spectral mask can be programmed such that the PLC devices do not use or cause intereference in certain specified bands.

Orthogonal Channel Adaptation, Modulation and Coding: A robust, relatively low data rate scheme *(ROBO)* featuring high time and frequency redundancy, low order modulation and very powerful error coding is designed to reach almost all nodes in the PLC network. In addition, each PLC packet has a *Frame Control (FC)* segment that uses a highly reliable scheme to ensure that key parameters critical to the functioning of the PLC system, are reliably received by all nodes in the network. *Tone Maps* are used for high speed communication between a specific pair of nodes, to communicate the particular OFDM carriers and modulation and error coding schemes to be used. Tone maps are adjusted periodically based on on-going channel monitoring.

Efficient Medium Access Control Framing and ARQ: PLC communication uses a highly efficient MAC/PHY framing strategy to ensure low overheads. Futhermore channel contention, reservation and backoff mechanism are optimized to maximize throughput. Also, high speed PLC features a carefully crafted error detection and retransmission (ARQ) strategy to ensure reliable communication even in the unfavorable channel conditions.

III. HIGHLIGHTS OF HOMEPLUG 1.0

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.

HomePlug 1.0 PHY

Orthogonal Frequency Division Multiplexing (OFDM): In HomePlug 1.0, 128 evenly spaced carriers are specified in the range 0-25 MHz. A programmable tone mask is used (in default configuration) to identify the 84 carriers that fall inside the 4.5-20.7 MHz range, among which eight are permanently masked to avoid conflict with Amateur radio bands.

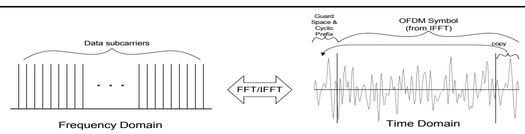


Figure 1 – OFDM Symbol from IFFT

Figure 1 illustrates the generation of an OFDM symbol from the unmasked carriers via an IFFT process. Each OFDM symbol is 8.4 µs long, with 5.12 µs (256 samples) corresponding to the new OFDM symbol and 3.28 µs being a cycling prefix obtained from the last 172 samples. Figure 2 shows the key elements of the PHY Frame, namely the *Preamble*, the *Frame Control (FC*) and a variable number of *Data (Payload)* OFDM symbols. Figure 3 gives further details..

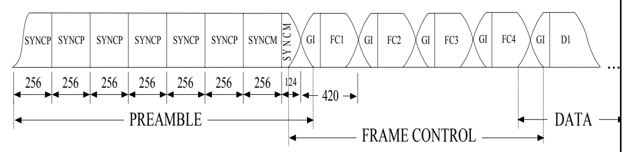


Figure 2 – PHY Frame OFDM Symbols

Preamble: The preamble is constructed from 7.5 special OFDM symbols without cyclic prefixes, and is 38.4 µs in duration. This frame segment is used for synchronization, automatic gain control and optionally for phase reference. The time needed to detect the preamble is the Physical Carrier Sense (PCS) interval and dictates contention slot size.

Frame Control: The Frame Control consists of 4 OFDM symbols in which all unmasked carriers are used in conjunction with a Turbo Product Code (TPC) for error correction. The four FC symbols contain 25 information bits received with high reliability. These bits, structured as shown in Figure 3(b), provide information for the correct operation of the HomePlug 1.0 protocol. (See [3] for further details).

Payload: The Payload consists of a variable number of 20- and 40-OFDM symbol blocks, protected by Reed-Solomon/ Convolutional concatenated encoding. HomePlug 1.0 features fairly smooth adaptation from 1 to 14 Mbps; some 140 intermediate rates are supported by combining available modulation schemes and FEC coding rates. The effect of this smooth adaptation is seen in the stability of HomePlug 1.0 in good and bad channels when compared with the larger variations from IEEE 802.11 a and b. (See Figure 4)

Priority Resolution (PR): The two Priority Resolution symbols (see Figure 3(a)) each consist of six OFDM symbols, lasting 30.72 µs and are used to establish four levels of priority. The PR slots are 35.84 μs long, which takes into account the time to process the 30.72 μs symbols. Like the Frame Control, both Preamble and PR symbols must be received reliably by all nodes in the network, so all unmasked OFDM carriers are modulated and encoded in a standard way.

Figures 5 and 6 show the HomePlug 1.0 Transmitter and Receiver block diagrams. The Transmitter block shows the separate processing of Frame Control (FC) and Data bits. The data is first scrambled, then encoded, punctured, and interleaved before being mapped according to selected tone maps onto the OFDM carriers. After IFFT, a preamble and cyclic prefix are inserted (if needed) followed by a shaping filter to effect sharp band edges. At the receiver a synchronization block detects the presence of a preamble signal, and the subsequent frame control and data symbols undergo receive side processing to de-modulate data, and to de-code the bitstreams of interest.

For ease of implementation, cost and other reasons, HomePlug 1.0 uses differential modulation with only DBPSK and DQPSK schemdes. In addition all carriers used in each OFDM symbol have the same modulation scheme.

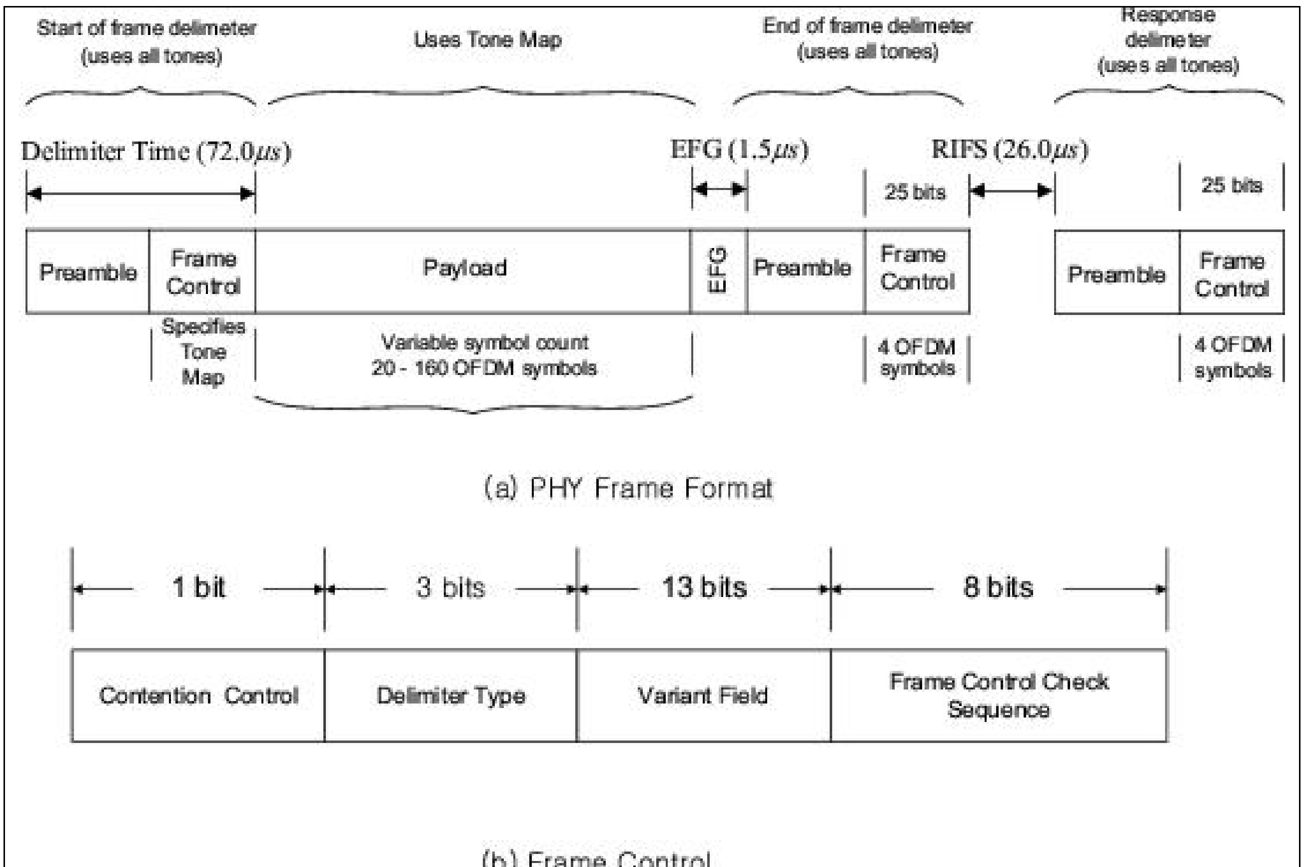


Figure 3 - HomePlug 1.0 PHY Frame: (a) Frame Format and (b) Frame Control

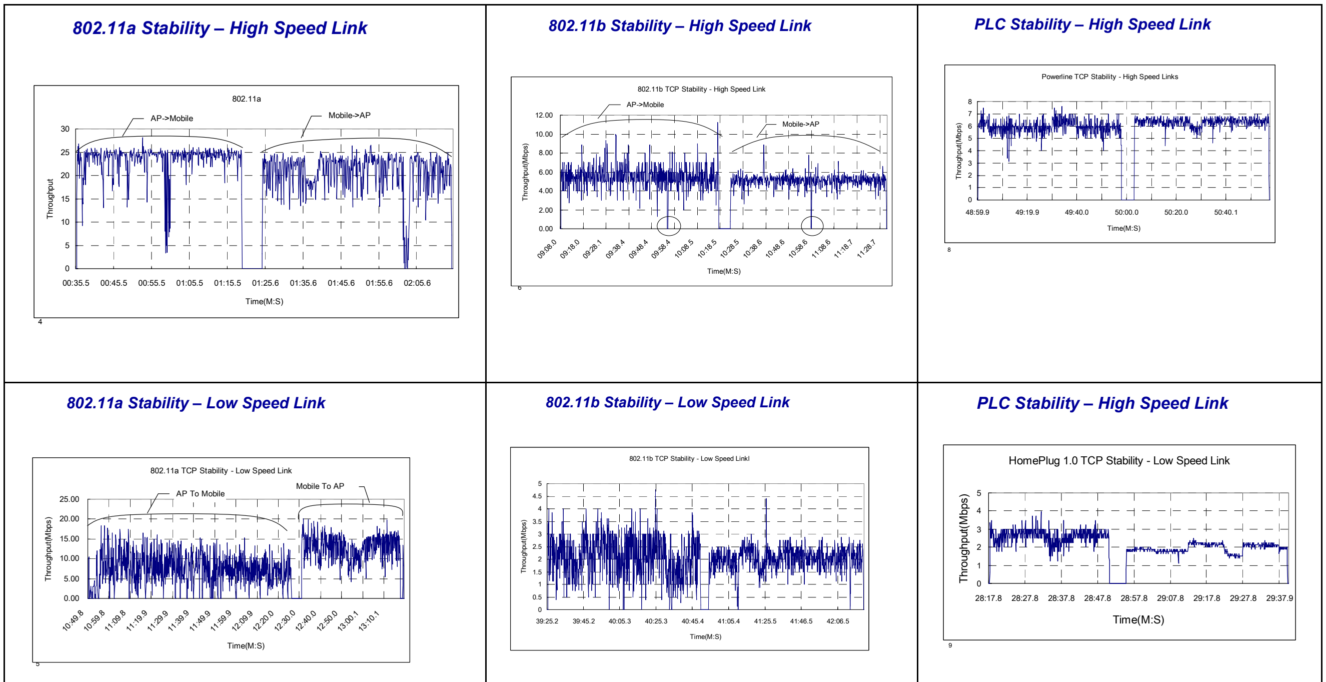


Figure 4 – Adaptation and Stability Comparison or HomePlug 1.0 vs IEEE 802.11a and b

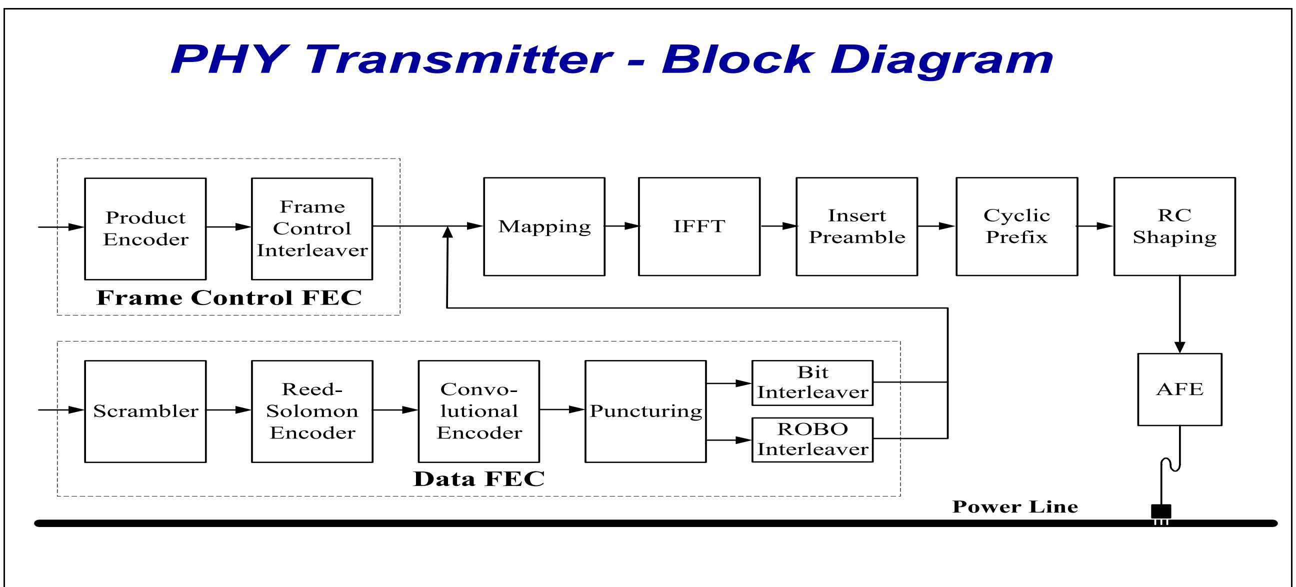


Figure 5 - HomePlug 1.0 OFDM Transmitter

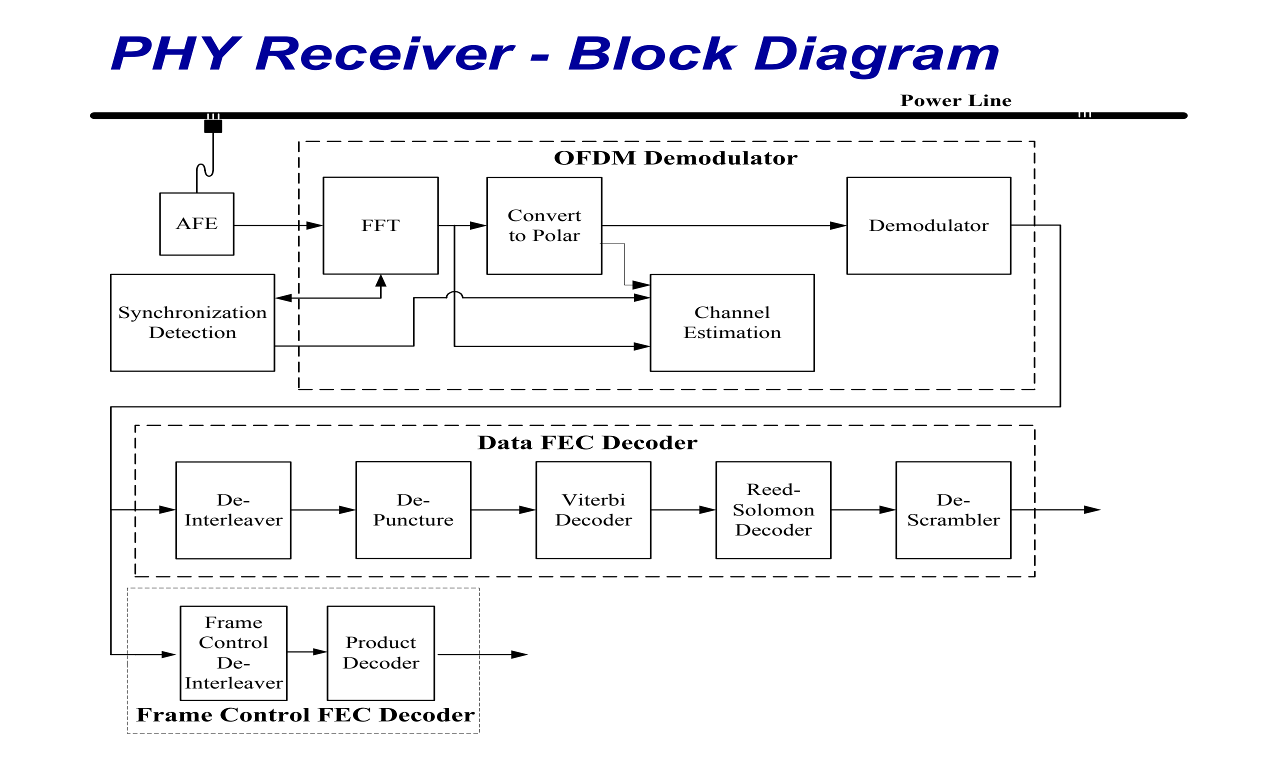
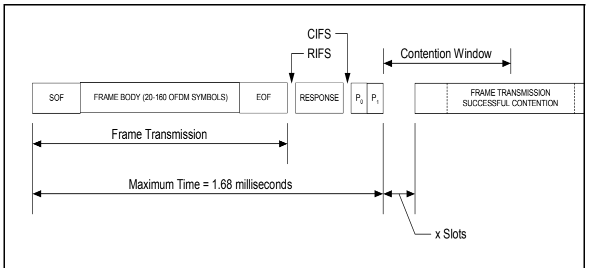


Figure 6 - HomePlug 1.0 OFDM Receiver

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. Figure 3(a) shows the basic frame structures and timing involved in Medium Access Control. The payload is prepended with a delimiter contructed from a Preamble and Frame Control as described earlier. After a period denoted End of Frame Gap (EFG) of 1.5 µs, an End-of-Frame (EOF) delimiter is added by repeating the Preamble and Frame Control, thus increasing the likelihood that all nodes will be synchronized and correctly receive the important information contained in the Frame Control fields.

All nodes wait for a period of Response InterFrame Spacing (RIFS) of 26 µs for the response to be sent in the form of a response delimiter consisting of the preamble sequence and the Frame Control symbols. The Frame Control fields shown in Figure 3(b) contain VCS, priority, and acknowledgement information, needed for the proper operation of the protocol.



Backoff Procedure

Priority	Contention Window Size
3	[8, 16, 16 32]
2	[8, 16, 16 32]
1	[8, 16, 32, 64]
0	[8, 16, 32, 64]

Figure 7 – Basic Channel Access Mechanism

Figure 7 shows how channel contention proceeds at the end of the response. If the Contention Control (CC) bit is set in the Frame Control of the response, then the node presently sending data at a certain priority will continue to attempt to send data ("bursting" - only Priority CA2 and CA3 nodes are allowed to do this), but could be preempted by higher priority nodes asserting their priority in PR0 and PR1. Priority slot PR0 begins after an interval of Contention Interframe Spacing (CIFS) from the end of the response delimiter. Nodes seeking access to the channel must first assert priority CA0-CA3 in PR0 and PR1.

Nodes of the highest winning priorities will then contend for the medium in the contention slots and the node that wins the contention begins to transmit data. Colliding and losing nodes will chose new backoff values from the backoff window for that priority according to the backoff schedule shown in Figure 7. Note that unlike the 802.11x backoff procedure, both colliding and losing nodes in the contention procedure may choose new backoff values, depending on a new variable called *the deferment counter*, which checks how many times a particular node has lost contention.

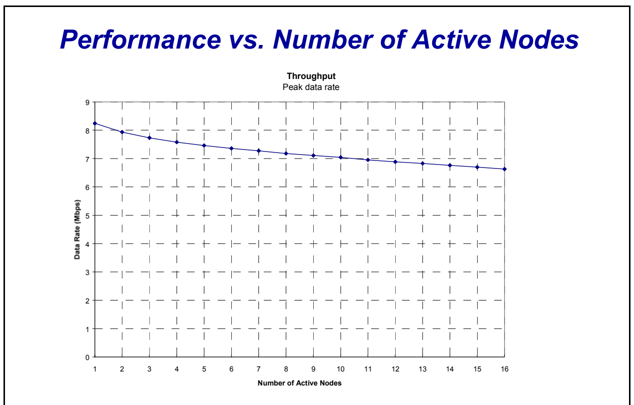


Figure 8 – MAC Throughput Vs Nodes

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.

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. Figure 8 shows how the theoretical MAC throughput for HomePlug 1.0 varies with the number of nodes.

Futher details of the operation of the HomePlug 1.0 protocol and the functions of the various fields, such as Frame Control, are contained in [3].

IV. OVERVIEW OF HOMEPLUG AV

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.

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. Figure 8 shows the structure of the HomePlug AV symbol and Table 3 gives the values of the key PHY parameters.

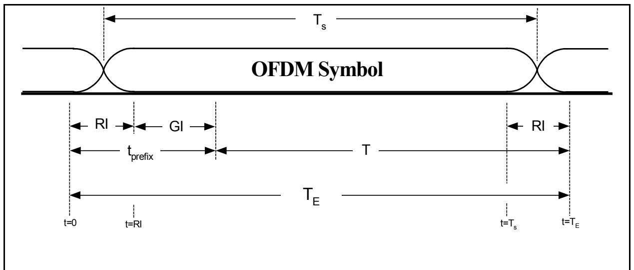


Figure 8 – HomePlug AV OFDM Symbol

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. Likewise, when the system encounters a channel where the delay spread is larger than the guard interval, subcarrier SNRs are not impacted as greatly due to the fact that the percentage of the IFFT interval affected is less.

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

Table 3 – HomePlug AV OFDM Symbol Characteristics

Symbol	Description	Time Samples	Time (µs)
T	IFFT Interval	3072	40.96
t_{prefix}	Cyclic Prefix Interval	RI+GI	4.96+GI
T_E	Extended Symbol Interval ($T + t_{prefix}$)	$T+t_{prefix}$	45.92+GI
RI	Rolloff Interval	372	4.96
T_S	Symbol Period	3072+GI	40.96+GI
GI_{FC}	Frame Control Guard Interval	1374	18.32
GI	Data Symbol Guard Interval, generically	417, 567, 3534	5.56, 7.56, 47.19
GI_{417}	Guard Interval, length=417 samples	417	5.56
GI_{567}	Guard Interval, length=567 samples	567	7.56
GI_{3534}	Guard Interval, length=3534 samples	3534	47.19

large number of carriers both in and around the desired notched band, or additional filtering. Figure 9 details the carrier power rollof for the three guard intervals. Though it varies with guard interval, it can be seen that if all carriers within approximately 115kHz of a desired notched band are turned off, the energy will be at least 30dB down in the notched band. Figure 10 shows the deep notching achieved in HomePlug AV.

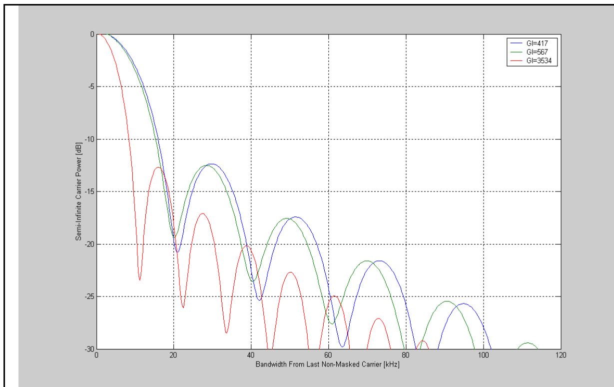


Figure 9 – Notching by turning Off Carriers

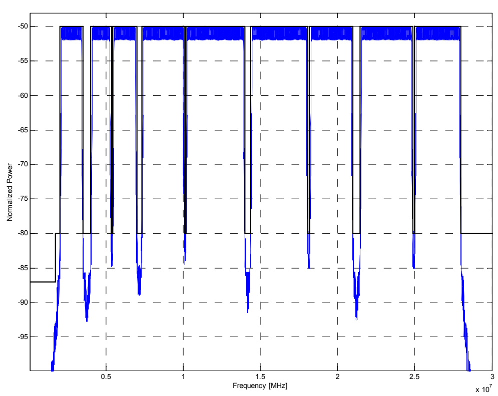


Figure 10 – Deep Notching in AV

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.

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.

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.

The major elements of the HomePlug AV transmitter and receiver are shown in Figure 11. Note that in the transmitter, HomePlug 1.0 Frame Control, HomePlug AV Frame Control and HomePlug AV packet body are generated separately, and are similarly decoded independently at the receiver.

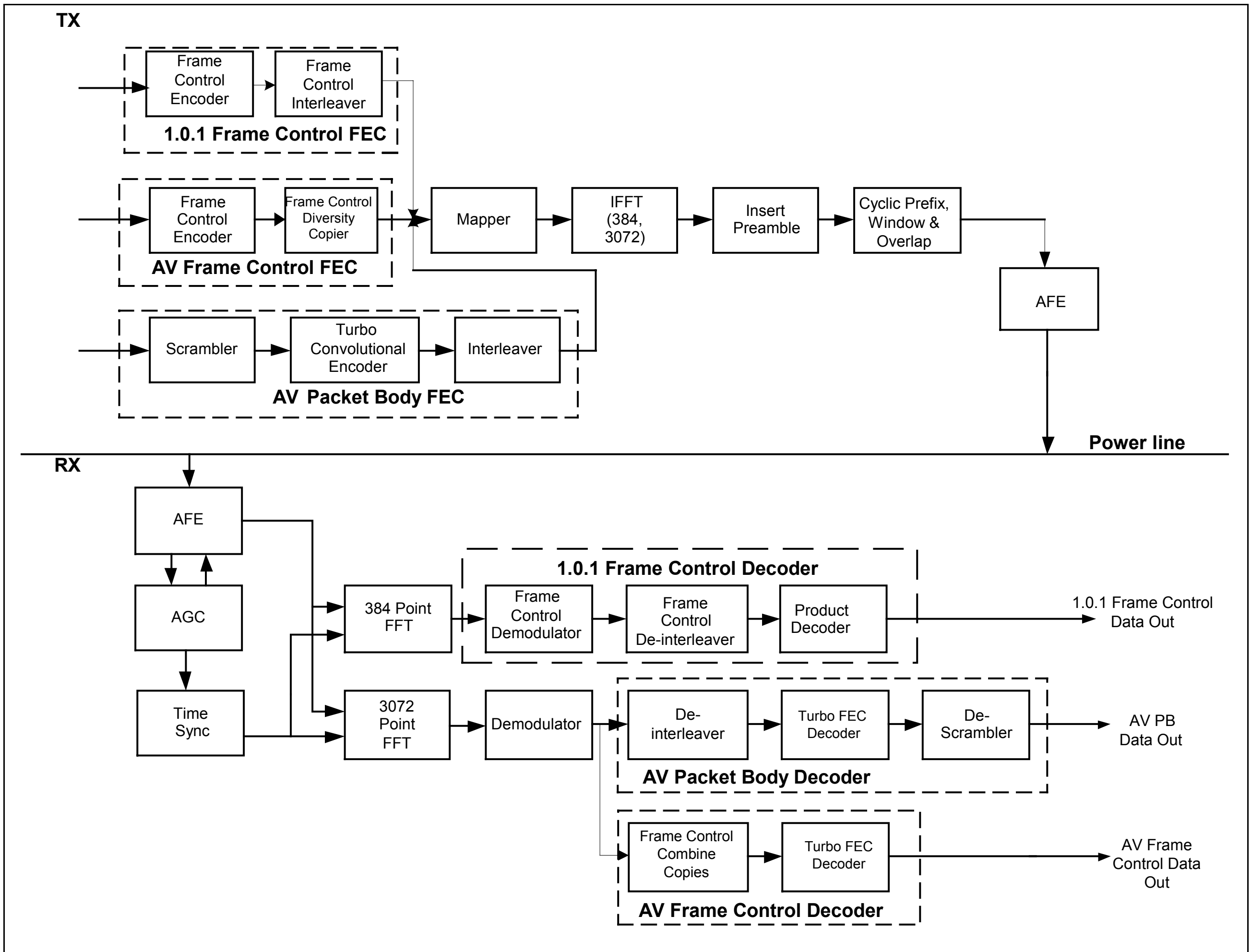


Figure 10 – HomePlug AV Transmitter and Receiver Block Diagrams

<u>HomePlug AV Medium Access</u>

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.

<u>Framing and Segmentation</u>

In HomePlug 1.0, relatively low PHY rates made it reasonable to transmit a single incoming host packet in one or more MPDUs (MAC Protocol Data Units). The order of magnitude increase in PHY rates achieved by HomePlug AV make this approach very inefficient, so incoming host packets are aggregated into a stream of MAC frames, with a total of six bytes of header and ICV (integrity check value) per MAC frame. The MAC frame stream is then segmented into fixed length blocks called PHY Blocks (PBs) that are independently encrypted and corrected. One or more PBs are sent in each MPDU, with each PB carrying a four-byte header to allow correct reassembly.

SR-ARQ Error Control

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.

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.

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.

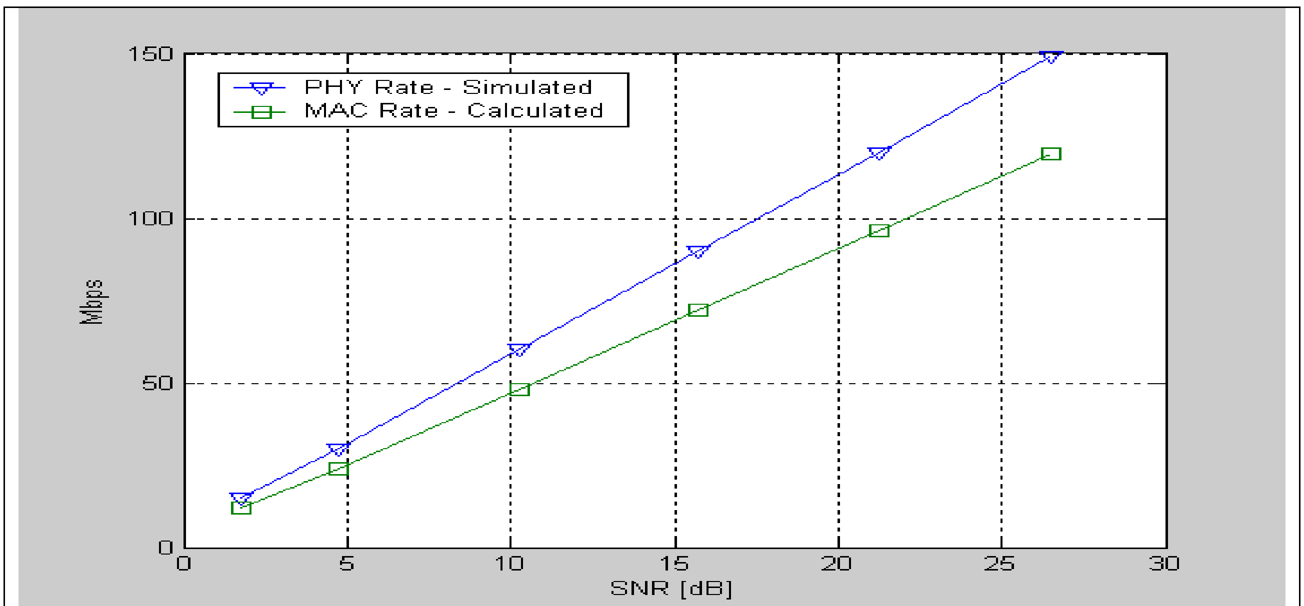


Figure 12 Simulated and Calculated PHY and MAC Data Rates Vs SNR

V. COMMENTS AND CONCLUSIONS

HomePlug AV has made many significant improvements over the already successful HomePlug 1.0 protocol. It is much more efficient and provides stringent QoS gurantees that are impossible to meet in HomePlug 1.0.

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.

HomePlug AV is capable of complete house coverage and will support multiple streams of high and standard definition television, and stereophonic hi-fi music, while still supporting high speed data applications. Figure 11 shows the HomePlug AV PHY Rate and MAC throughput, as a function of signal to noise ratio. No other technology can provide such data rates with whole-house coverage and thus HomePlug AV is expected to provide synergistic solutions for home entertainment equipment manufacturers and content providers.

Broadband Powerline access (BBL) is also certain to benefit from the emerging set of high speed PLC chips, with symmetric access speeds of 20-40 Mbps or more expected to the the home. Due regard is being given to designing emerging standards so BPL and PLC LANs can co-exist. In this regard it is worthwile to note the recent formation of the IEEE Technical Committee on PLC which is actively promoting PLC and BPL reearch, and forming relationships with traditional academic and professional communications organizations.

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