HomePlug 1.0 Technology White Paper

With the inevitable arrival of broadband access, the demand for sending digital voice, video and Internet data within the home increases continuously. While retrofitting the house with special wires is one option, it is expensive and time consuming. With multiple outlets in every room, residential powerlines are already the most pervasive network in the home. HomePlug standards allow the use of this existing infrastructure to provide high speed networking capabilities.

Affordable broadband Internet communication to residential customers is now available via Cable Modems and various flavors of Digital Subscriber Lines (DSL). In turn there is a growing need for in-home networks to share this single full-time Internet access link, while supporting a wide range of digital data and multimedia communication services. While it is a simple matter to use a 10/100 Base-T network hub to link several computers in a single room or in a small office environment, it is much more challenging to provide network connections in several rooms in a typical home. One option is to re-wire the home with network cabling (typically 10/100 Base-T CAT-5 cabling) which is quite an expensive proposition especially if existing homes are to be retrofitted with data communication cables.

With multiple outlets in every room, residential powerlines are already the most pervasive network in the home. Using this existing infrastructure to provide high speed networking capabilities provides several benefits. First of all, there is no need for expensive rewiring of the house. Secondly, almost all devices that need to be networked are already connected to the AC wiring. Thus, home networking becomes as simple as plugging the device in the AC outlet.

HomePlug Powerline Alliance, a non-profit industry association, was formed in March of 2000 by a group of industry leading companies to enable standards based powerline networking products. The first industry standard [1] was released in June 2001. In this white paper we provide an overview of the HomePlug 1.0 standards.

Powerline Medium

Home powerline is originally devised for distribution of power at 50-60Hz. The use of this medium for communications at higher frequencies presents some technically challenging problems. Power line networks are usually made of a variety of conductor types, joined almost at random, and terminating into loads of varying impedance. Such a network has an amplitude and phase response that varies widely with frequency. At some frequencies, the signal may arrive at the receiver with relatively very little loss, while other frequencies may be driven below the noise floor. Furthermore, the channel characteristics can also vary with time as the load on the network changes.

Powerline networks are also affected by interference. Electric appliances with brush motors, switching power supplies and halogen lamps produce impulse noise that can reduce the reliability of communication signals. Due to high attenuation over the powerline, the noise is also location dependent. Apart from these, ingress sources such as amateur radio transmission can render certain frequencies unfit for communication.

HomePlug 1.0 products overcome these challenges by using an adaptive approach that uses robust transmission technique combined with sophisticated forward error correction (FEC), error detection, data interleaving, and automatic repeat request (ARQ).

HomePlug Physical Layer

Orthogonal Frequency Division Multiplexing (OFDM) is the basic transmission technique used by the HomePlug. OFDM is well known in the literature and in industry [1,2]. It is currently used in DSL technology [3], terrestrial wireless distribution of television signals, and has also been adapted for IEEE's high rate wireless LAN Standards (802.11a and 802.11g). The basic idea of OFDM is to divide the available spectrum into several narrowband, low data rate subcarriers. To obtain high spectral efficiency the frequency response

of the subcarriers are overlapping and orthogonal, hence the name OFDM. Each narrowband subcarrier can be modulated using various modulation formats. By choosing the subcarrier spacing to be small the channel transfer function reduces to a simple constant within the bandwidth of each subcarrier. In this way, a frequency selective channel is divided into many flat fading subchannels, which eliminates the need for sophisticated equalizers.

The OFDM used by HomePlug is specially tailored for powerline environments. It uses 84 equally spaced subcarriers in the frequency band between 4.5MHz and 21MHz. Cyclic prefix and differential modulation techniques (DBPSK, DQPSK) are used to completely eliminate the need for any equalization. Impulsive noise events are overcome by means of forward error correction and data interleaving. HomePlug payload uses a concatenation of Viterbi and Reed-Solomon FEC. Sensitive frame control data is encoded using turbo product codes.

An Adaptive Approach

The powerline channel between any two links has a different amplitude and phase response. Furthermore, noise on the powerline is local to the receiver. HomePlug technology optimizes the data rate on each link by means of an adaptive approach. Channel adaptation is achieved by Tone Allocation, modulation and FEC choice. Tone allocation is the process by which certain heavily impaired carriers are turned off. This significantly reduces the bit error rates and helps in targeting the power of FEC and Modulation choices on the good carriers. HomePlug allows for choosing from DBPSK 1/2, DQPSK 1/2 and DQPSK 3/4 on all the carriers. The end result of this adaptation is a highly optimized link throughput.

The HomePlug networking specifications are the only globally recognized standards for high–speed powerline networking.

Certain types of information, such as broadcast packets, cannot make use of channel adaptation techniques. HomePlug uses an innovative modulation called ROBO, so that information is reliably transmitted. ROBO modulation uses a DBPSK with heavy error correction with bit repetition in time and frequency to enable highly reliable communication. ROBO frames are also used for channel adaptation.

HomePlug MAC

The choice of Medium Access Control (MAC) protocol provides a different set of challenges. Home networks should be able to support a diverse set of applications ranging from simple file transfer to very high QoS demanding applications such as Voice-over-IP (VoIP) and Streaming Media. The HomePlug MAC is built to seamlessly integrate with the physical layer and addresses these needs.

HomePlug MAC is modeled to work with IEEE 802.3 frame formats. This choice simplifies the integration with the widely deployed Ethernet. HomePlug MAC appends the Ethernet frames with encryption and other management before transmitting it over the powerline. A segmentation and reassembly mechanism is used to in cases where the complete packet cannot be fit in a single frame.

Frame Formats

HomePlug technology uses two basic frame formats (refer Figure 1). A Long Frame consists of a Start of Frame (SOF) delimiter, Payload and End of Frame delimiter (EOF). A Short Frame consists of a Response Delimiter and is used as part of the Stop-and Wait automatic repeat request (ARQ) process. ARQ mechanism causes retransmission of corrupt packets, thus reducing the packet error rate.

All the delimiters share a common structure. A delimiter consists of a Preamble and Frame Control information field. The Preamble is a form of spread spectrum signal that is used to determine the start of a delimiter. This is followed by Frame Control information, which is encoded using a robust Turbo Product Code and can be detected reliably even at several dB below the noise floor. Among other things, delimiters convey timing information that is used by MAC to determine the availability of the medium. The robust design of the delimiter helps the nodes to obtain a very high level of synchronization, thus reducing unintended collisions. The details of the various field contained in the Frame Control are given in Table 1. The Payload of the Long Frame delimiter is encoded based on the channel adaptation. The first 17 bytes of the payload contain the Frame Header. This field contains the source address, destination address and segmentation information.

HomePlug technology limits the maximum length of the payload field in the Long Frame to 160 OFDM Symbols (~1.3 msec). This manifests as better guarantees of QoS as the delay incurred by higher priority traffic due to on going lower priority transmission is reduced. If the packet cannot be fitted into a Long Frame, a segmentation and reassembly mechanism is used to send it in multiple Long Frames. The frame header contains information that is used by the receiver to properly reconstruct the segmented packet. The Payload is protected by a Frame Check Sequence (FCS) to detect uncorrected errors.

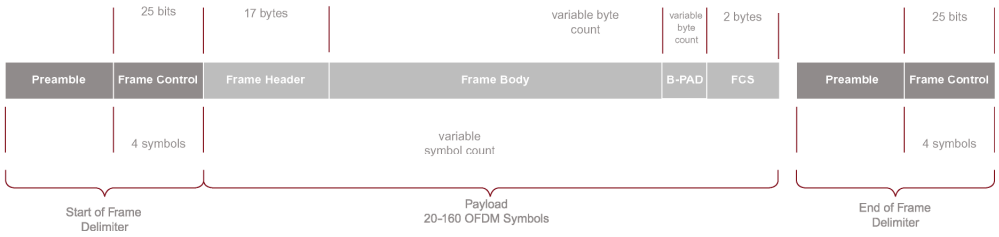


Figure 1: Long Frame Format

Millions of HomePlug based products have shipped throughout North America, Europe and Asia.

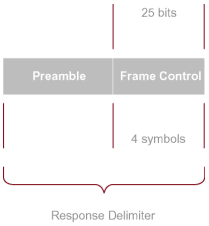


Figure 2: Short Frame Format

Channel Access Mechanism

The channel access mechanism used by the HomePlug MAC is a variant of the well-known CSMA/CA protocol. A typical CSMA/CA protocol would require nodes to sense the medium (this is the carrier sensing part) for other traffic. If the medium is busy, nodes will defer from transmitting until the medium becomes idle. When the medium becomes idle, nodes will wait for a randomly chosen duration (this is the collision avoidance part). A node will transmit only if it detects no other traffic on the medium during this randomly chosen duration. HomePlug channel access scheme builds upon this mechanism by providing prioritized access along with high network utilization. The overall protocol includes a carrier sensing mechanism, a priority resolution mechanism and a backoff algorithm.

The carrier sense mechanism helps HomePlug nodes to synchronize with each other. At the heart of this mechanism are the delimiters. HomePlug technology uses a combination of Physical Carrier Sense (PCS) and Virtual Carrier Sense (VCS) to determine the state of the medium (i.e., if the medium is idle or busy and for how long). PCS is provided by the HomePlug PHY and basically indicates whether a preamble signal is detected on the medium. VCS is maintained by the HomePlug MAC layer and is updated based on the information contained in the delimiter (refer Table 1). Delimiters contain information not only on the duration of current transmission but also on which priority traffic can contend for the medium after this transmission. PCS and VCS information is maintained by the MAC to determine the exact state of the medium.

Table 1: Frame Control Information Fields

Delimiter Type	Fields	Meaning
Start of Frame (SOF)	Type	This can be SOF with response expected or an SOF with no response expected depending on whether a Short Frame delimiter is expected at the end of this Long Frame
	Contention Control	When set to 1, this prevents all HomePlug nodes with packets of priority level equal to or less than the current Long Frame's priority from accessing the channel. However, higher priority nodes can still interrupt this transmission
	Frame Length	This indicates the length of the payload in multiples of OFDM symbol blocks
	Tone Map Index	This is an index to the channel adaptation information stored at the receiver. Note that the variable length Payload is encoded using the maximum transfer rates that can be achieved by the link.
End of Frame (EOF)	Type	This can be EOF with response expected or an EOF with no response expected depending on whether a Short Frame delimiter is expected at the end of this Long Frame.
	Contention Control	The information conveyed is same as that conveyed by this field in SOF delimiter. This redundancy helps in better synchronization.
	Channel Access Priority (CAP)	This field indicates the priority of the current Long Frame.
Response (Resp)	Type	This can be ACK (positive acknowledgment), NACK, (negative acknowledgment indicating faulty reception) , or FAIL (negative acknowledgment indicating lack of resources)
	Channel Access Priority (CAP)	This field indicates the priority of the preceding Long Frame

Connecting HomePlug enabled products is easy, convenient, and cost–effective.

The Priority resolution mechanism provides prioritized access of the medium in a highly distributed manner. Due to the distributed nature of this mechanism, there is no need for a central node to coordinate access over the medium as in the case of some networking technologies. HomePlug allow up to four different priority levels. At the heart of this priority resolution mechanism are the priority resolution slots (PRS) and the priority resolution signals. Priority resolution signals use a form of spread spectrum signal that has a high tolerance to delay spread and is also very robust. High tolerance to delay spread prevents destructive interference when multiple nodes assert in the same priority resolution slot. After the end of every transmission, two slots are allocated for priority resolution. Figure 3 shows the occurrence of priority resolution signals with respect to the end of previous transmission and the subsequent contention period. After priority resolution slots, contention will be only between nodes that have the highest available priority in the network. For example, when all four priorities are present in the network, Priority 3 and Priority 2 nodes will transmit priority resolution signal in PRS0. Priority 1 and Priority 0 nodes will detect this signal, causing them to defer to the higher priority traffic. Priority 3 nodes will transmit a priority resolution signal in PRS1 which will be detected by the Priority 2 nodes, causing them to defer. Thus only Priority 3 nodes will contend in the Contention Period.

Information about frame priority can be indicated to the HomePlug MAC by higher network layers using VLAN tags as defined in IEEE 802.1Q Clause 9. Table 2 provides the HomePlug recommendations for priority usage over the powerline. The over all design of the HomePlug priority mechanism results in a very high level of guarantees on the QoS parameters.

Figure 3: Priority Resolution and Backoff scheme

Table 2: Recommended use HomePlug priority

Powerline Channel Access Priority	User Priorities (from VLAN tag)	Application Class
Priority 3	7,6	"Voice" - characterized by less than 10 msec delay and jitter (example: VoIP)
Priority 2	4,5	"Video" or "Audio" - characterized by less than 100 msec delay
Priority 1	0,3	Bulk transfers and other back ground traffic
Priority 0	1,2	Best effort traffic

The backoff algorithm used by HomePlug MAC is designed to provide high network utilization (which manifests itself as high network throughput) even under heavily loaded conditions. It is also tailored to seamlessly integrate with the priority level construction and the applications that each of these priorities is expected to support. Note that only nodes that have the highest priority available in the network will contend during the Contention Period and all other nodes will defer. From a HomePlug view of the powerline network, all traffic with priority a less than the maximum available traffic priority in the network is pretty much ignored. Lower priority traffic will has to wait till all the higher priority traffic is transmitted.

HomePlug networking eliminates cabling used to extend the reach of wireless and broadband networks. for home networking, gaming, audio/video, security, and VoIP.

As with other CSMA/CA algorithms, the backoff slot is chosen to be a random integer between 0 and the Contention Window Size. The growth of the contention window under homeplug is controlled by the estimation of traffic on the network as well as on the priority of the traffic. This helps HomePlug nodes achieve higher network utilization and also control the latency for higher priority traffic.

Segmentation and Reassembly Mechanism

HomePlug uses an adaptive approach to maximize the throughput on each link. Furthermore, the maximum size of the long frame is limited to 160 OFDM symbols for the payload. For cases in which the complete Ethernet packet cannot be fitted in a single long frame, segmentation and reassembly mechanism is used. The necessary information for proper reassembly at the receiver is included in the segment control field of the frame header. Multiple segments can be transmitted in a single burst to obtain high throughputs. However, each segment is required to go through priority resolution mechanism. This ensures that a segment burst can be interrupted by a higher priority traffic, thus reducing the latency for higher priority traffic. HomePlug allows extension of this segment bursting across multiple Ethernet packets to provide contention free access.

QoS Features

- HomePlug MAC is designed to provide guarantees of QoS. This enables HomePlug based home networks to support applications like VoIP and Streaming media. Below is a list of some of the salient features:
- Supports up to 4 different priority classes based on VLAN tag (IEEE 802.1Q),
- Completely distributed approach reduces the implementation complexity,
- Optional support for contention free access,
- Segmentation and Reassembly ensures that higher priority traffic does not get excessively delayed due to on going lower priority packet transmission,
- Aggressive backoff algorithm for higher priority traffic (Priority 3 and Priority 2) ensures lower latencies,
- Variable packet discard timer and maximum retry limit ensures that excessively delayed packets are discarded.

HomePlug Performance

Throughput performance of HomePlug can be measured at various layers. The interpretation of the various throughputs presented in this document is as follows:

Physical layer throughput: This is the rate at which data can be transferred in the payload of a long frame.

MAC layer throughput: This is the rate at which the bytes of Ethernet frame are transferred.

TCP layer throughput: This is the rate at which the payload of TCP is transferred.

Table 3 provides the maximum physical layer throughputs for various modulations and FEC choices. This assumes that 84 carriers are used per OFDM symbol.

Table 4 provides the maximum throughput at various layers (using DQPSK 3/4).

Table 5 provides a comparison of HomePlug throughput with other technologies.

HomePlug AV is built from the ground up to support entertainment applications, such as HDTV and home theatre. Key members of the HomePlug Alliance, which includes consumer electronics companies and service providers, are driving the HomePlug AV standard.

Table 3: Physical Layer throughputs for various modulation and FEC choices

	Modulation	FEC	Physical Layer Throughput (Mbps)
DQPSK 3/4	DQPSK	3/4 Convolution Code and Reed-Solomon Code	13.78
DQPSK 1/2	DQPSK	1/2 Convolution Code and Reed-Solomon Code	9.19
DBPSK 1/2	DBPSK	Convolution Code and Reed-Solomon Code	4.59 Code and Reed-Solomon Code
ROBO	DBPSK	1/2 Convolution Code, Reed-Solomon Code and each bit is repeated four time	1.02

Table 4: Throughput at various layers

	Throughput (Mbps)
Physical layer throughput	13.78
MAC layer throughput	8.2
TCP layer throughput	6.2

Table 5: Comparison of HomePlug with other technologies

	HomePlug	10 Mbps Ethernet	IEEE 802.11b	HomePNA (2 Baud)	HomePNA (4 Baud)
Physical Layer	13.78	10	11	16	32
MAC Layer	8.2	9.8	7.48	14.6	26.9

HomePlug Field Tests

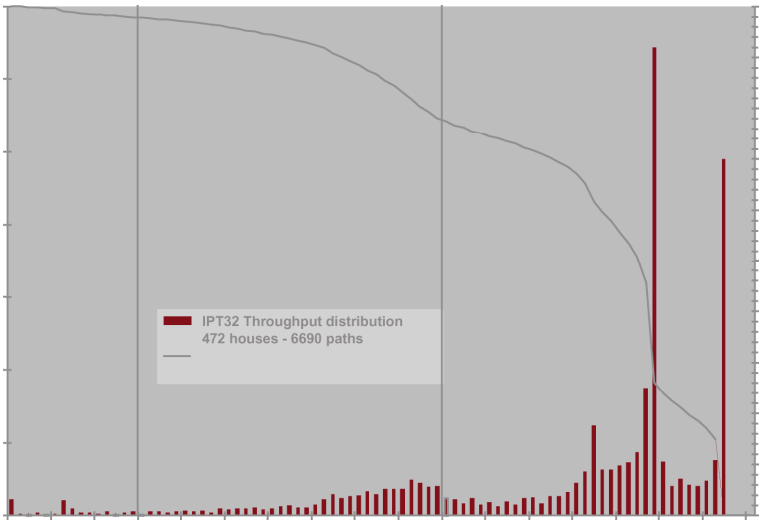
HomePlug uses existing powerline inside the house for home networking. To address concerns on how well the technology performs in the real world, HomePlug powerline alliance put HomePlug technology through extensive field testing. Tests were conducted in 500 houses throughout USA and Canada. More than 7000 paths were tested by volunteers and HomePlug engineers.

These trials included two node field tests, that involved testing the throughput between a pair of HomePlug devices. Two node tests were conducted by volunteers in 450 houses, 6690 power line links, throughout United States and Canada. Figure 4 shows the distribution of throughput obtained from these tests. The bar chart is a histogram of the various throughputs sorted into bins of 100 kbps throughput. The y-axis for the

bar chart is at the left of the chart and shows the number of paths that fell into each bin of 100 kbps. The rightmost bar corresponds to paths that achieve the maximum rate that the technology supports, which is about 8.2 Mbps. Nearly 1000 paths out of 6690 achieved this rate. The curve shows the percentage of paths that exceeds a throughput greater than the value represented on the x-axis. The y-axis of this curve is on the right of the chart. These results showed that

- 77% of the power line links will support at least 5Mbps of MAC throughput
- 98% of the power line links will support at least 1.5Mbps MAC throughput.

Figure 4: Throughput results obtained from two node field tests



The HomePlug Powerline Alliance is playing a key role in delivering Internet access through Broadband Powerline (BPL) networking, and is the only organization that is ensuring optimal co–existence between in–home and access powerline networks.

Security

As multiple homes are usually served from a common transformer, physical powerline networks extend beyond the boundaries of a single residence. Privacy is established by creating logical networks through the use of encryption (Figure 5). HomePlug's privacy and security scheme is based on the 56-bit Data Encryption Standard (56-bit DES).

Each station maintains a table of encryption keys and associated Encryption Key Select (EKS) values (Table 6). The EKS values serve as an index or identifier for each encryption key. When transmitting a frame, an encryption key is used to encrypt each frame body and the associated EKS is included in the frame header. Upon reception of the frame, the receiving station uses the EKS to select the associated encryption key from its table of keys to properly decrypt the frame body.

Table 6: Example Table of Encryption Keys

EKS	Encryption Key	Note
0x00	0x08856DAF7CF58185	Default Encryption Key (unique for each device)
0x01	0x46D613E0F84A764C	Network Encryption Key (common for a logical network)
…	…	"
0xFF	…	"

All transmissions in a logical network are encrypted with a shared Network Encryption Key (NEK). A unique NEK defines a logical network. To participate in a given logical network, a station must have the NEK and associated EKS for the network.

To ease the process of selecting encryption keys, HomePlug defines a means of using ASCII passwords to generate encryption keys. Keys are generated from passwords using industry standard cryptography and hashing algorithms. In this fashion, users may select unique and easy to remember passwords to define their logical networks.

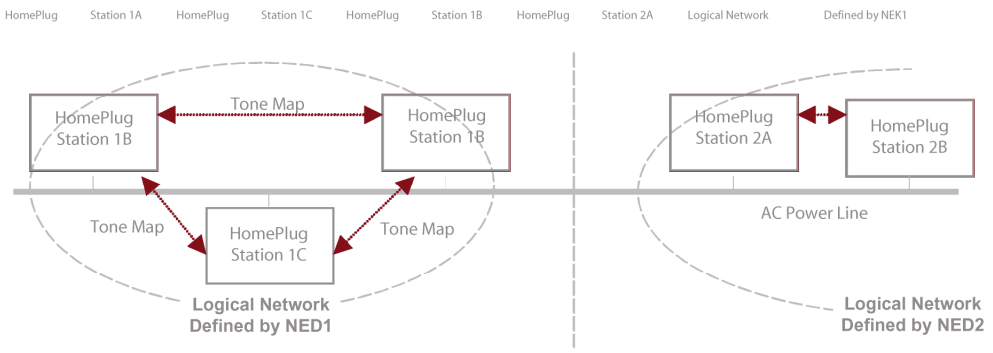
For simplicity, most HomePlug devices are shipped with a common network password of “HomePlug” to generate an NEK using EKS 0x01. This allows out-of-the-box communication between stations. The use of a common network password (and thus common NEK) yields a non-private configuration.

To achieve a private configuration, a unique network password is selected and entered into each station on the logical network. The logical network’s NEK/EKS pair may be entered locally into each station by configuring stations with the new network password. Alternately, the NEK/EKS pair may be transmitted over the powerline to each station being added to the logical network. This is performed using HomePlug MAC management frames. The transmission of these special management frames is kept secure by using private encryption keys, known as Default Encryption Keys (DEK), that are factory programmed to be unique for each HomePlug device. The DEK of each station to be added to the network must be known at the station transmitting the management frames. Only the receiving station will be capable of decrypting the frame using its DEK. The DEK is only used for the secure exchange of NEK values over the powerline. All other communication between stations makes use of the NEK for encryption.

HomePlug 1.0, HomePlug AV, and HomePlug BPL work together to create a harmonious environment for in–the–home and to–the–home networks.

Another informal level of security comes from the uniqueness of the channel between any two stations on a network. This stems from the uncontrolled nature of the powerline wiring. The channel estimation process between two stations results in a pair of Tone Maps of usable carriers, FEC coding rate and modulation method to be used by the stations for each direction of communication. Tone Maps are also regularly reassessed to adapt to the changing nature of the powerline network. As a result, any third station attempting to inappropriately monitor or become engaged in the communications from another point in the network would typically require its own different Tone Map to each of the stations.

Figure 5: HomePlug Logical Networks



Compliance and Coexistence

HomePlug standards use the unlicensed frequency band between 4.5 - 21MHz for transmitting the signal over the powerline. According to FCC rules, HomePlug is a secondary user in this band. FCC has two primary requirements with respect to emissions performance of such devices:

Products must meet FCC part 15 radiation limits

Product must not cause harmful interference to licensed users of the band.

HomePlug has expended substantial efforts to ensure that products designed to the HomePlug specification can meet these requirements. To meet the radiation limits imposed by FCC part 15 rules, the specification limits the maximum signal level that can be injected on to the power line. Tests conducted by FCC certified labs in various regions of United States show that the maximum signal levels incorporated in the specifications result in emissions that are below the part 15 limits. HomePlug also limits its power spectral density around the amateur-radio bands by inserting 30-dB notches for the HAM bands in 4.5- to 21-MHz HomePlug frequency range. Due to this notching of HAM bands, only 76 OFDM carriers are usable in HomePlug products operating in United States. Joint testing conducted by HomePlug and ARRL showed that, in general, with a moderate separation of the antenna from the structure containing the HomePlug signal, interference was barely perceptible. HomePlug is also compatible with other low speed powerline technologies like CEBus, X10 and LonsWorks as they operate in different frequencies.

The HomePlug Powerline Alliance is the world's only organization that certifies high–speed powerline products.

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HomePlug 1.0 Specifications

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About the HomePlug Powerline Alliance

The HomePlug Powerline Alliance, Inc. is an industry-led initiative established to create specifications for home powerline networking products and services and to accelerate the demand for these products and services worldwide through the sponsorship of market and user education programs. Currently, the Alliance is comprised of about 50 industry-leading companies. HomePlug Sponsor companies include Arkados, Inc. a subsidiary of CDKNet.com, Inc. (OTC BB:CDKN), Cogency Semiconductor, Comcast (CMCSK), Conexant (CNXT), DS2, EarthLink (ELNK), Intellon, RadioShack (RSH), and Sharp (SHCPFM). Additional information about the Alliance including a complete listing of certified products is available at www.homeplug.org.

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