W H I T E   P A P E R

PowerPacket™ Primer

Introduction

Home networking provides three choices for No New Wires™ physical media - phone wiring, wireless, and powerline. The powerline is arguably the most difficult medium of these three, but it does have two appealing attributes. No RF conversion hardware is needed, so the cost can be low compared to wireless solutions. This characteristic also exists for phoneline. More importantly, power outlets are available essentially everywhere someone might want to use a networked device at home. This is the biggest distinction from phoneline, which has between 2 and 3 jacks in the average US home.

Intellon's PowerPacket technology, the basis of the HomePlug Powerline Alliance industry specification, is a carefully crafted version of Orthogonal Frequency Division Multiplexing (OFDM). OFDM is a spectrum efficient modulation technique that enables transmission of very high data rates in frequency selective channels. Data rates in excess of 100 Million bits per second (Mbps) are possible. PowerPacket is a multiple carrier system with characteristics that make it adaptable to environments with harsh multi-path reflections without equalization. OFDM modulation is essentially the simultaneous transmission of a large number of narrow band carriers, sometimes called subcarriers, each modulated with a low data rate, but the sum total yielding a very high data rate. The history of OFDM dates back to 1966, when R. W. Chang published his paper on the synthesis of band-limited orthogonal signals for multichannel transmission (Bell System Technical Journal). The remainder of this white paper describes the powerline as a transmission medium and explains the particulars of PowerPacket, Intellon MAC/PHY OFDM technology.

The powerline as a transmission medium

The powerline medium is a harsh environment for communication. The channel between any two outlets in a home has an unpredictable transfer function caused by the nearly random interconnection of circuit branches and loads. The channel has an amplitude and phase response that varies widely with frequency. The amplitude response may vary over the band of interest from a few dB to more than 80 dB. The powerline is also subject to time variation in the channel response as devices switch on and off.

Several classical approaches can be applied to overcome frequency selective channels. Spread spectrum can be used on these channels and is effective for lower data rates. But, spread spectrum has an averaging effect that makes it impossible to reach the data rates attained by PowerPacket in the same bandwidth. Equalization can also be used to overcome amplitude and phase distortion caused by the channel. Complexity is the main Achilles heel of equalization; however, it is a step in the right direction in that equalization is a form of adaptation to the channel. PowerPacket makes efficient use of the medium by adapting which carriers hold information and the modulation rate of the carriers to compensate for the channel transfer function and achieve high rates on typical channels.

Theoretical data rate of any channel is proportional to Signal to Noise Ratio (SNR). The previous transfer function discussion addresses how much signal gets to the receiver but leaves out the effect of noise – a big consideration with powerline.

Typical sources of noise are brush motors, fluorescent and halogen lamps, switching power supplies, and dimmer switches. Narrowband RF ingress also occurs from sources such as amateur band radio transmitters. Noise on the powerline is non-Guassian, causing Intellon to design PowerPacket with a combination of sophisticated forward error correction (FEC), interleaving, error detection in the PHY. This is overlaid with an automatic repeat request (ARQ) protocol to provide the most reliable service to the Network Layer.

PowerPacket Overview

The PowerPacket PHY uses orthogonal frequency division multiplexing (OFDM) as the basic transmission technique. It is currently widely used in DSL technology, in terrestrial wireless distribution of television signals, and has been adopted for the IEEE's high rate wireless LAN standard (802.11a). PowerPacket technology also uses concatenated Viterbi and Reed Solomon FEC with interleaving for payload data, and turbo product coding (TPC) for frame control fields.

The MAC protocol in the PowerPacket technology is a variant of the well-known carrier sense multiple access with collision avoidance (CSMA/CA) protocol, similar to 802.11. This protocol uses a classic, listen-before-talk strategy and transmission after a randomly selected delay to avoid collisions. Several features have been added to support priority classes, provide fairness, and allow the control of latency.

PowerPacket PHY

OFDM takes the high-speed serial data stream to be transmitted and processes it as 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. Carrier spacing is chosen to be equal to the inverse of the data rate to achieve orthogonality.

OFDM carrier spacing is generally chosen such that each carrier experiences a flat response in the channel. The need for equalization in PowerPacket is completely eliminated by using differential phase modulation. Figure 1 illustrates differential phase modulation where the data is encoded as the difference in phase between the current and previous symbol in time on the same carrier.

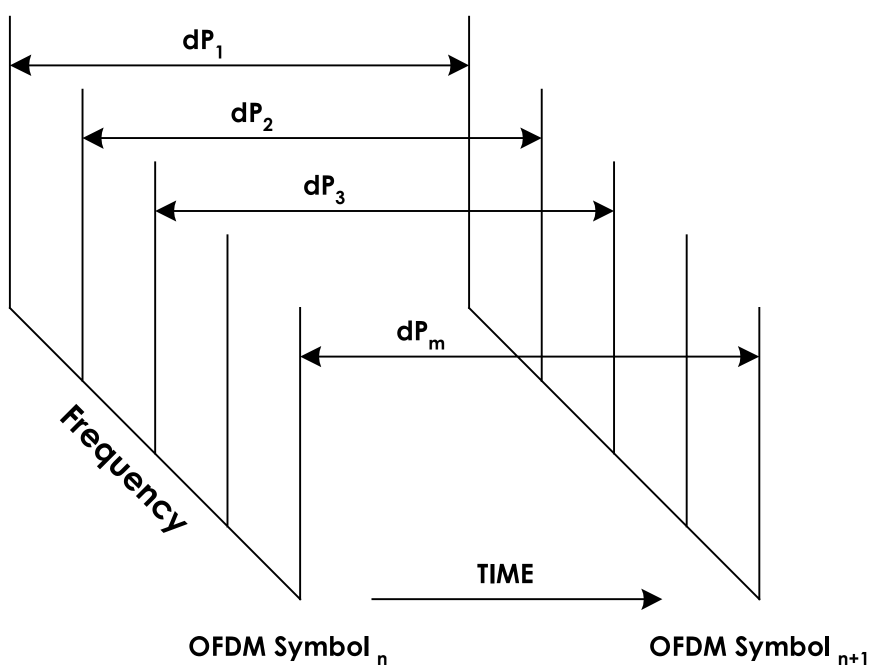


Figure 1. PowerPacket Differential Modulation

OFDM waveforms are typically generated using an inverse FFT (IFFT) in which the frequency domain points (input to the transform) consist of the set of complex symbols that modulate each carrier. The output of the IFFT is a time-domain signal, called an OFDM symbol. Each symbol has a duration equal to the reciprocal of the subcarrier spacing. Since an FFT is reversible, 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.

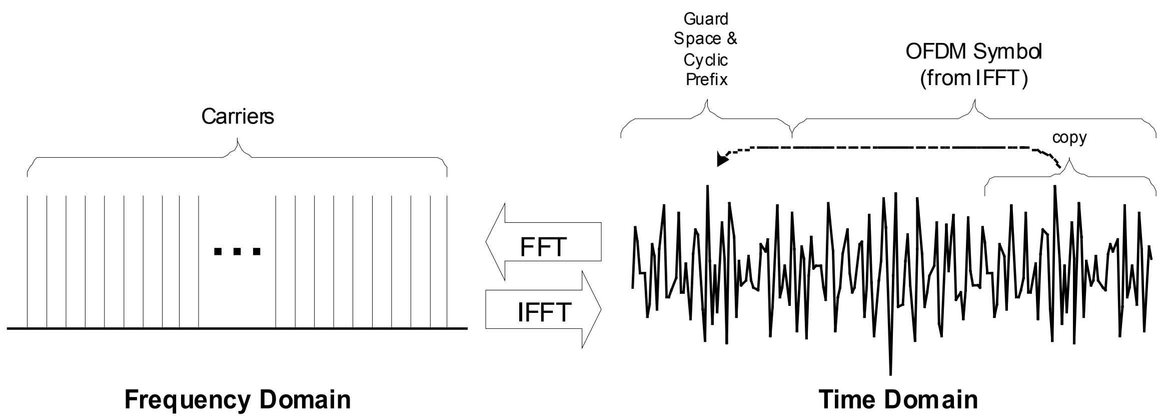


Figure 2. Symbol Creation by IFFT

One of the signal processing tricks used by PowerPacket is the addition of a cyclic prefix, which is essentially a replication of the last few microseconds of the OFDM symbol. The cyclic prefix is a "throw-away" portion of the transmitted symbol allowed to be corrupted by inter-symbol interference. Without the cyclic prefix, some of the samples used in the FFT would contain energy from either the previous or the following OFDM symbol.

The PowerPacket transmission frame consists of a start-of-frame delimiter, a payload, and an end-of-frame delimiter, as shown in Figure 3. Delimiters comprise a preamble sequence followed by a TPC encoded frame control field. The preamble sequence is a known pattern chosen to be reliably detected by all receivers regardless of channel conditions. Unicast transmissions are acknowledged by the transmission of a response delimiter. Start of Frame, End of Frame, and Response delimiters all have the same symbol structure but contain fields pertinent to their function.

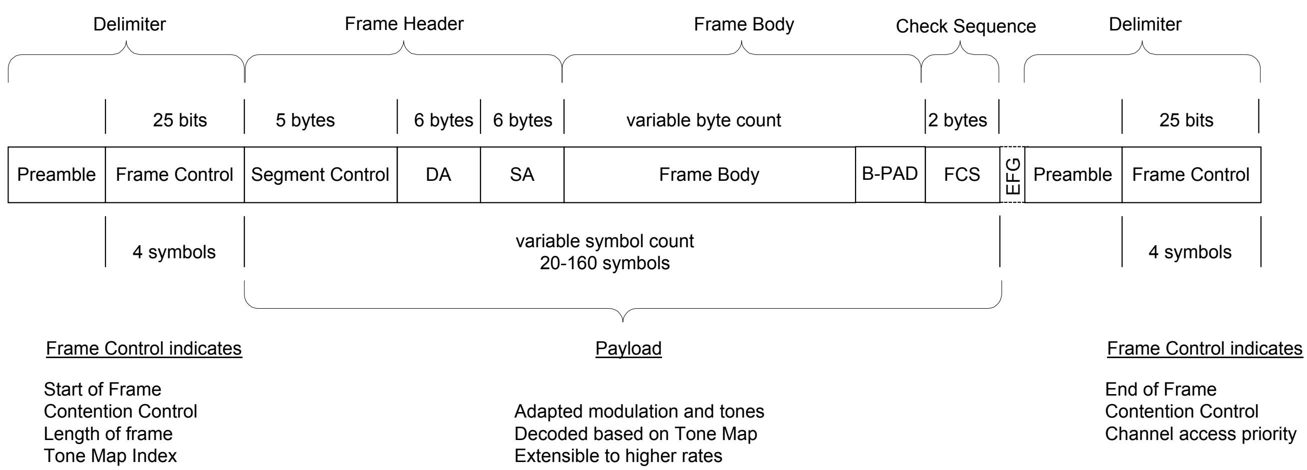


Figure 3. PowerPacket Frame Format

The payload portion of a frame is rate adaptive according to the quality of the channel between the transmitter and receiver. Rate adaption occurs in three ways: by not using some carriers to transport data, by changing the modulation of those carriers in use between DQPSK and DBPSK, and by changing the convolutional FEC rate between ¾ and ½. This technique of negotiating the best payload data rate is fundamental to PowerPacket's ability to achieve a high data rate on the powerline.

The lowest data rate, strongest coding is 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 the best throughput.

The PowerPacket PHY occupies the band from about 4.5 to 21 MHz. Intellon's ICs perform digital filtering to meet HomePlug's transmitter power spectral density (PSD) mask, including the 30 dB notches required to avoid interference with amateur radio operators.

PowerPacket MAC

The PowerPacket frame format is shown in Figure 3. PowerPacket uses both physical carrier sense and virtual carrier sense to infer whether another station is transmitting. Physical carrier sense is the detection of transmitted OFDM symbols from another station. Virtual carrier sense is a timing-based tracking of whether the medium is occupied. Information is placed in the frame control field of each delimiter that allows a receiver to determine how long the channel will be busy with that transmission, even if the receiver subsequently loses tracking (physical carrier sense) of the frame. These mechanisms substantially improve performance in a network like powerline where some stations may experience great variation in receive signal strength.

Collisions cannot be detected directly during transmission due to the large dynamic range of the system. In other words, a transmitter hears himself at full strength and is deaf to a weak colliding transmission from a remote station. Collisions are instead inferred by the absence of an expected acknowledgement from the destination. All unicast transmission are acknowledged with a response delimiter. PowerPacket also makes use of negative acknowledgement by allowing the receiver to transmit a NACK or FAIL, if a frame was received with errors or could not be processed by the receiver due to resource limitations.

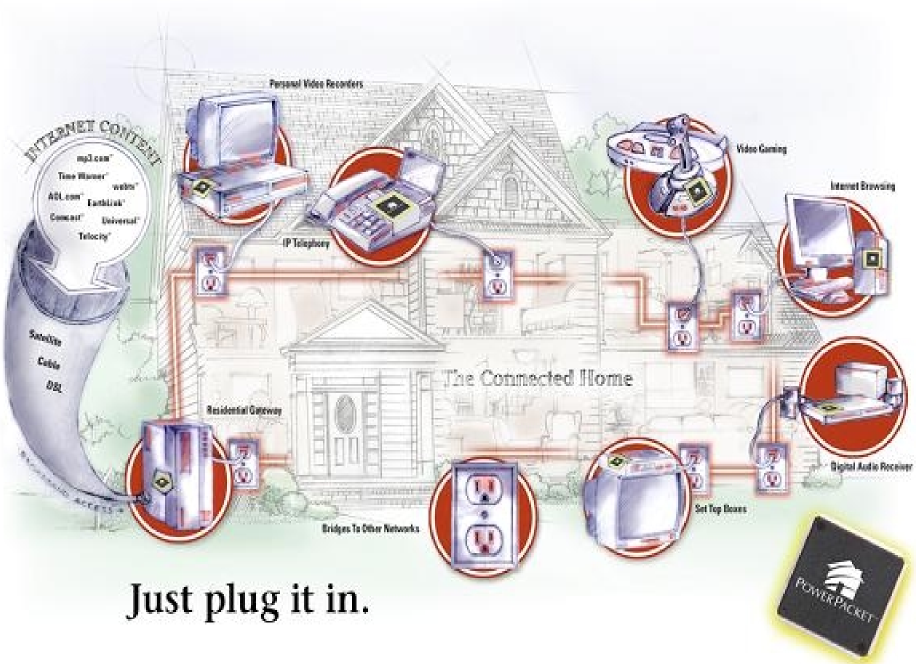
Channel access is based on a randomized contention window with exponential backoff, similar to Ethernet. The contention window is preceded by a priority resolution period that narrows the field of contending stations to those with the highest priority frames queued. When one node completes a transmission, other nodes with packets queued to transmit, signal their priority in a priority resolution period. A binary coding of priority level is used to signal the intention to contend in the next window. The encoding with robust OFDM symbols allows all stations on the network to determine whether any other station with a higher priority has claimed the contention window.

Each station that makes it past the priority resolution period randomly selects a transmission slot in the contention window and begins counting down to its slot number as time passes. The contention window grows with increasing numbers of unsuccessful attempts to access the channel. If a station detects another station's transmission before its own slot number is reached, it pauses counting and switches to receive mode. Once the other transmission is over, the station can resume counting slots in the next contention window.

Since PowerPacket is rate adaptive, the transmission time for a given packet size varies. Long transmission times thwart a protocols ability to offer Quality of Service (QoS) because a high priority frame may be forced to wait for a long, slow transmission to complete. PowerPacket overcomes this problem by requiring segmentation of frames that exceed a certain duration. Higher priority frames can then jump in between the slower transmission's segments. To reduce the chance for collision among equal priority members, PowerPacket uses segment bursting, which allows all segments of packet to be transmitted back-to-back unless interrupted by a higher priority. An extension of this capability is contention-free access in which a station transmits a limited number of frames to different destinations without interruption. Contention-free access improves QoS for certain types of multimedia traffic.

Channel adaptation occurs when a station first needs to transmit to another station 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). Channel adaptation has directionality in that the set usable carriers, modulation, and FEC coding to use for subsequent transmissions is specified by the receiver and may be different in the reverse direction.

A logical network is created by PowerPacket's privacy mechanism in which all stations in the network share a common encryption key. Encryption of all frames is then performed by a 56-bit DES algorithm using cipher block chaining.



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POWERPACKET™

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