HOMEPLUG STANDARD (POWERLINE ETHERNET)

By Steve Gardner, Brian Markwalter, and Larry Yonge

Ethernet-class networks over standard home power links are coming, thanks to ASIC-based signal processing advances that keep a lid on the interference and transfer function degradations that compromise the power line transmission medium.

The vision of the networked home has driven many a business plan, but product offerings to date have been too limited in capability or in market potential to achieve the dream. Advances in ASIC density, however, enable the use of sophisticated signal-processing techniques at price points that are making Ethernet-class home networks via wireless, phone lines, and now power lines a cost-effective reality.

Home networking is a different animal than networking in the workplace. The applications are different, the traffic patterns are different, and the media available to carry the data are different. Certainly home networking users will want to transfer files between their computers and share peripherals such as printers. They will want gateways to broadband access so they can share their Internet connection between multiple devices.

Users will also want other services, such as voice-over-IP (VoIP), streaming media for entertainment, and support for multiplayer networked games. And while some newer houses are wired with Cat5 cable suitable for Ethernet, most are not. The choices for the physical medium - phone wiring, wireless, and power line - all present a mixed bag of attributes.

The power line is certainly the most difficult medium of these three, but it does have two appealing attributes. First, as with phone lines, no RF conversion hardware is needed, so the cost can be low compared to wireless solutions. But more importantly, power outlets are almost everywhere someone might want to use a networked device at home.

Aiming to stem consumer confusion and market fragmentation, a group of industry leading companies formed the HomePlug Powerline Alliance to create an industry standard for high-speed home networking via power lines. An extensive field trial is planned to validate the v1.0 specification beginning in the first quarter of 2001.

The Power Line as a Transmission Medium

The power line medium is a harsh environment for communication. The channel between any two outlets in a home has the transfer function of an extremely complicated transmission line network with many stubs having terminating loads of various impedances. Such a network has an amplitude and phase response that varies widely with frequency.

At some frequencies the transmitted signal may arrive at the receiver with relatively little loss, while at other frequencies it may be driven below the noise floor. Worse, the transfer function can change with time. This might happen because the homeowner has plugged a new device into the power line, or if some of the devices plugged into the network have time-varying impedances (which can be the case with switching power supplies or motors).

As a result, the nature of the channel between outlet pairs may vary over a wide range. In some cases, a broad swath of bandwidth may be suitable for high quality transmission, while in other cases the channel may have a limited capacity to carry data.

An Adaptive Approach

Due to these frequency variations, efficient use of the medium requires an adaptive approach that compensates for the channel transfer function in some way. HomePlug technology includes an effective and reliable method of performing adaptation that achieves high rates on typical channels, but which adjusts the bit rate to fight through really harsh channels.

In addition to the transfer function problem, and equally significant, interference on the power line must be considered. The most severe interference sources rarely have properties similar to the easily analyzed white Gaussian noise produced by receiver front ends. Instead, the interference can be either impulsive or frequency selective in nature, and sometimes both.

Typical sources of noise are brush motors, fluorescent and halogen lamps, switching power supplies, and dimmer switches. In addition, ingress sources such as amateur band radio transmitters can be significant. The net impact of these different interference sources is that raw received data bits tend to have significant numbers of bit errors, which must somehow be corrected. The HomePlug technology contains a combination of sophisticated forward error correction (FEC), interleaving, error detection, and automatic repeat request (ARQ) to ensure that the channel appears completely reliable to the network layer protocols.

The topology of power distribution to the home is another factor that must be considered. In a typical US neighborhood, a distribution transformer provides power to a relatively small number of homes (perhaps six). The distribution transformer effectively blocks the power line networking signals from crossing into the main power grid, but it does little to stop signals in one of the homes it powers from propagating to another home. Thus networking signals generated in one home may show up (albeit attenuated) on the power line in another home. This creates urgent concerns about privacy, similar to those encountered in wireless systems.

Makers of equipment for low-speed power line networking in the band below 1 MHz have struggled for years with the impact of circuit breakers and two-phase power distribution. Circuit breakers have substantial attenuation in the band used by these devices, so paths from one circuit to another may experience substantially more attenuation than same-circuit paths. Also, most homes have two-phase wiring and there may be no physical connection between some circuits other than the connection at the distribution transformer. Power line communication between such circuits relies on coupling between them, which can easily create 20 dB of loss at frequencies below 1 MHz. Fortunately, the losses from circuit breakers and cross phase coupling are less severe in the band occupied by the HomePlug signal, typically causing only a few dB of additional loss.

HomePlug Overview

Any workable solution to reliable communication on the power line medium must include both a robust physical layer (PHY) and an efficient media access control (MAC) protocol. The MAC protocol controls the sharing of the medium among multiple clients, while the PHY specifies the modulation, coding, and basic packet formats.

The HomePlug PHY uses orthogonal frequency division multiplexing (OFDM) as the basic transmission technique. OFDM is well known in the literature and in industry. It is currently widely used in DSL technology and also in terrestrial wireless distribution of television signals. In contrast to these technologies, however, HomePlug uses OFDM in a burst mode rather than in continuous mode. HomePlug technology also uses concatenated Viterbi and Reed Solomon FEC with interleaving for payload data and turbo product coding (TPC) for sensitive control data fields.

The MAC protocol in the HomePlug technology is a variant of the well-known carrier sense multiple access with collision avoidance (CSMA/CA) protocol. Several features have been added to support priority classes, provide fairness, and allow the control of latency. The use of CSMA/CA means the

PHY must support burst transmission and reception; that is, each client enables its transmitter only when it has data to send and, upon finishing, turns off its transmitter and returns to the receive mode. OFDM divides the high-speed data stream to be transmitted into multiple parallel bit streams, each of which has a relatively low bit rate. Each bit stream then modulates one of a series of closely spaced carriers. The property of orthogonality is a result of choosing the carrier spacing equal to the inverse of the bit rate on each carrier. The practical consequence of orthogonality is this: If we perform a Fast Fourier transform (FFT) of the received waveform over a time span equal to the bit rate on an individual carrier, the value of each point in the FFT output is a function only of the bit (or bits) that modulated the corresponding carrier, and is not impacted by the data modulating any other carrier.

When the carrier spacing is low enough that the channel response is relatively constant across the band occupied by the carrier, channel equalization becomes easy. Implemented in the frequency domain, equalization can be achieved by a simple weighting of the symbol recovered from each carrier by a complex valued constant. Many different types of modulation can be used on the individual carriers.

The need for equalization in HomePlug is completely eliminated by using differential quadrature phase shift keying (DQPSK) modulation where the data is encoded as the difference in phase between the present and previous symbol in time on the same subcarrier (see Figure 1). Differential modulation improves performance in environments where rapid changes in phase are possible.

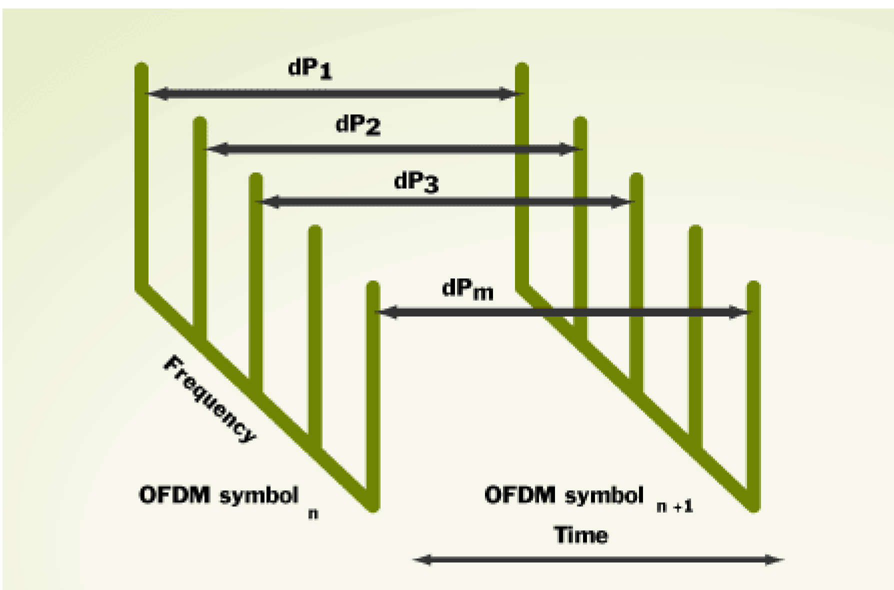

FIGURE 1: *Differential phase encoding across symbols.*

Unlike DSL, HomePlug does not use higher order quadrature amplitude modulation (QAM). With relatively short packets, the overhead required for channel assessment and for estimation of gain and carrier phase creates a capacity penalty that more than offsets any potential gain from the modulation efficiency.

OFDM waveforms are typically generated using an inverse FFT (IFFT) in which the frequency domain points consist of the set of complex symbols that modulate each carrier. The result of the IFFT is called an OFDM symbol. Each symbol has a duration equal to the reciprocal of the subcarrier spacing and generally a long time compared to the data rate. At the receiver, the data can be recovered via a forward FFT, converting back to the frequency domain. Figure 2 shows the process of conversion between the frequency domain and the time domain.

Note that the time domain waveform also includes a cyclic prefix, which is essentially a replication of the last few microseconds of the OFDM symbol. The purpose of the cyclic prefix is to absorb the intersymbol interference that results from the fact that the delay presented by the channel is not constant with frequency.

Without the cyclic prefix, some of the samples used in the FFT would contain energy from either the previous or the following OFDM symbol. If the cyclic prefix is as long as the worst case delay variation across the frequency band, then by waiting until the end of the prefix to start taking samples to use in the FFT, we assure that the FFT is not degraded by the neighboring symbols.

Formed from a series of OFDM symbols, the HomePlug data-bearing packet consists of a start-of-frame delimiter, a payload, and an end-of-frame delimiter (see Figure 3). For unicast transmissions, the destination station responds by transmitting a response delimiter indicating the status of the reception (ACK, NACK, or FAIL).

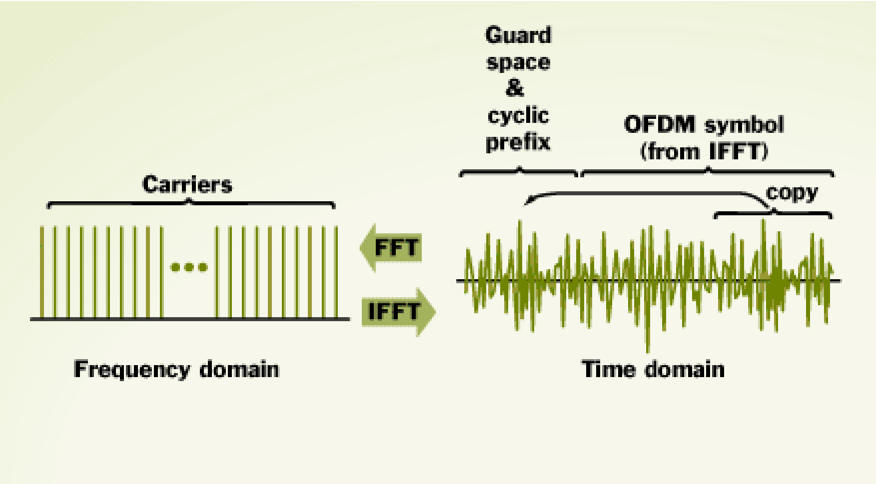

FIGURE 2: *Transform from the frequency to the time domain and adding the cyclic prefix.*

The delimiter consists of a preamble sequence followed by a TPC encoded frame control field. The preamble sequence is chosen to provide good correlation properties so each receiver can reliably detect the delimiter, even with substantial interference and a lack of knowledge of the transfer function that exists between the receiver and the transmitter interference.

The frame control contains MAC layer management information (for example, packet lengths, and response status). The low rate TPC and interleaving used on the frame control provide good immunity to frequency selective impairments as well as broadband interference. All three delimiter types have the same structure, but the data carried in the delimiter varies depending on the delimiter function.

Unlike the delimiters, the payload portion of the packet is intended only for the destination receiver. Payload data is carried only on a set of carriers that have been previously agreed upon by the transmitter and intended receiver during a channel adaptation procedure.

Because only carriers in the "good" part of the channel transfer function are used, it is not necessary to use such heavy error correcting coding as is required for transmissions intended for all receivers. This combination of channel adaptation and lightening of the coding for unicast payloads allows HomePlug to achieve high data rates over power line.

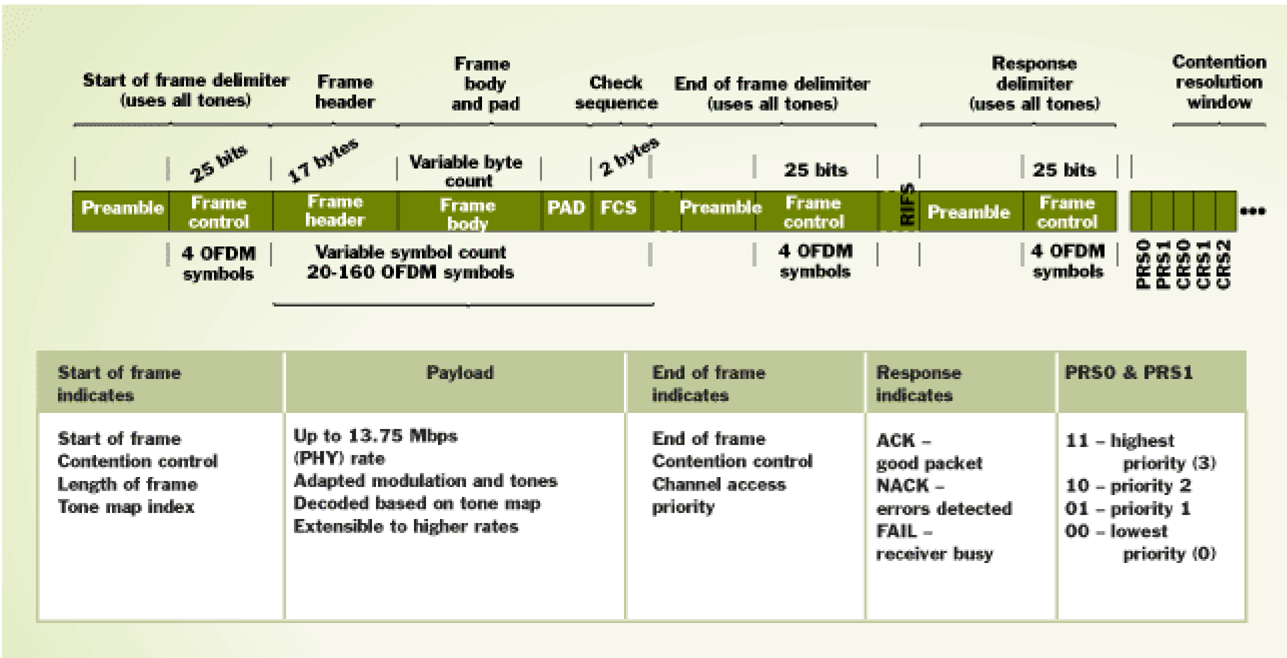

Figure 3: *HomePlug transmission format.*

The adaptation has three degrees of freedom:

- De-selection of carriers at badly impaired frequencies
- Selection of modulation on individual carriers (DBPSK or DQPSK)
- Selection of convolutional code rate (1*2 or 3*4).

In addition to these options, the payload can be sent using ROBO mode, a highly robust mode that uses all carriers with DBPSK modulation on each and heavy error correcting code with bit repetition and interleaving. ROBO mode does not use carrier de-selection and thus can generally be received by any receiver. The mode is used for initial communication between devices that have not performed channel adaptation, for multicast transmission, or for unicast transmission in cases where the channel is so poor that ROBO mode provides greater throughput than de-selection of carriers with lighter coding.

The HomePlug PHY occupies the band from about 4.5 to 21 MHz. The PHY includes reduced transmitter power spectral density in the amateur radio bands to minimize the risk of radiated energy from the power line interfering with these systems. The raw bit rate using DQPSK modulation with all carriers active is 20 Mbps. The bit rate delivered to the MAC by the PHY layer is about 14 Mbps.

The MAC layer

The HomePlug transmission format is shown in Figure 3. The MAC uses a virtual carrier sense (VCS) mechanism and contention resolution to minimize the number of collisions. Upon receipt of a preamble, the receiver attempts to recover the frame control.

The frame control indicates whether the delimiter is a start of frame, end of frame, or response delimiter. Start of frame delimiters specify the duration of the payload to follow, while the other delimiters implicitly define where the end of transmission lies. Thus, if a receiver can decode the frame control in the delimiter, it can determine the duration for which the channel will be occupied by this transmission, and it sets its VCS until this time ends.

If it cannot decode the frame control, the receiver must assume that a maximum-length packet is being transmitted and set the VCS accordingly. In this case it may subsequently receive an end-of-frame delimiter and thus be able to correct its VCS.

The destination always acknowledges unicast packets at the MAC layer by transmitting the response delimiter. If the source fails to receive an acknowledgment, it assumes that a collision has caused the failure. The destination may also choose to signal FAIL if it has insufficient resources to process the frame, or it can signal NACK to indicate that the packet was received with errors that could not be corrected by the FEC.

The contention resolution protocol includes a random back-off algorithm to disperse the transmission times of frames queued (or being retransmitted due to collision) while the channel was busy, and also provides a way to ensure that clients obtain access to the channel in order of their priority.

When one node completes a transmission, other nodes with packets queued to transmit signal their priority in a priority resolution inter-val (indicated by PRS0 and PRS1 in Figure 3). The signals for this purpose use on/off keying and are designed so the priority of the highest priority user can be easily extracted, even when multiple users signal different priorities at the same time.

Slot Choices

Nodes with queued frames having priority equal to the highest priority signaled choose a slot in a contention resolution window in which they will initiate transmission if no other node begins transmission in an earlier slot. Each node chooses its slot at random over an interval that grows with increasing numbers of unsuccessful attempts to access the channel. If a node was preempted in a previous contention resolution window, it continues counting slots from where it left off rather than choosing a new random value. This approach improves the fairness of the access scheme.

Collision can occur if a node wishing to transmit fails to recognize a preamble from another node, or if the earliest chosen slot in the contention resolution window is selected by more than one node. The preamble design is robust enough to ensure that the missed preamble rate is so low that this source of collisions has only minor impact, so the latter cause produces the majority of collisions.

Segmentation and reassembly is provided to improve fairness and reliability, and to reduce latency. The MAC also includes features that allow the transmission of multiple segments with minimal delay in cases where there are no higher priority frames queued with other nodes, and it provides a capability for contentionless access in which access to the channel may be passed from node to node.

A common misconception is that contention-based access schemes have potentially unbounded latency. In the HomePlug MAC, the latency is bounded by the expedient of discarding packets that cannot be delivered in the time required by the application.

It has been shown that the percentage of HomePlug packets discarded through this approach is low enough to be encompassed by the tolerated missed packet rate for low latency applications such as

VoIP or streaming media. The combination of this feature and priority classes makes HomePlug well suited to applications requiring QoS.

Channel adaptation occurs when clients first join a logical network and occasionally thereafter, based on either a timeout or on detected variation in the channel transfer function (which might be either an improving or degrading condition). Any node can initiate a channel adaptation session with any other node in its logical network. The adaptation is a bi-directional process that causes either node to specify to the other the set of tones, modulation, and FEC coding to use in subsequent payload transmissions.

Privacy is provided through the use of 56-bit data encryption standard (DES) applied at the MAC layer. All nodes on a given logical network share a common encryption key. The key management system includes features that enable the distribution of keys to nodes that lack an I/O capability.

The Alliance

The HomePlug Powerline Alliance is a not-for-profit corporation established to provide a forum for the creation of open specifications for high-speed home power line networking products and services. The alliance is open to all companies that sign the adopter/participant agreement and make a small dues payment. Further information is available at the HomePlug Web site: www.homeplug.org.

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