**Master of Science in Internetworking – MS Thesis**

Examiner and Supervisor: Prof. Björn Pehrson
bjorn@it.kth.se

# Powerline Carrier (PLC) Communication Systems

Khurram Hussain Zuberi
zuberi@ieee.org

9 September 2003

ROYAL INSTITUTE OF TECHNOLOGY

Department of Microelectronics and Information Technology, IMIT
Royal Institute of Technology, KTH
IT-Universitetet, Kista, Stockholm, Sweden

*Once upon a time, before the advent of electricity, home automation had a different name: servants*

**Yahoo Internet Life Magazine, July 2002**

*Dedicated To My Loving Mother*

## Abstract

This thesis serves as a general and technical reference on the "Powerline Carrier (PLC) Communication Systems" with the presentation of a comprehensive and detailed analysis on the standards, characteristics, technologies, products and development associated and currently being deployed in the PLC communication systems. Since the developments and research on the subject had been relatively new and information scattered, the lack of collective information had been the primary initiative behind this research.

The advantages and benefits of using power line as the medium of data transmission at homes is investigated. Various standards and regulations are highlighted. Summary and comparisons are presented based on the findings of the research done at various European cities on exploring powerline as a communication medium with study of transmission impairments and other factors pertaining to the channel characteristics and performance. The technologies underlining the powerline communications are presented along with a discussion on the functionality of each technology including the data transmission rates, limitations, drawbacks, quality of service, and other important factors. A market survey of the presently available products/modules in the Powerline Networking area is carried out, summarizing all the HomePlug-certified products available in the powerline industry for the Swedish 220V 50 Hz power circuits; also highlighting the salient features available for each product. Different tests are performed using various vendors' powerline modules and the results documented, to help set a small office home office (SOHO) powerline demonstration network at the Telecommunications Systems Laboratory (TS Lab), IMIT, IT-University, Kista, Sweden. Some laboratory exercises are produced that students can perform to understand the concept and benefits of powerline networking technology. The thesis concludes with a look at the on-going technological developments in the area along with suggestions for future research possibilities.

With current available data transmission speeds of 14 Mbps and a remarkable increase promised in the near-future, Powerline Carrier Communication Systems are a preferred choice over Wireless or other Home Networking technologies due to factors including ease of installation, availability of AC outlets, higher throughput, low cost, reliability and security. PLC Communication Systems are also a potential candidate for the deliverance of xDSL and Broadband Internet services (data, multimedia etc.) along with electricity (and automation control signals) to the consumers by the energy utilities.

## Acknowledgments

I wish to express my deep gratitude to Jamison Lowe of Phonex Broadband Corporation, USA for kindly sending me the NeverWire 14 set of powerline modules that were used for testing and demonstration for this thesis. I will hand over these modules to the IT-University, so that other researchers or students can benefit from their usage.

I will also like to thank Trygve Refvem of GigaFast Ethernet (HomePlug) Norway for kindly lending me the HomePlug series of modules which were used in conjunction with the NeverWire modules for testing and demonstration for this thesis.

I am also thankful to Tim Charleson of the Plugtek Powerline eLibrary, who allowed me to use the library resources free of cost for my research.

My sincere wishes to all the Technical Support and other helpful persons from various companies and resources whom I contacted from time to time regarding certain queries, and who were not only prompt in replying but also gave me many enlightening suggestions and technical details for their products.

I also would like to thank my colleagues and friends at the TS Lab who helped me in various testing scenarios with their laptops and time.

Finally I wish to express my thanks to my Examiner and Supervisor, Professor Björn Pehrson, for his confidence in letting me work on this exciting and challenging thesis.

# Contents

# 1 Introduction

This chapter serves as an introduction to the chapters that follow. In the general introduction, the need for a powerline network is discussed briefly with a brief overview of some basic concepts and terminologies on which this thesis is based. In section 1.2 the project specification is presented, clarifying the scope and objectives of this master thesis. In section 1.3 the standards and regulations pertaining to the powerline communications are discussed. Finally, in Section 1.4 the organization of this thesis is highlighted.

## 1.1 General Introduction

In the present age of Information Technology, the present focus is both on creation as well as dispersion of information. In order to be able to reach the end users for the provision of information, the popular technologies currently being used include telephone wires, Ethernet cabling, fibre optic, wireless and satellite technologies. However each has its limitations of cost and availability to reach the maximum number of users.

The advantage of using electric powerlines as the data transmission medium is that every building and home is already equipped with the powerline and connected to the power grid. The power line carrier (PLC) communication systems use the existing AC electrical wiring as the network medium to provide high speed network access points almost anywhere there is an AC outlet. In most cases, building a home network using the existing AC electrical wiring is easier than trying to run wires, more secure and more reliable than radio wireless systems like 802.11b, and relatively inexpensive as well [13]. For most small office home office (SOHO) applications, this is an excellent solution to the networking problems.

For many years, systems have been built to communicate low bandwidth analog and digital information over residential, commercial and high voltage power lines. Powerline have been considered for the transmission of electricity in the past. However, with the emergence of modern networking technologies including broadband, there is a more-than-ever need for the utility and service providers to discover solutions that are able to deliver the services to the consumers at minimum cost and maximum performance. Only recently have companies turned serious attention to communicating over power lines for the purpose of data networking. The potential of powerline as a powerful medium to be able to deliver not only electricity or control signals, but even full duplex high-speed data and multimedia content, is being explored now. Since the developments in the field of powerline networking is fairly new, the information is mostly dispersed and there is a lack of collective reference material that summarizes the existing technologies, available solutions and technology trends in the powerline carrier communications.

Before going into the depth of technicalities, a brief introduction of the electric power distribution follows. For the discussion of this thesis, the terms powerline carrier (PLC) communication systems or residential powerline circuit (RPC) or distribution line communication (DLC) systems refers to the low voltage part of the electrical power distribution network. Basically, this comprises everything attached to the secondary side of the distribution transformer i.e. the medium voltage (MV) to low voltage (LV) transformer, including the low voltage network within the consumer's/customer's premises and all the loads attached to it. Figure 1 shows a typical electric power distribution network for a European city.

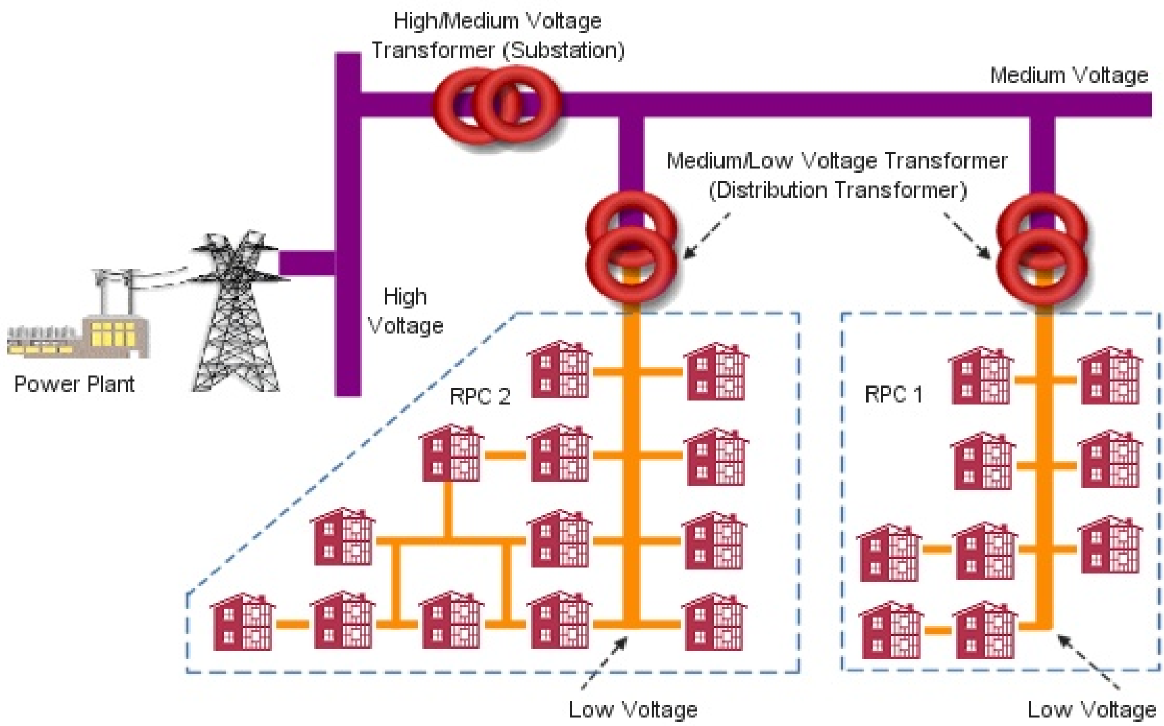



Fig. 1 A typical European electrical power distribution network

Although the power distribution circuits in other parts of the world have a similar structure, certain differences can be noticed [66] with respect to the RPC:

● In Europe:
- 3 phase system, 400 V between phases; loads are typically connected between a phase and zero (-> 240V). Heavy loads are connected between two phases. In certain older RPC's the voltage between phases is 240 V. In this case loads are connected between two phases.
- Operating frequency: 50 Hz.
- Typically 400 houses are connected to a single distribution transformer in a city environment; these houses can be found in a circle with an average radius of 400m.

● In the USA:
- 2 phase system, 220 V between phases; loads are typically connected between a phase and zero (-> 110V). Heavy loads are connected between two phases.
- Operating frequency: 60 Hz.
- Typically about 5 to 20 houses are connected to a single distribution transformer. These houses are located in close proximity to this distribution transformer.

● In Japan:
- 2 phase system, 200 V between phases; loads are typically connected between a phase and zero (-> 100V). Heavy loads are connected between two phases.
- Operating frequency: 50 Hz in the eastern part (Tokyo); 60 Hz in western part.

The discussion for this thesis is based on the European style residential power circuits.

## 1.2 Project Specification

This master thesis has been completed according to the following specifications that outlined the scope and objectives at the beginning of the thesis work.

### 1.2.1 Report and Presentation

The project is defined as "Power Line Carrier (PLC) Communication Systems" and goal of the project is to make a research study with a report and presentation on the existing powerline carrier communication systems, the availability of services (data transmission rates, quality of service, security, video voice and multimedia data transfers), the industry standards, protocols and technologies (this includes study of X10, OFDM, LonWorks, CEBus and HomePlug among others).

### 1.2.2 Market Survey

A market survey would include brief description of devices that are being used in powerline communication and a reference would be included of firms which have implemented it (including Intellon, Echelon, Siemens, ABB, and others).

### 1.2.3 Lab Demonstrator

The Project also includes setting up a demonstrator at Telecommunication Systems Laboratory (TS Lab) at the Department of Microelectronics and Information Technology, IMIT, Royal Institute of Technology, KTH and the IT-University, Kista, Sweden. For this purpose, a module from some manufacturer will be recommended, which can be bought and installed at some suggested locations to demonstrate the purpose.

### 1.2.4 Lab Exercises

Another task is designing a few laboratory exercises that students can do to understand PLC communication systems. This would include the use of the module used in Lab Demonstrator, with the manufacturer's software or recommendation.

### 1.2.5 Limitations

The master thesis is not funded by KTH or any other source. However for the installation of Lab Demonstrator, it is the responsibility of Supervisor to arrange the funding. Also, since this thesis is part of a degree course, the time span for thesis is 800 hours or 20 weeks.

## 1.3 Standards and Regulations

Lack of centralized standardization has been one of the major factors behind the late deployment of powerline networks. This section highlights the standards and regulations pertaining to the powerline communications. The discussion here is based on [66].

### 1.3.1 European Committee for Electrotechnical Standardization (CENELEC)

For Western Europe (i.e. the countries forming the European Union plus Iceland, Norway and Switzerland) the regulations concerning RPC are described in CENELEC standard EN 50065 entitled “Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148.5 kHz”. In part 1 of this EN-standardization-paper, entitled “General requirements, frequency bands and electromagnetic disturbances” [1], the allowed frequency band and output voltage for communications over the RPC are indicated.

The *frequency range* which is allowed for communications ranges from 3 to 148.5 kHz and is subdivided into five sub-bands which are shown in Table 1 below.

The maximum allowed transmitter output voltage is also defined in [1]:

● For the frequency band from 3 – 9 kHz:
The transmitter should be connected to a 50 Ω // (50 µH + 1.6 Ω) RPC-simulation-circuit. In principle the transmitter output voltage should not exceed 134 dB (µV) ≡ 5 V.

● For the frequency band from 9 – 95 kHz:
The transmitter should be connected to a 50 Ω // (50 µH + 5 Ω) RPC-simulation-circuit. Different maximum transmitter output voltages apply for a narrow-band (i.e. a 20-dB bandwidth of less than 5 kHz in width) and broad-band transmitters (i.e. a 20-dB bandwidth of more than 5 kHz in width):

- Narrow-band signals:
  The maximum allowed peak voltage at 9 kHz equals 134 dB (µV) ≡ 5 V, exponentially decreasing to 120 dB (µV) ≡ 1 V at 95 kHz.

- Broad-band signals:
  The maximum allowed peak voltage equals 134 dB (µV).

Furthermore, in any 200 Hz wide frequency band the maximum transmitter output voltage should not exceed 120 dB (µV).

● For the frequency band from 95 to 148.5 kHz:
The transmitter output voltage should not exceed 116 dB (µV) ≡ 0.63 V. In certain cases an exception can be made allowing 134 dB (µV).

| Band | Frequency Range | Usage |
|---|---|---|
| | 3 kHz – 9 kHz | Limited to energy providers; However, with their approval it may also be used by other parties inside the consumer premises. *(No "letter" description exists, due to the fact that this band was defined at a later stage)* |
| A-band | 9 kHz – 95 kHz | Limited to energy providers and their concession-holders. |
| B-band | 95 kHz – 125 kHz | Limited to energy provider's customers; No access-protocol is defined for this frequency band. |
| C-band | 125 kHz – 140 kHz | Limited to energy provider's customers; In order to make simultaneous operation of several systems within this frequency band possible, a carrier-sense multiple access-protocol using a center frequency of 132.5 kHz was defined. |
| D-band | 140 kHz – 148.5 kHz | Limited to energy providers customers; No access-protocol is defined for this frequency band. |

Table 1. CENELEC frequency range

From [2] it was discovered that CENELEC has started working on a new standard for frequencies up to 30 MHz. This will allow high speed digital access to consumer's premises via the utility wiring.

### 1.3.2 Federal Communications Commission (FCC)

In North America, the FCC regulates transmitted power and bandwidth. The frequency band allowed here ranges from 0 to 530 kHz [allocated at 100 – 450 kHz] which is considerably larger than Europe. Part 15 of the FCC rules allows powerline communication outside the AM frequency band (outside 535 to 1705 kHz) [4].

In Europe the bandwidth for consumer use is limited to 30 kHz, 15 kHz, 8.5 kHz, and 86 kHz bands [10].

### 1.3.3 HomePlug Powerline Alliance

The HomePlug™ Powerline Alliance's [46] mission is to enable and promote rapid availability, adoption and implementation of cost effective, interoperable and standards-based home powerline networks and products. The first publicly available HomePlug products were demonstrated in early 2002 at the CES and CeBIT exhibitions. At these shows, HomePlug member companies unveiled HomePlug-compliant home networking products such as bridging and routing devices, network interface cards, and combination 802.11b access point/powerline. Members of the HomePlug alliance tested the technology in an extensive field trial of 500 homes throughout North America. Based on the success of this field trial, the completion of the HomePlug 1.0 Specification was announced in June 2001.

The HomePlug 1.0 protocol is highlighted in [91] and [42] as follows: HomePlug 1.0 uses a Physical Layer (PHY) protocol based on equally spaced, 128-carrier Orthogonal Frequency Division Multiplexing (OFDM) from 0 Hz to 25 MHz, in conjunction with concatenated Viterbi and Reed Solomon coding with interleaving for payload data and turbo product codes for control data. 84 carriers are used to transmit data. BPSK, DBPSK, DQPSK or ROBO (a robust form of DBPSK) modulation is used for data, with a cyclic prefix for synchronization.

A pair of nodes first determines which subcarriers are usable, and what form of modulation and error correction should be applied to the channel. This 'tone map' is used for subsequent communication between the nodes. Broadcast packets and frame delimiters use all subcarriers with robust modulation and forward error correction codes so that all nodes are able to interpret them; the rest of a unicast frame uses the higher speed specified by the tone map.

The presence of large attenuation prevents detection of collisions, so HomePlug 1.0 uses CSMA/CA for its MAC protocol. Powerline modules determine if the medium is idle or not, using virtual carrier sense (VCS). If it has been idle for Extended InterFrame Space (EIFS), the station can send the segment without contention. If it is busy, it waits for CIFS (Contention InterFrame Space) or RIFS (Response InterFrame Space) after the end of the current transmission. The delimiter informs the listening node's VCS when the transmission will end and whether a response is expected, for synchronization. The receiver sends ACK, NACK (or NAC), or FAIL after RIFS when it is needed, taking top priority. ACK indicates successful delivery, while NACK (or NAC) indicates an error detected at the receiving end. FAIL indicates that the receiver was unable to buffer the segment. Otherwise, stations wait until the end of the CIFS period; then they use two priority resolution slots to select the highest priority level traffic waiting. Nodes with this traffic contend for the medium during the contention window using a randomly selected delay. Initially, there are eight contention resolution slots, and upon collision, nodes increase this to 16, then 32, according to a backoff schedule. Large contention windows are used to avoid costly collisions. In the case of frame control errors or collision, stations must wait for EIFS.

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 [42].

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. Products conforming to the HomePlug standards are designated as “HomePlug-certified products” [47] and they are entitled to use the official “HomePlug certification mark” as shown in Figure 2 below.

Fig.2 HomePlug certification mark

Founded in 2000 by 13 industry leaders (3Com, AMD, Cisco Systems, Compaq, Conexant, Enikia, Intel, Intellon, Motorola, Panasonic, Radio Shack, SONICblue, and Texas Instruments) the HomePlug Powerline Alliance enables and promotes the rapid availability and adoption of cost effective, interoperable and standards-based home powerline networks and products. HomePlug, which has grown to more than 90 member companies, has chosen Intellon’s PowerPacket technology [40] as the baseline upon which the alliance’s first industry specification is build.

### 1.3.4 Other Relevant Standards

Other regulatory standards pertaining to powerline carrier communications include:

● The IEC 870 international standard on telecontrol, teleprotection and associated telecommunications for electrical power systems, as well as the IEC 1107 and 1142 standards pertaining to equipment for electrical energy measurement and load control.

● The CENELEC ENG1107 standard specifies equipment for electrical energy measurement and load control.

● In Japan a frequency band ranging from 10 to 450 kHz is allowed.

● The Consumer Electronics Association (CEA) R7 Home Network Committee [54] [88] ensures that the current and future Home Networks can coexist within a home and share information through the use of industry standard interfaces.

● The Institute of Electrical and Electronics Engineers (IEEE) has also published a set of recommendations and standards pertaining to the powerline communications available at [3].

● The International Electrotechnical Commission (IEC) has standardized the distribution line communications (DLC) through Technical Committee No 57 (Power System Control and Associated Communications), Working Group 9 (Distribution automation using distribution line carrier systems) [Chapter1-5]. All systems discussed in IEC TC57/WG9 use frequencies below 150 kHz [6].

● The PLCforum [7] is a leading international Association that represents the interests of manufacturers, energy utilities and research organizations active in the field of access and in-home PLC (power line communications) technologies. Since its creation in Interlaken (Switzerland) at the start of 2000, the number of members and permanent guests has increased and today stands at more than 60.

● ETSI (the European Telecommunications Standards Institute) [8] is a non-profit organization whose mission is to produce the telecommunications standards that will be used for the decades to come throughout Europe and beyond. Based in Sophia Antipolis (France), ETSI unites nearly 700 members from 50 countries inside and outside Europe, and represents administrations, network operators, manufacturers, service providers, technical bodies and users. ETSI technical specifications on Powerline Telecommunications (PLT) are highlighted in [16] [17] and [18].

## 1.4 Organization of this Thesis

The remainder of this thesis is organized as follows. In chapter 2 an overview of the various digital data communication techniques relevant to this master thesis are presented. In chapter 3 the potential of Home networking and automation is explored with the limitations and applications. Various economic and technical aspects of home networking are presented and the available technologies compared. A special focus is given to the powerline networking and a technical description of the powerline networking technology is presented. In chapter 4 the powerline as a communication channel is discussed. Various transmission impairments and factors governing the powerline for data transmission are studied. Research already being done on analyzing the electrical properties of powerlines for data transmission is studied and various conclusions presented. This chapter gives the reader an idea of the on-going studies on evaluating the performance and characteristics of powerline as a communication channel for data transmission. In chapter 5 a technical discussion of all the major technologies in the powerline networking area is presented. The technologies are studied in depth and their major working principles and characteristics are highlighted. In chapter 6 the results of market survey are presented, which was conducted to highlight the major vendors and products available in the powerline networking area, as well as suggest some potential products for the purpose of demonstration at the TS Lab in Kista, Sweden. In chapter 7 the scenario and results of powerline network demonstration at the TS Lab are presented based on the available modules from Phonex Broadband Corporation and GigaFast Ethernet Inc. In chapter 8 the laboratory exercises are presented which students can perform to understand the concept of powerline networking. In chapter 9, finally some conclusions are drawn and certain suggestions are proposed for future research and investigation.

# 2 Data Communication Techniques

This chapter focuses on the data transmission techniques commonly in practice. The topics and areas relevant to this master thesis work are highlighted in this section. This section is intended to give only a general review of the data communication techniques. Material for this chapter is derived from [9], [10] and [11] mostly.

Analog and digital formats are means used to move information across any medium. Physical layer is responsible for transportation of a raw bit stream from one node to another. For actual data transmission, various physical media can be used (including magnetic media, twisted pair, baseband coaxial cable, broadband coaxial cable, fiber optic, powerline, wireless or radio, microwave, satellite etc.). However, for this discussion we will focus on the data transmission techniques related to the powerline environment.

## 2.1 Baseband Digital Signals

A baseband waveform has a special magnitude that is nonzero for frequencies, $f$ in the vicinity of the origin (i.e. $f = 0$) and negligible elsewhere.

### 2.1.1 Line Coding

Line coding is a method of making regeneration more reliable. Binary 1's and 0's may be represented in various serial-bit signaling formats knows as the *line code*. The two major categories of line codes are return-to-zero (RZ) and non-return-to-zero (NRZ). With RZ coding the waveform returns to zero-volt level for a portion (usually one-half) of the bit interval. The waveform for the line code is further classified according to the rule that is used to assign voltage levels to represent binary data. Following are some of the waveforms:

*Unipolar Signaling*: In positive logic unipolar signaling, a binary 1 is represented by a high level (positive voltage) and a binary 0 is represented by a zero level. This type of signaling is also called as on-off keying.

*Polar Signaling*: Binary 1's and 0's are represented by positive and negative levels of the same magnitude.

*Bipolar Signaling*: Binary 1s are represented by alternately positive or negative values. The binary 0 is represented by a zero level.

*Manchester Signaling*: Each binary 1 is represented by a positive half-bit period pulse which is followed by a negative half-bit period pulse. Similarly, a binary 0 is represented by a negative half-bit period pulse followed by a positive half-bit period pulse. Manchester signaling is very popular because it combines the clock and the message into one signal. Manchester signaling is also known as the split-phase encoding.

Figure 3 below presents a comparison of the above mentioned digital wave forms.

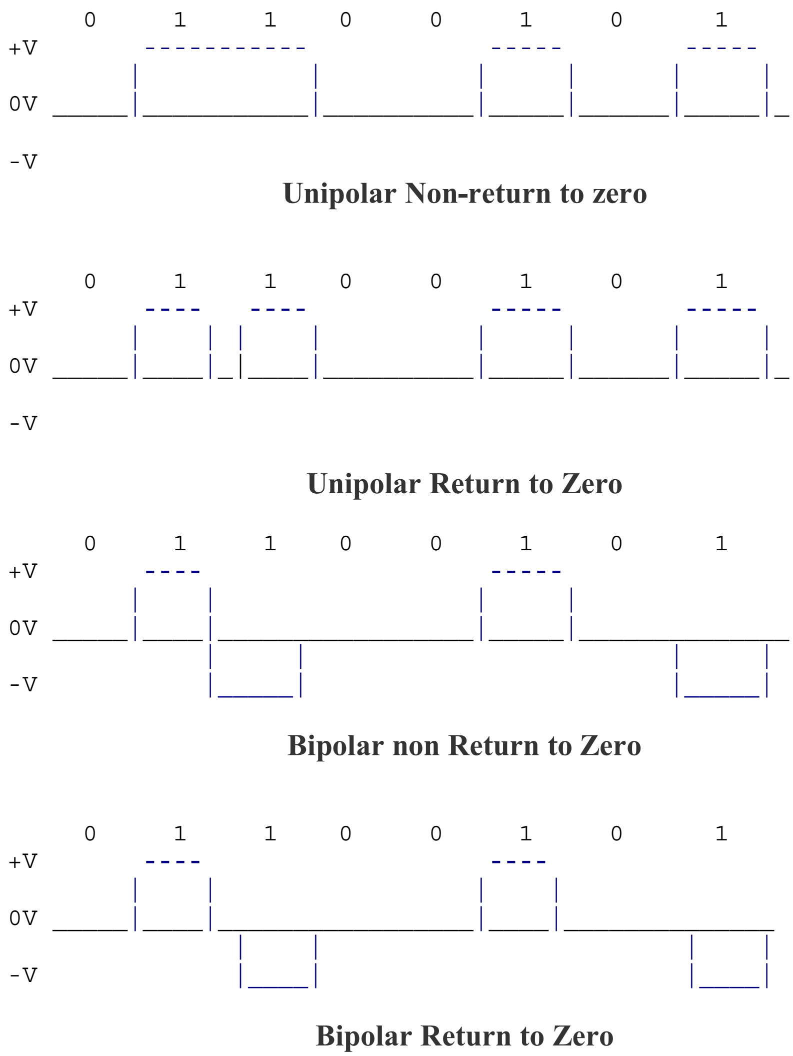



Fig. 3 Comparison of Digital Wave Forms

Each of the line codes has certain advantages and disadvantages associated with it. For example, the unipolar NRZ line code has the advantage of using circuits that only require one power supply, but it has the disadvantage of requiring channels that are dc coupled (i.e. frequency response down to $f=0$) since the signal has a non-zero dc value. The Manchester code combines the data and clock signal but requires a bandwidth that is two times the bandwidth of the bit rate.

### 2.1.2 Multilevel Line Coding

The line codes described above only use two logical levels. If the signal has more than two possible values, then the signal is known as a multilevel signal. One way to reduce signaling bandwidth is to convert a binary signal to a multilevel signal. In practice, filtered multilevel signals are often used to modulate a carrier for transmission of digital information over a communication channel, providing a relatively narrow bandwidth.

### 2.1.3 Clocking (Network Synchronization)

Any digital network synchronization between sender and receiver must be maintained. Synchronization signals are clock-type signals that are necessary within a receiver (or repeater) for detection of the data from the input signals. Synchronization is imperative in a digital transmission system. If the timing of arrival or transmission is off, then the information will be distorted. Regardless of whether voice, data, video, or image traffic is present, the presentation of a digital stream of 1's and 0's is contingent on a timed arrival between the two ends.

The clock-signals have a precise frequency and phase relationship with respect to the received input signal, and they are delayed when compared to the clock signals at the transmitter since there is propagation delay through the channel.

There are number of ways to synchronize a digital network, but the issue must definitely be addressed. Digital communication usually needs at least three types of synchronization signals:

- bit sync: to distinguish one bit interval from another
- frame sync: to distinguish groups of data
- carrier sync: for bandpass signaling with coherent detection

Systems are designed so that the synchronization is derived either directly from the transmitted signal or from a separate channel that is used only to transmit the sync information. Systems with bit synchronizers that derive the sync directly from the corrupted signal need a sufficient number of alternating 1's and 0's in the data to be able to maintain the synchronization. The loss of synchronization because of strings of all 1's or 0's can be prevented by adopting one of the following alternatives:

- Bit interleaving (i.e. scrambling): in this case the source data with strings of 1's and 0's are scrambled to produce data with altenating 1's and 0's.
- Bit stuffing: if a certain number of 1's or 0's (e.g. 5) are transmitted after each other, the transmitted automatically inserts a bit of opposite value, that the receiver later removes from the data stream.
- Changing to a completely different type of line code that does not require alternating data for bit sync. Manchester NRZ can be used, but it requires a channel with twice the bandwidth of that needed for a polar NRZ code.

Clocking or timing differences between the transmitter and receiver can exist. Therefore, while the receiver is expecting a bit that the transmitter has not sent, a slip occurs. Slips are likely to be present because of multiple factors in any network. The can result from the two clocks at the ends being off or from problems that can occur along the link. Problems along the link can be accommodated however, using pulse stuffing or other techniques. Each device along the link has a buffer capability, creating a simple means of maintaining synchronization. Pulse stuffing can be done independently for each multiplexer along the way, enhancing overall reliability of the network, with the disadvantage of creating an overhead at each multiplexer.

## 2.2 Signal Modulation Techniques

Modulation is a technique that enables information to be transferred as changes in an information-carrying signal. Modulation is used both for analog and digital information; in the case of analog information, it is effected continuously (soft transitions). In the case of digital information, it is effected step by step (state changes). The unit performing modulation and the corresponding demodulation is called *modem*. In analog transmission of information, amplitude modulation and frequency modulation are used.

### 2.2.1 Amplitude Modulation (AM)

Amplitude Modulation (AM) is the simplest form of modulation. The amplitude of the carrier wave is varied in accordance with some characteristic of the modulating signal (which may be analog or digital). The following equation represents an AM signal:

$$s(t) = A_c \, [\, 1 + m(t) \,] \cos \omega_c t$$

where;

$m(t)$ = the modulating signal
$\omega_c$ = the carrier frequency
$A_c$ = constant, specify power level

Amplitude modulation is used to transmit analog voice (300-3,400 Hz) modulated on radio frequencies around 450 MHz in the mobile radio system NMT 450, and to transmit TV images in cable-TV networks. The bandwidth of an AM signal is twice the bandwidth of the modulating signal. That is because amplitude modulation results in two sidebands; the frequency above the carrier frequency is called the upper sideband and the frequency below is called the lower sideband. There are Single Side Band (SSB) modulation techniques that suppress one of the sidebands and the resulting SSB-AM signal has the same bandwidth as the modulated signal.

### 2.2.2 Frequency Modulation (FM) and Phase Modulation (PM)

Frequency modulation is used for broadcasting on the FM band (hence the term FM), the sound channel for TV, and certain mobile communication systems. Phase modulation and frequency modulation are special cases of angle-modulation signaling. An angle-modulated signal is represented by:

$$s(t) = A_c \cos [\, \omega_c t + \theta(t) \,]$$

For PM, the phase is directly proportional to the modulating signal:

$$\theta(t) = D_p \, m(t)$$

where;

$m(t)$ = the modulating signal
$D_p$ = phase-sensitivity of the phase modulator

For FM, the phase is proportional to the integral of $m(t)$:

$$\theta(t) = D_f \int_{-\infty}^{t} m(\sigma) \, d\sigma$$

where;

$D_f$ = frequency deviation constant

The reason for calling it frequency modulation lies in the fact that the instantaneous frequency varies about the assigned carrier frequency $f_c$ directly proportional to the modulating signal $m(t)$.

The instantaneous frequency is the frequency that is present at a particular instant of time and should not be confused with the term frequency as used in the spectrum of the FM signal. Thus the spectrum shows what frequencies are present in the signal over all time. Figure 4 below illustrates the concept of AM and FM.

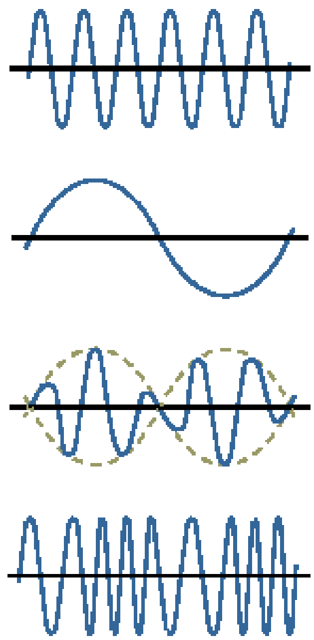



Fig.4 Amplitude and Frequency Modulation

## 2.3 Digital transmission of information

Modulation makes it possible to transmit digital, binary information (1's and 0's) on analog carriers (such as radio and light waves). Digital transmission is, in effect, analog transmission of digital information. In the modulation process, a bit or a group of bits is translated into rapid state changes, such as amplitude or phase shift. Digitally modulated bandpass signals are generated by using AM, PM, FM, or QAM (quadrature amplitude modulation) signaling. For digital modulated signals, the modulating signal, $m(t)$ is a digital signal given by some binary or multilevel line code. The basic modulation methods are:

- amplitude-shift modulation
- frequency-shift modulation, and
- phase-shift modulation

In many cases, the purpose of modulation is to squeeze in as many bits per hertz as possible; for example, onto a bandpass-filtered telephone line (300-3,400 Hz) or a limited radio frequency band.

### 2.3.1 Shift Modulation

Figure 5 below shows how amplitude, frequency or phase shift conveys digital information.

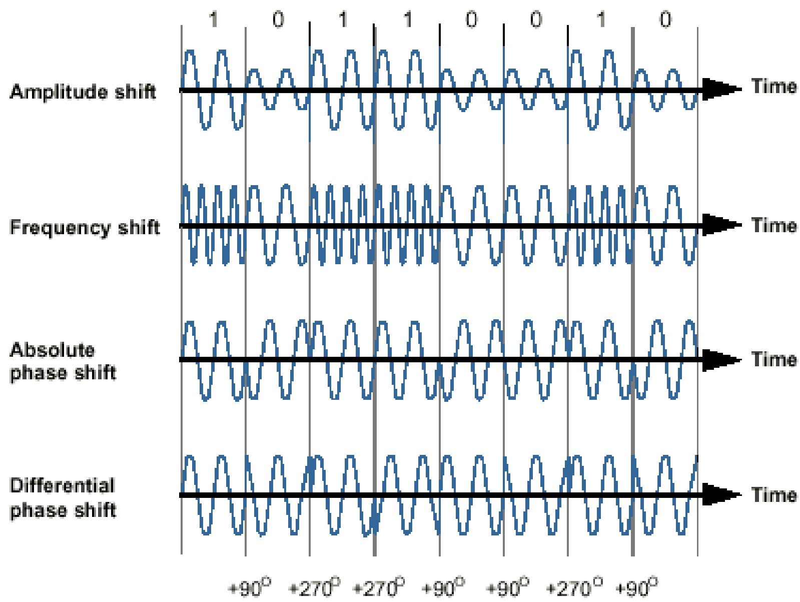



Fig. 5 Shift modulation for digitally transmitted information

Frequency-shift modulation is also called frequency-shift keying (FSK). Similarly, another name for phase-shift modulation is phase-shift keying (PSK). In phase-shift modulation, the phase is shifted differentially relative to the previous phase (for example, +90° for 0, and +270° for 1), or absolutely, in which case each modulation state is represented by a specific phase (0° for 0, and +180° for 1) relative to a nominal phase (one that is known both by the transmitter and the receiver). The differential variant permits less complicated demodulation equipment and is therefore more common.

An uncomplicated variant of amplitude modulation is used for optical fibre transmission: light on (full amplitude) or light off (no amplitude). On-Off keying (OOK) is a form of AM signal and is therefore sometimes also called Amplitude Shift Keying (ASK). The approach is to let the carrier wave represent a binary one, and no carrier represents a binary zero. Since OOK is an AM-type signaling, the required bandwidth of an OOK signal is 2 times the bit rate. That is, the transmission bandwidth, $B_t$ of the OOK signal is $B_t = 2B$ where B is the bandwidth of the modulated signal. Figure 6 below explains the concept.

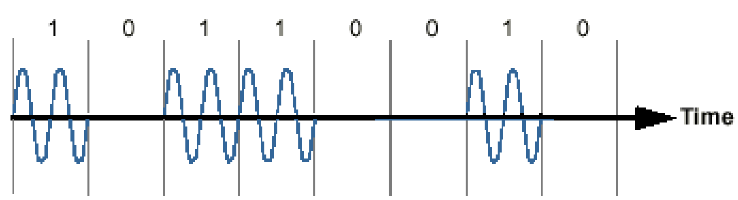



Fig.6 On/off modulation of light in an optical fibre

### 2.3.2 Bit rate and modulation rate

There is a distinction between bit rate and modulation rate. Bit rate (the digital bandwidth) is specified by the unit bit/s - that is, by the number of ones and zeros transferred per second. Modulation rate specifies the number of possible state changes per unit of time. The unit baud, which is a less complicated way of expressing "modulation states per second", is used for modulation rate.

If we use a modulation method that comprises four different states, then each state can represent a combination of two bits, and all combinations are covered: 00, 01, 10 and 11. Figure 7 illustrates the concept.

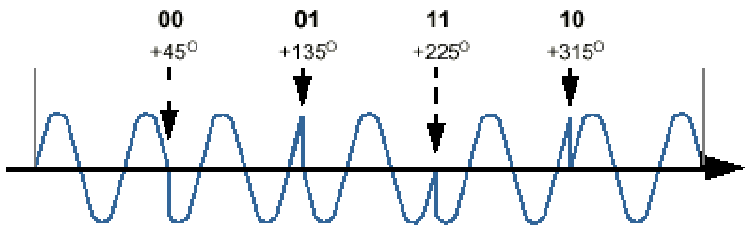



Fig. 7 A phase-shift-modulated signal with four states

Since each state change represents two bits, the baud value is half the bit/s value; thus 1,200 baud equals the bit rate 2,400 bit/s. For example, in modems for 2,400 bit/s, four different phase-shift states are used. The carrier frequency is 1,800 Hz.

Accordingly, 16 different modulation states, or four bits per state, at the same bit rate of 2,400 bit/s would give the modulation rate 600 baud.

### 2.3.3 Modulation Combinations

In many cases, the basic methods amplitude-, phase- and frequency-shift modulation are combined. The mobile telephony system GSM, for example, uses a mix of phase shift and frequency shift.

The combination of amplitude-shift modulation and phase-shift modulation is called quadrature amplitude modulation (QAM). This combination permits more bits per hertz than the methods are capable of transmitting separately. If the transmitter is a PM transmitter with an *M* level digital modulation signal, *M*-ary phase-shift keying (MPSK) is generated at the transmitter output. A plot of the permitted values of the complex envelope would contain *M* points, one value for each of the *M* multilevel values, corresponding to the *M* phases that the signal is permitted to have. The case for *M*=4 is called Quadrature Phase Shift Keyed (QPSK) signaling. QAM signal constellations are not restricted to having permitted signaling points only on a circle, as the MPSK case. The general QAM signal is defined as:

$$s(t) = x(t) \cos \omega_c t - y(t) \sin \omega_c t$$

Figure 8 below shows QAM with 16 modulation states that are combinations of eight phase-shifts and eight amplitudes.

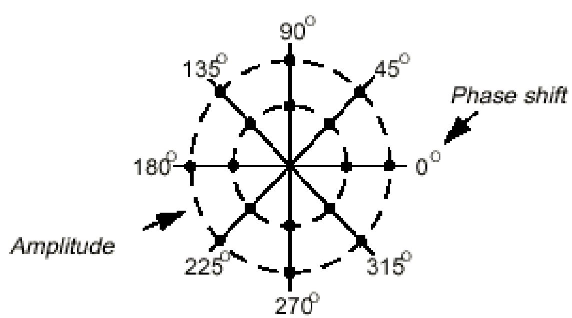



Fig. 8 QAM with 16 modulation states

## 2.4 Spread Spectrum Systems

Spread Spectrum (SS) uses wide band, noise-like signals (which makes the signals hard to detect). Spread Spectrum signals are also hard to intercept or demodulate. Further, Spread Spectrum signals are harder to jam (interfere with) than narrowband signals. These *low probability of intercept* (LPI) and anti-jam (AJ) features are why Spread Spectrum technique has been used by the military for many years [12]. Spread signals are intentionally made to be much wider band than the information they are carrying to make them more noise-like.

Many types of SS systems exist. To qualify as SS system, two criteria should be met by a system:

- The bandwidth of the transmitted signal *s*(t), needs to be much greater than that of the message *m*(t).
- The relatively wide bandwidth of *s*(t) must be caused by an independent modulating waveform *c*(t), called the spreading signal; and this signal must be known by the receiver in order for the message signal to be detected.

The two most common types of SS modulation techniques are *direct sequence* (DS) and *frequency hopping* (FH).

### 2.4.1 Direct Sequence Spread Spectrum (DS-SS)

The principal of direct sequence spread spectrum (DS-SS) is to spread the signal on a larger frequency band by multiplexing it with a signature (the code). The system works over a fixed channel. To spread the signal, each bit of the packet to be transmitted is pre-modulated by a code. At the receiver, the original signal is recovered by receiving the whole spread channel and demodulating by the same code. Since it uses only a small part of the total bandwidth used by the system, any narrowband interferer will appear much weaker to direct sequence system. Figure 9 below shows a DS-SS signal.

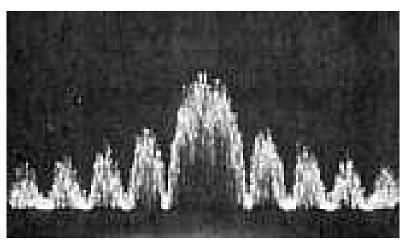


Fig. 9 A Spectrum Analyzer Photo of a Direct Sequence (DS) Spread Spectrum Signal

The modulator uses the same code as the transmitter to match the received signal, further decreasing the signal not modulated by the code, called as process gain of code.

### 2.4.2 Frequency Hopping Spread Spectrum (FH-SS)

Frequency hopping spread spectrum uses a set of narrow band channels and walk through all of them in a sequence. It does just what its name implies. That is, it "hops" from frequency to frequency over a wide band. The specific order in which frequencies are occupied is a function of a code sequence, and the rate of hopping from one frequency to another is a function of the information rate. The transmitted spectrum of a frequency hopping signal is quite different from that of a direct sequence system. The bandwidth of a frequency hopping signal is simply *w* times the number of frequency slots available, where *w* is the bandwidth of each hop channel. Figure 10 illustrates a FH-SS signal.

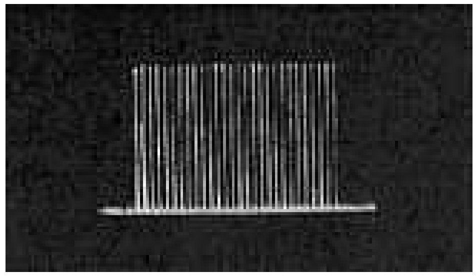


Fig. 10 A Spectrum Analyzer Photo of a Frequency Hopping (FH) Spread Spectrum Signal

The system avoids interferences by never staying on the same channel; if a channel is so bad that the system can not use it, it just waits for the next good channel.

## 2.5 Error Reduction Techniques

Transmission errors in a digital communications system can be reduced by the use of two main techniques:

- Automatic Repeat Request (ARQ)
- Forward Error Correction (FEC)

In an ARQ system, when an error in a block of data is detected by the receiver circuit, it requests that the data block should be retransmitted. In an FEC system, the transmitted data is encoded so that the receiver can detect as well as correct errors. These procedures are also classified as *channel coding* because they are used to correct errors caused by channel noise. FEC techniques are used to correct errors on simplex (one-way) channels where returning an ACK/NAC indicator is not feasible.

The choice between using the ARQ or the FEC technique depends on the particular application. ARQ is often used in computer communication system because it is relatively inexpensive to implement, and there is usually a full-duplex (two-way) channel so that the receiving end can transmit back an acknowledgement (ACK) for correctly received data or a request for retransmission (NAC) when there is an error in received data. FEC is preferred in systems with large transmission delays because if the ARQ were used, the effective data rate would be small and the transmitter would have long idle periods while waiting for the ACK/NAC indicator.

## 2.6 Medium access methods

As all the devices on a communication network share the same physical medium, techniques are required to prevent the devices from transmitting at the same time. These techniques are collectively known as the medium access methods. Based on [10], this section describes three medium access methods:

- Polling
- Contention
- Token passing

### 2.6.1 Polling

In a polling system, one device works as the network master and all other devices function as slaves to this master. The master queries each device in turn as to whether it has any data to transmit. If the answer is yes, the device is permitted to transmit data. If, however, the answer is no, then the master moves on and asks or polls the next slave device.

### 2.6.2 Contention

Contention is the opposite of polling. In a contention system if one device has to transmit, it does so. The latest generation of contention based medium access methods is called as Carrier Sense Multiple Access with Collision Detection or Collision Avoidance (CSMA/CD or CSMA/CA).

Under CSMA/CD when a station wants to transmit data, the station first listens to the medium to see if any other transmission is going on. If the medium is quite, the station goes ahead with the transmission. If the medium is busy, the station waits for a random time and listens again.

It is possible for two stations to transmit at the same time (sense the wire at the same time, conclude that the network is idle, and begin transmitting simultaneously), resulting in a collision. By using CSMA/CD the station can recognize collision and take corrective action.

### 2.6.3 Token Passing

Token passing uses a “token”, which is a small frame of data, to grant a device permission to transmit over the medium. Whichever station has the token can put data on the medium. When a station is done transmitting, it releases the token and the next station willing to transmit acquires the token.

If polling and contention define the extremes of total control and total anarchy, the token passing medium access method exists somewhere in the middle of the spectrum.

## 2.7 Conclusions

This chapter presented the basic concepts of a digital communications system for data communication. The transmission of data over electric power line presents various challenges, and most of the material presented ahead makes use of the terms and techniques discussed in this chapter. Enabling data communication over powerlines is a careful combination of various approaches, with certain modifications and enhancements pertaining to the resilient and hostile nature of powerline for transmission of data.

# 3 Home Networking over Powerlines

In the present digital age of information technology, the demand for sending digital voice, video, and Internet data to and around a home, office or other building increases continuously. Installation of wires to support this is expensive, disruptive and time consuming process. In the context of a home networking environment, “no new wires” is the term applied to a suit of technologies that utilize the existing wiring systems to distribute high-speed data and video throughout the home (or small office). Phoneline and powerline systems are two dominant “no new wires” technologies. With the recent trend of deregulation and privatization of electric utility providers, these businesses can now be classified into three major types: power generation, transmission, and local distribution. The local distribution area is highly competitive as well as presents numerous challenges and opportunities to the utilities, including the provision of new services in addition to the electric power and building brand recognition. The utilities can take advantage of the existing wiring infrastructure for provision of certain services. Telecommunication carriers, for example, are interested in a reliable way to move their content and services to the various devices in the home. Home networks are a way to achieve this.

## 3.1 Home Networking and Automation

With present broadband networks establishing new benchmarks in terms of speed and reliability, there is a rapidly growing small office home office (SOHO) networking scenario, where a consumer has two or more PCs, printers, scanners, or digital home entertainment devices. The need for enabling all these devices to communicate to each other as well as the Internet, along with the control of home appliances by the consumer are some of the driving factors demanding a home networking solution. From [48], “Home networking has long been characterized as a solution in search of a problem. The Internet has brought both solutions and new problems – and, most significantly, new content and applications to justify the deployment of home networks.”

## 3.2 Home Networking Challenges

Commercial networks are being designed specifically to carry data between computers. They typically use fiber optic, twisted pair, or coaxial cables to minimize noise and interference over the communication medium on the network. Most homes today do not have dedicated high-speed network cabling installed and the labor costs requirement for the installation of such dedicated cabling is very high for the homeowners to fund on their own. Home presents some novel and unusual challenges that have not been primary concerns in network deployments until now. For home networking to be successful, solutions must exist that utilize the existing wiring infrastructures [15] [50]. Hence, the challenges for companies that are creating home networking technologies are based on the following criteria:

- Existing wiring infrastructure should be utilized by the technology
- Ease of installation and maintenance
- Ease of use and simplicity (use of existing standards and software platforms)
- Quality of service (QoS) mechanism should be included providing low latency for telephony and other voice application
- Data rates of 10 Mbps or higher should be supported to allow consumers distribute multimedia in real time
- Extensibility
- Data type versatility (audio, video, etc.)
- Should provide automatic security to protect intrusion and leakage of data
- Technology needs to be relatively cheap to other existing solutions

There have been certain dissatisfactory approaches to home networking in the past as well. Consumers have long been promised a networked home, but only few vendors have actually attempted to provide it, and the approaches taken thus far have been either piecemeal or too complex [48]. Two PCs sharing files is not the vision of a fully networked home that consumers have been presented over the years. Nor will complicated systems requiring the consumer to be network managers will win their hearts and minds. Squabbling over interconnectivity standards within the electronic industry has also been a road block to developing usable home networking solutions. Many of the forces that lead to the creating of business networks – the need to optimize the use of resources, distributed data availability, cooperation, backup, and centralized administration – are becoming requirements for the home [50], so a drive towards home networking can be seen now to hook together the increasingly sophisticated computational components in the home to achieve more from the whole than the sum of the parts.

However, all these problems are being addressed and will inevitably be solved. OEM's are providing the consumers with latest and comparatively fast technologies with ease of use and relatively cheaper prices as compared to other existing solutions.

## 3.3 Home Networking Technologies

This section is based on the findings of [51]. The broad approaches to home networking are highlighted in this section.

Many types of broadband home networking are now available. With each type addressing certain user needs and application requirements, none has been comprehensive enough to satisfy the need for all applications and thus new technologies are being built constantly to better address the needs. Practically the ideal solution is a combination of technologies that would be used in many homes.

Broadband Home Networks (BHN) can operate over various physical media. Broadband home networks fall into three major categories: structured wiring, existing wiring, and wireless.

- **Structured wiring** requires the installation of new cabling in the walls. Both the cabling (typically unshielded twisted pair [UTP] or fiber) and its installations are defined by standards highlighted in [52].

- **Existing wiring** makes use of electrical, telephone, or coax wiring already installed in the walls.

- **Wireless** avoids the use of wires by transmitting through the air.

Table 2 shows a comparison of these approaches.

| Differentiator | Structured wiring | Existing wiring | Wireless |
|---|---|---|---|
| Best uses | New construction and remodeling | Interconnecting stationary devices | Mobile devices such as laptops, palmtops and webpads |
| Cost | High (for installation) | Low | Low |
| Useful lifetime | Very long | Relatively Short | Short |
| Number and location of "outlets" | Wherever needed | Multiple electrical outlets in every room; many rooms with telephone outlets; few rooms with coax outlets | Ideally throughout the home |
| Current data rate (Mb/s) | 100 | 10-14 | About 10 |
| Future data rate (Mb/s) | 1000 or more | 30-250 | 25-100 |
| Security | Highly secure | Less secure | Less secure |
| Standardization | Well-defined global standards | Competing standards | Competing standards |

Table 2. Broadband home networking by physical medium

### 3.3.1 Structured Wiring Technologies

Structured wiring provides high bandwidth and excellent security. To handle the full range of current applications, a complete installation for today requires several cabling types, including UTP for telephone and data, and coax for video. Fast Ethernet at 100 Mbps over UTP is widely used for data applications. While having sufficient bandwidth for video, it does not currently include the QoS support. With the introduction of HD video to home, it is believed that the home backbone network would be required based on the structured wiring to interconnect sections of the home. EIA and CEA are developing the R-7.4 VHN Home Network Standard for this purpose [51].

### 3.3.2 Existing Wiring Technologies

As the structured wiring is relatively expensive to install in the existing home, various companies now develop technologies based on the existing wiring in the walls of the home.

**Phoneline technologies** use the existing telephone wiring. The Home Phone Networking Alliance (HomePNA) [53] has recently defined a 3.0 specification that reaches an unprecedented data rate of 128 Mbps with optional extensions reaching up to 240 Mbps. As the only home networking industry specification capable of reaching above 100 Mbps and with inherent deterministic Quality of Service (QoS), HomePNA technology complements wireless networking technologies providing the ideal high speed backbone for a home multimedia network requiring a fast and reliable channel to distribute multiple, feature-rich digital audio and video applications throughout a home (the earlier HomePNA 2.0 specification was about 10 Mb/s). The International Telecommunication Union (ITU) has already adopted global phoneline networking standards G.989.1, G989.2 and G989.3 based on the HomePNA 2.0 specification. HomePNA members companies are working together and will shortly present recommendations based on version 3.0 to the ITU-T. The HomePNA 3.0 physical interface is based on version 2.0 physical layer technology and is fully backwards compatible and interoperable with HomePNA version 2.0 network components. A typical HomePNA network is shown in Figure 11.

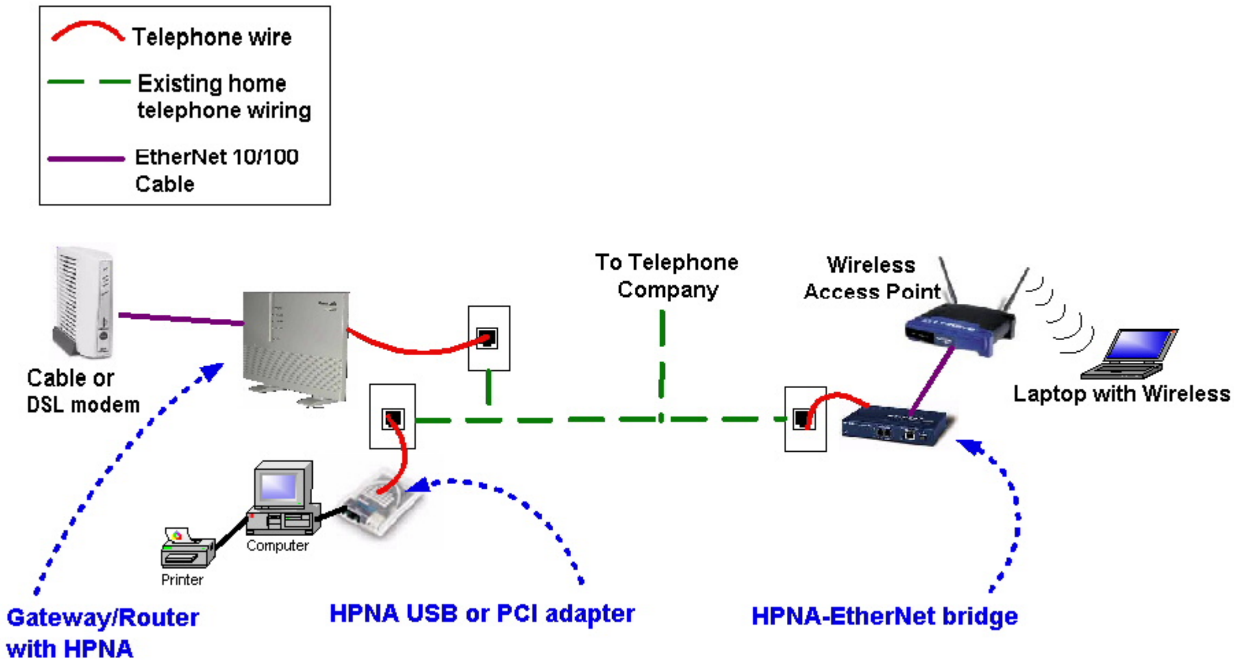



Fig. 11 Typical HomePNA Network [Courtesy: HomePNA]

**Powerline technologies** use the existing electrical wiring. There are many competing technologies which are highlighted in the Chapter 5 in this thesis. The HomePlug Powerline Alliance [46] has brought several vendors together and defined various standards for powerline. CEA R7 Home Network Committee [54] is also working to ensure current and future Home Networks can coexist within a home and share information through the use of industry standard interfaces. Powerline networking technology is explained in details in Section 3.4 ahead.

**Coax technologies** use the coax cabling. A Home Cable Network Alliance (HomeCNA) [55] is working towards defining a specification.

Table 3 compares the existing wiring technologies.

| | Phoneline | Powerline | Coax |
|---|---|---|---|
| Current data rate | 1-10 Mbps | 1-14 Mbps | TBD |
| Future data rate | 30-100 Mbps | 30-250 Mbps | TBD |
| QoS support | Yes | Yes | TBD |
| Standardization | Stable | In flux ~ Stable | In flux |

Table 3. Home networking technologies using existing wiring

### 3.3.3 Wireless Networking

Wireless Local Area Networking (WLAN) does not belong to the evolution path of the mobile networks, but started as a wireless extension to the enterprise LAN networks. Confined to a second tier role for a long time, it has recently affected a breakthrough from its original application towards home and public space, appearing as a disruptive technology due to its undisputed cost to performance ratio. Some see WLAN as a replacement for mobile networks, whereas it should be seen from its strong points more as a complement to the wide-area third generation (3G) network, offering close interworking to ensure proper delivery of services according to the most appropriate available access network [56].

Wireless networking avoids the cost of pulling new wires and the challenges of using existing wiring. There are many competing technologies and associated standards and advocacy groups in this area:

**IEEE 802.11** [57] is a family of evolving standards, originally designed for enterprise networking and now moving into home. 802.11b at 2.4 GHz is the current version. 802.11a at 5GHz is the future, although the proposed 802.11g at 2.4 GHz may be a “bridge” technology [51].

**HomeRF** [58] was a family of wireless LAN technologies specifically designed for the home. With the incompatibility with 802.11b, the group seemed to favor 802.11a in the next generation. The HomeRF Working Group disbanded in January 2003. HomeRF Specification Revision 2.01 provides support for communication of both data and voice in a home environment using the unlicensed 2.4 GHz ISM band.

**Bluetooth** [59] [60] short-range radio technology, developed by Ericsson and others, makes it possible to transmit signals over short distances between phones, computers and other devices. Bluetooth was designed for short-range personal networking and is being extended for longer ranges.

**HiperLAN** [61] is a family of ETSI standards for wireless LANs. The standards are similar to IEEE 802.11 family, but also include QoS and support asynchronous transfer mode (ATM) as well as Ethernet.

**Ultra Wideband** [62] is based on the low-power spread spectrum technique.

An overview of broadband wireless access (BWA) systems is given in [63]. Table 4 summarizes the above mentioned wireless access technologies, based on [51].

| | **IEEE 802.11** | **HomeRF** | **Bluetooth** | **HiperLAN** | **Ultra Wideband** |
|---|---|---|---|---|---|
| Frequency Spectrum | 2.4 GHz now<br>5 GHz future | 2.4 GHz | 2.4 GHz | 2.4 GHz now<br>5 GHz future | 3-6 GHz |
| Current data rate (Mbps) | About 10 | About 10 | About 1 | About 10 | NA |
| Future data rate (Mbps) | 54 | NA | TBD | 54 | 100 |
| QoS support | No; planned for future | Yes | Yes | Yes | Planned |

Table 4. Wireless home networking technologies

## 3.4 Powerline Networking

In the powerline carrier (PLC) communication systems, the powerline is used not only used for energy transmission, but also is used as a medium for data communication. Powerline networking is an emerging home networking technology that allows the end-users or consumers to use their already existing electrical wiring systems to connect home appliances to each other and to the Internet. Home networks utilizing the high-speed powerline networking technology are able to control anything which plugs into the AC outlet. This includes lights, television, thermostats, and alarms among others. Powerline communications fall into two broad distinct categories: access [15] and in-house [16]. Figure 12 illustrates the concept.

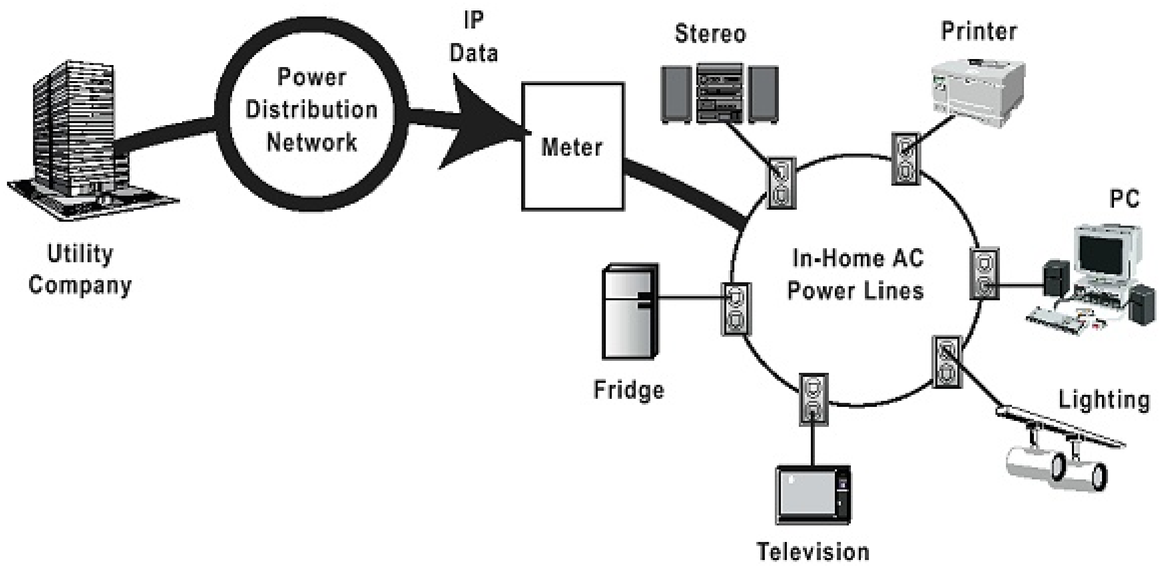



Fig.12 Powerline Networks [Courtesy: Xilinx]

**Access** powerline technologies are responsible for sending data over the low-voltage electric networks that connect the consumer's home to the electric utility provider. The powerline access technologies enable a "last mile" local loop solution which provides individual homes with the broadband connectivity to the Internet.

**In-house** (sometimes also termed as in-home) powerline technologies communicate date exclusively within the consumer's premises and extends to all of the electrical outlets within the home. The same electrical outlets which provide AC power are acting as access points for the network devices.

The access and in-house powerline networking solutions both send data signals over the powerline however the technologies differ fundamentally. The focus of access technologies is on delivering a long-distance solution, competing with xDSL and broadband cable technologies. The in-house technologies focus on delivering a short-distance high-bandwidth solution (≥10 Mbps) that competes with other existing in-home interconnection technologies like phoneline and wireless [15].

The *access* or *medium voltage* (MV) powerline technology is capable of providing broadband data transmission and provides that extra link where the telecommunication network does not reach without expensive infrastructure extensions. Broadband powerline communication systems are commercially available. They provide data transmission over the Low Voltage power grid from the Low Voltage transformer station to the household power socket. Connection to the telecommunication network presently requires a direct connection via fiber, copper pairs or wireless. An example of access powerline networks is the “ABB Medium Voltage Powerline Solution” [49] that provides cost effective broadband data transmission over the existing Medium Voltage power line and brings a significant improvement in the infrastructure costs of powerline communication projects. The ABB system, certified for use up to 24 kV, provides data transfer rates of up to 10 Mbps and is based on tried and tested components. Powerline communication provides power grid owners with new, interesting business opportunities. The Medium Voltage powerline communication solution, combined with Low Voltage powerline to the home allows the power utility to offer cost-effective, wide-coverage, broadband data services. The Medium Voltage powerline solution closes the gap between the Low Voltage network and the telecommunication network. Figure 13 shows a powerline access technology network.

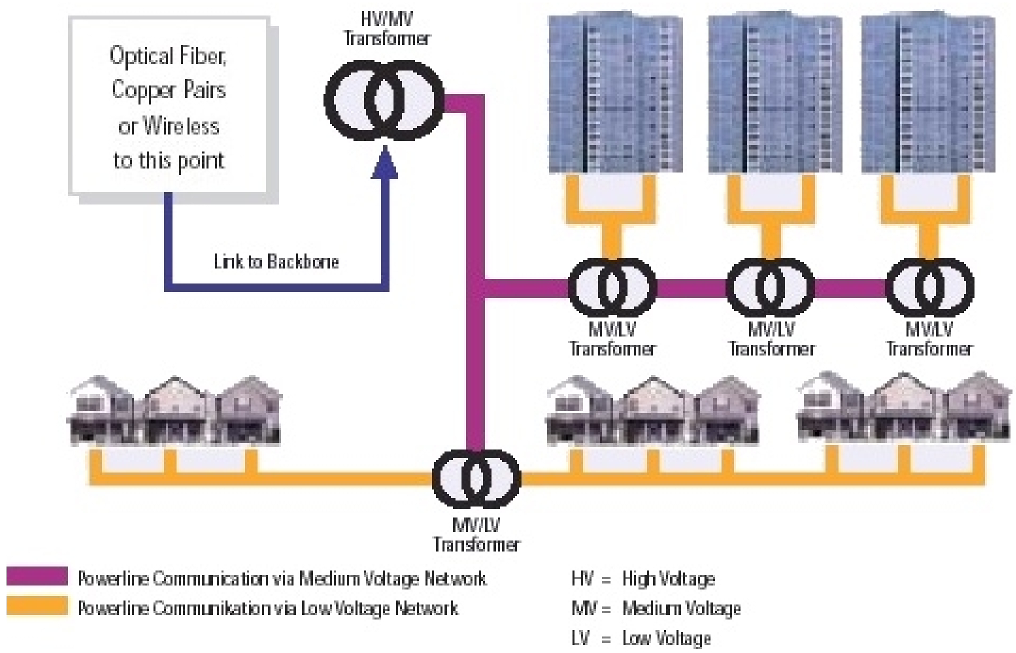



Fig. 13 Powerline Access Technology (MV) Network [Courtesy: ABB]

In the *in-house* or *low voltage* (LV) powerline technology, to support the data transmission over the power grid, a powerline carrier Controller (PLC Controller) is installed, typically in the local transformer. The PLC Controller is coupled upstream to the telecommunication network, either via traditional methods, or using some innovative/proprietary solution from the energy provider (for example, the ABB Medium Voltage Powerline Solution). Downstream, the PLC Controller handles the data transmission (Internet and Voice) over the existing low voltage network to the home and the in-house low voltage network. Connecting the PC or other household devices to the network can be done simply by plugging a powerline module/modem into the household power socket. Using powerline modules at home, or in the office provides network facilities for PCs and printers just by plugging into the in-house low voltage network. Direct connection of a telephone to the powerline modem provides voice connection. The low voltage in-house network is easily transformed into a local telephone network simply by using a number of powerline modems plugged into power sockets as needed [49]. Figure 14 below explains this concept.

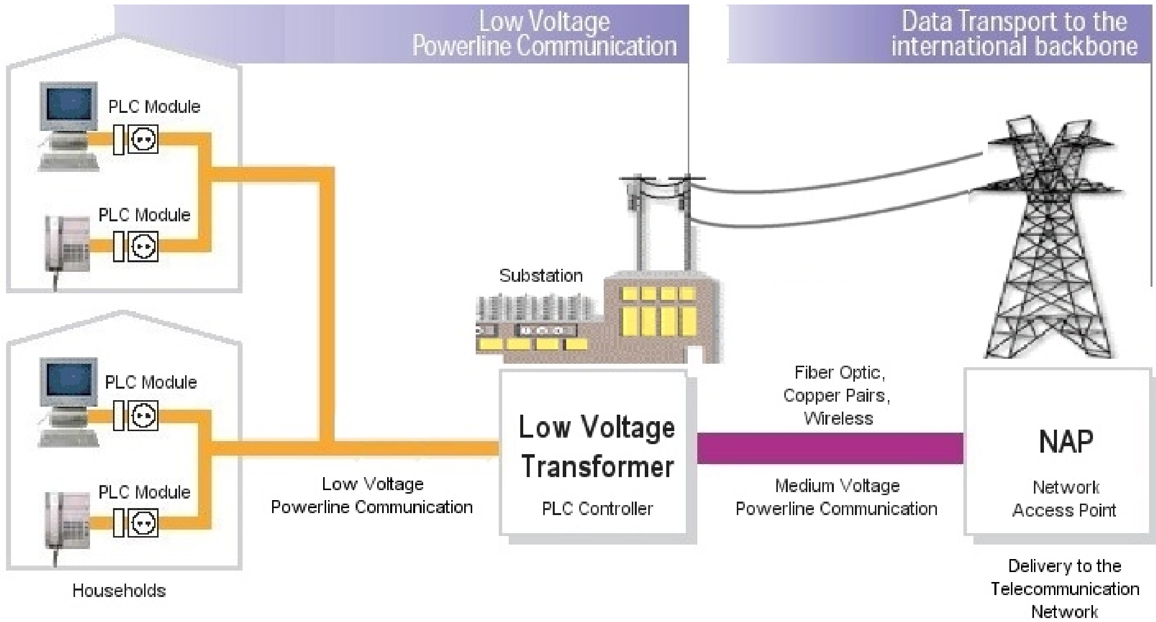



Fig. 14 Powerline In-House Technology (LV) Network

ETSI Technical Specification explained in [16] specifies the procedures to ensure the co-existence of access and in-house PLC systems in the spectrum from 1.6 to 30 MHz. The ETSI specification presents a technical mechanism for co-existence between access and in-house systems; with reference to the Network Architecture Model, it presents the co-existence of the interfaces $I_{P\text{-}yL}$ (interface between access Head End and Network Termination Low Voltage) and $I_{P\text{-}yP}$ (interface between in-house Central Node and Network Termination Premises or between several Network Termination Premises).

The discussion of this thesis is limited to the in-house powerline technologies which are also termed as the residential power circuit (RPC) or distribution line communication (DLC) systems i.e. the powerline communication systems referring to the low voltage part of the electrical power distribution network, comprising everything attached to the secondary side of the medium to low voltage distribution transformer. PLC communications within the European A-band have been the main subject for this thesis. The Home Networking scenario is presented with the powerline communication system intended for consumer usage (home, apartment, SOHO) where the powerlines are owned privately and the power line system is owned and operated by administrative entity.

### 3.4.1 Components of an In-House Powerline Network

A typical in-house powerline network consists of the following elements:

- House wiring inside of the building
- Appliance wiring (power cords)
- The appliances themselves (load devices)
- The electric meter (circuit breaker)
- Powerline networking modules (modems, bridges, routers, etc.)

Figure 15 shows a typical In-house powerline network scenario.

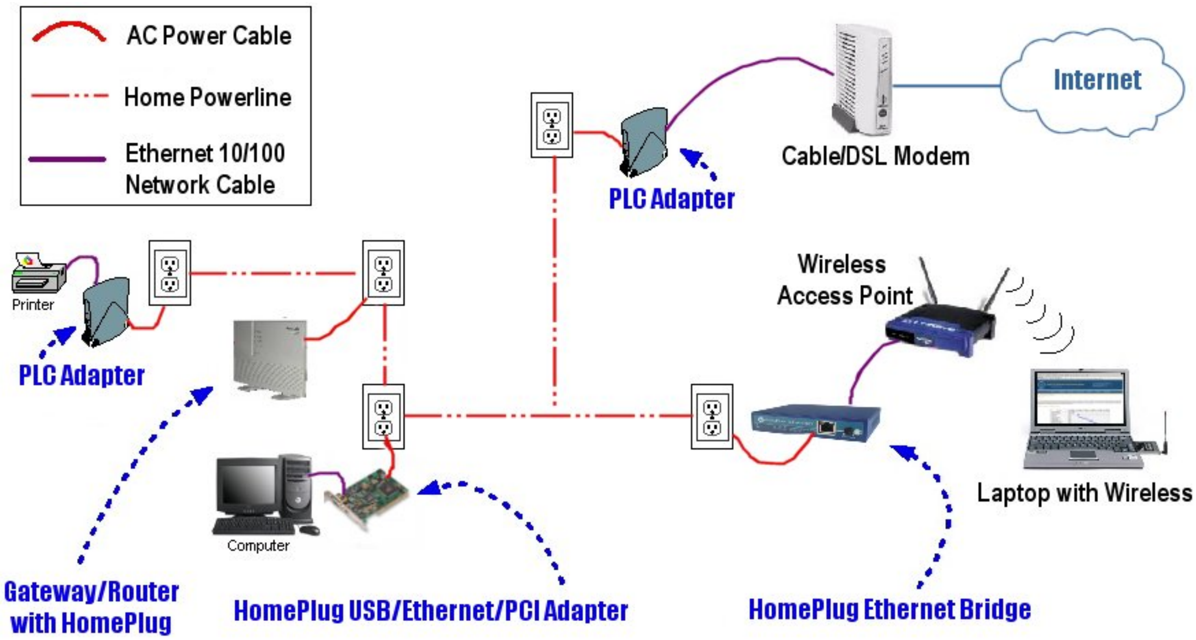



Fig. 15 A typical In-House Powerline Networking Scenario

### 3.4.2 Advantages of In-House Powerline Networking

This section highlights the advantages of using powerline as the transmission medium for in-home networking.

**Ubiquity of electrical outlets**: The main advantage of using powerline for home networking is the availability of multiple power outlets in every room. Thus, the “no new wiring” concept eliminates the need to do additional wiring (or rewiring) the home.

**Data transmission capability**: Powerline networking takes advantage of the unused capacity of the power cable to transmit data over the existing home power cabling.

**Distribution of multimedia**: Powerline networking is capable of distributing audio, video, and other real time services alongside data, throughout the home.

**Speed**: With the technological advancements, powerline networking is capable of distributing data at 14 Mbps speed and future data transmission rates include 100 Mbps, making it an advancing technology with a future.

### 3.4.3 Disadvantages of In-House Powerline Networking

This section highlights some of the major disadvantages associated with In-house powerline networks.

**Noise**: The greater amount of electrical noise on the line limits practical transmission speeds to somewhat lower values.

**Noise Sources**: Vacuum cleaners, light dimmers, electric lamps, kitchen appliances, drills are examples of noise sources that affect the performance of a powerline-based home network.

**Minimum Security levels**: HomePlug certified products have a built-in 56-bit DES encryption, however it is not turned on by default and thus powerline does not necessarily provide a secure media.

**Data attenuation**: Presence of various elements on the powerline network makes data attenuation a considerable issue in powerline networking.

**High costs of residential appliances**: In comparison to the phoneline network equipment, the powerline networking modules are more costly and this also needs addressing to make powerline a preferred technology for home networking.

**Lack of standardization**: Regularity issues in some international markets are also preventing the development of global standard for distributing data over existing in-house powerline systems.

### 3.4.4 Technical Obstacles of an In-House Powerline Network

The powerline network is prone to various technical obstacles when it comes to transferring data at considerable speeds. The typical data and communication networks (like corporate LANs) use dedicated wiring to interconnect devices. But powerline networks, from their inception, were never intended for transmitting data. Instead, the networks were optimized to efficiently distribute power to all of electrical outlets throughout a building at frequencies typically between 50-60 Hz [15]. Thus, all the original designs of electrical networks never really considered using the powerline medium for communicating data signals at other frequencies.

Due to this reason, the powerline is a more difficult communications medium than other types of isolated wiring (like for example, the Category 5 cabling used in Ethernet data networks). The physical topology of the electrical network, the physical properties of the electrical cabling, the appliances connected, and the behavioral characteristics of the electric current itself all combine to create technical obstacles associated with a powerline network.

## 3.5 Typical Applications of Home Networking

The typical applications of Home Networking can be broadly classified into five categories: resource sharing, communications, home control, home scheduling, and entertainment/information.

### 3.5.1 Resource Sharing

Home networking allows all users in the household to access the Internet and applications at the same time. Additionally, files (not simply data, but also audio and video depending on the speed of the network) can be swapped, and peripherals such as printers and scanners can be shared. With home networking at work, the need for having more than one Internet access point, printer, scanner, and/or software packages is eliminated. Home networking technologies can successfully be used to distribute IP based data across the home with considerable speeds.

### 3.5.2 Communications

Home networking allows easier and more efficient communication between users within the household and better communication management with outside communications. Phone, fax, and e-mail messages can be routed intelligently in a home network. Access to the Internet can be attained at multiple places in the home with the use of terminals and Webpads etc.

### 3.5.3 Home Control and Automation Systems

Home networking can allow controls within the house, such as temperature and lighting, to be managed through the network and even remotely through the Internet. The network can also be used for home security monitoring with network cameras.

Powerlines have been used for home automation for many years. The most important types of home automation applications include controlling lights, ventilators, security systems, sprinklers, and temperature levels within the home. The home control networking systems market is undergoing a significant transition from closed-loop solutions to open, IP-aware solutions. The result is that the U.S home automation and controls equipment market is expected to grow from $1.1 billion in 1999 to $3 billion in 2005 [15]. Home control and automation systems are normally based on one of the three major powerline technologies namely, CEBus, LonWorks, or X-10. These technologies are discussed in depth in later sections of this thesis.

### 3.5.4 Home Scheduling

A home network would allow families to keep one master schedule that could be updated from different access points within the house and remotely through the Internet.

### 3.6.5 Entertainment and Provision of Information

Home networks enable a plethora of options for sharing entertainment and information in the home. Networked multi-user games can be played as well as PC-hosted television games. Digital video networking will allow households to route the video from DBS and DVDs to different set-top boxes, PCs, and other visual display devices in the home. Streaming media such as Internet radio broadcasts can be sent to the home stereos as well as PCs.

From [48], Table 5 below lists some of the home networking applications, what they can do for the consumer, how they're delivered, and their level of availability. Some of these are based on future scenarios, and some have been delayed because of the slowdown in current economic sector related to the IT industry. With the involvement of consumer towards the trial and usage of these applications, a shake-out will occur, and the ones with greatest appeal will survive and defined more precisely according to the needs and demands.

| Application | Activity | Products | Delivery Time |
|---|---|---|---|
| Entertainment<br>(Video, Audio, Music) | ● Distribute multimedia content throughout the home<br>● Video and music on demand | ● TV receivers, displays, DVDs, cable satellite receivers, MP3s, personal video recorders<br>●Various set-top boxes, desktop, and handheld display devices | Available |
| Information<br>News, business, sports<br>Calendar listings | ● Personalized newscasts, customized business and sports data<br>● Event listings targeted to personal agenda | PCs, set-top boxes, handheld devices | Available |
| Education | Home education, enrichment, homework, training, online seminars | TVs, set-top boxes, PCs, phones, software | ● Limited use today<br>● Growing acceptance during present decade |
| Telecommuting | Self-employed or remote access to corporate network | PCs, phones, display devices, software | Available |
| Communications | ● Voice and video communications<br>● Live conversations and stored messaging services<br>● Internet access | ● Phones (wired, mobile, cordless)<br>● Video cameras<br>● Display devices<br>● Modems, set-top boxes, wireless access devices | ● Available<br>● Expanded services coming |
| Financial Services | Banking and Investment | PCs, handheld devices | ● Limited<br>● Growing acceptance during present decade |
| Productivity<br>(Coordinate family events) | ● PC-shared peripherals and software<br>● Shared Internet access<br>● Calendar software | ● PCs, printers, modems, scanners<br>● Software<br>● ASP connections | ● Small reach presently<br>● Widespread expected between 2003-2005 depending on encouragement by utilities etc. |
| Home Management<br>(Power Controls) | Energy conservation<br>Remote power management | ● Major and small appliances<br>● Central heating/air conditioning | ● Limited<br>● Widespread expected between 2003-2005 depending on encouragement by utilities etc. |
| Security | Monitoring of household and individual homes | Surveillance Cameras, monitors, telecom connections | ● Available<br>● Widespread expected between 2003-2005 |

Table 5. Home Networking Applications

### 3.6 Conclusions

This chapter presented the various existing home networking technologies highlighting the advantages and salient features associated with each technology. The choice of a suitable home networking and automation technology is a combination of several factors governing the need and requirements of the consumer. Powerline networking concept is also presented in this chapter along with the pros and cons associated with the technology. Powerline networking offers several advantages over other available home networking technologies; the significant ones being the availability of power outlets in abundance in every home, the elimination of laying new wiring, the reliability and quality of service, and data speeds of 14 Mbps enabling delivery of information including data as well as multimedia to the SOHO scenario.

# 4 Powerline Carrier (PLC) Communications

Communications over Powerline is different than communications over dedicated network wirings (for example, UTP, STP, Fiber etc.). Powerline presents a difficult medium for transmission of information. Communication over the AC powerline is difficult because of the unpredictable noise and interference caused from sources such as halogen lamps, vacuum cleaners, blenders, washing machines, hair dryers, microwave ovens, etc. Also, the powerline is not controlled or constant over time. As compared to the Ethernet cabling, which is clean and has consistent characteristics, the powerline can have numerous appliances and equipment plugged in at any time (turned on or off any time, run for any length of time). The constant plugging and unplugging of various home electric devices, turning them on and off, causes the powerline characteristics to vary constantly and significantly [64]. Attempts to send data over this inconstant medium is what has stumped the powerline technology companies for a long time.

This section presents some of the characteristics of the powerline as a communication channel. As stated in the start of this thesis, the focus is on the residential power circuit (RPC) or the distribution line communication (DLC) i.e. the low-voltage grid of the overall powerline network with focus on in-house PLC technology. Most of the material for this section is based on the findings of [65] and [66].

## 4.1 Residential Power Circuit Communication

The Residential Power Circuit (RPC) or the Distribution Line Carrier (DLC) i.e. the low-voltage end of the powerline communications study network generally consists of three major parts, namely, the Multifunction node (MFN), the Concentrator & Communication Node (CCN), and the Operation and Management System (OMS) [66]. Figure 16 represents the parts connected in a typical communication system.

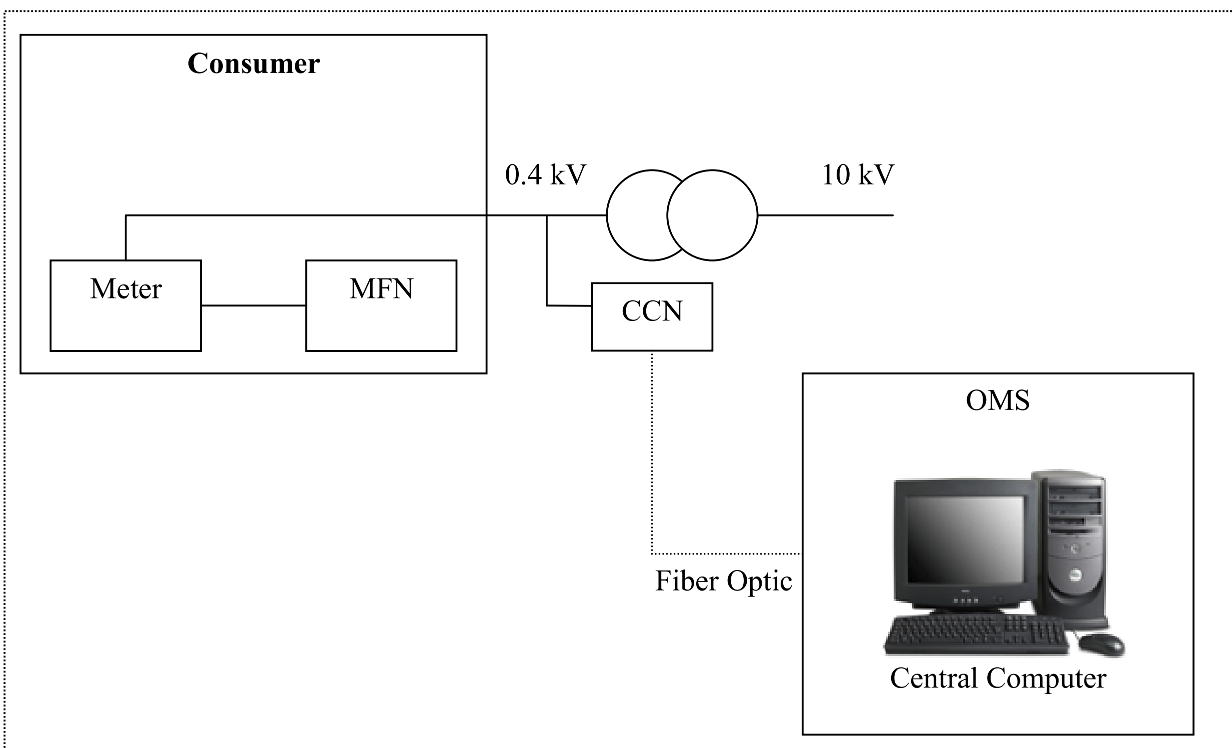



Fig. 16 Major parts of a RPC system and their interconnection

The MFN is a unit installed in each household either as an integrated or separate part of the electricity meter. It reads the meter value each hour and stores it in a memory. The memory can store up to many days of meter values.

The CCN manages all MFNs in an area, e.g. a low-voltage grid, and it is responsible for collecting their meter values. Typically, the CCN is installed in a sub station and it consists of an ordinary PC.

An OMS manages a set of CCNs. The meter values collected by the CCN are stored in the OMS where they can be accessed and analyzed.

Based on [65], an estimated $P_i$ of the probability for re-transmission of a transaction between the CCN and household number *i* (MFN number *i*), can be obtained as:

$$P_i = \frac{e_i}{N_i}$$

This parameter is an estimate of the probability of rejection of an individual transaction at the CCN due to channel impairments. $P_i$ is referred as an estimated channel impairment indicator to household *i*.

The average, P, of the channel impairment indicators, $P_i$ is a measure of the overall average quality of the K(=59) communication channels in a test area (the findings of [65] are based on the tests performed at the 59 households of Påtorp area located in Ronneby, Sweden) during an hour, and is obtained as:

$$P = \frac{1}{K} \sum_{i=1}^{K} P_i$$

The results of [65] predict that if the same amount of transactions are sent to each house, then about 10-15% of the transactions fail on average. Also the peak appears to occur during the morning and evening hours. The impairment seems to be considerably high during peak hours (around 20:00) and it was also shown that the impairments vary with time and a graph of consistency in behavior is also observed among the corresponding days of measurements.

The overall estimated re-transmission probability, $P_{CCN}$ is estimated as:

$$P_{CCN} = \frac{\sum_{i=1}^{K} e_i}{\sum_{i=1}^{K} e_i}$$

## 4.2 Noise Characteristics on the Residential Power Circuit

According to [67], power-line voltage disturbances can be categorized as follows:

**1. Wave-shape disturbances** (of the 50/60 Hz power-line voltage)

a) Overvoltages
- persistent (> 2 seconds)
- surge (< 2 seconds)

b) Undervoltages
- persistent (> 2 seconds)
- surge (< 2 seconds)

c) Outage
d) Frequency variations
e) Harmonic distortion

**2. Superimposed disturbances**

a) Persistent oscillations
- coherent
- random (stationary/non-stationary)

b) Transient
- impulses
- damped oscillations

Broadly speaking, the disturbances classified as "superimposed disturbances" qualify for the terms "noise" or "disturbance" and are thus considered interchangeable expressions for the context of this thesis.

From [66] and the findings of [68], the noise caused by a wide variety of consumer appliances can be categorized into four major categories:

***1. Noise Synchronous to the (50 or 60 Hz) power system frequency***:
Main sources for this type of noise are all kinds of switching devices e.g. certain power supplies and silicon-controlled rectifiers (SCR's) which are almost always found in the light dimmers in the form of triacs. Since these switches switch an integer number of times (typically once or twice) every power system frequency cycle, they produce noise at higher harmonics of this power system frequency [66]. The spectrum of this noise consists of a series of harmonics of the 100 Hz fundamental components. Photocopiers also generate strong noise impulses at twice the power system frequency [10]. From [67] this kind of noise can be classified as type 1e disturbance [also highlighted in Section 4.2]. From [66] however, the transient character of the noise impulses caused by switching makes it possible to classify this kind of noise as superimposed transient disturbances, i.e. type 2b.

***2. Noise with a smooth spectrum***:
Main sources for this kind of noise are appliances not operating synchronously with the powerline frequency, e.g. universal motors (i.e. relatively small motors with several windings) like electric drill etc. The actual noise originates from the brushes inside the motor that cause current switching at

intervals which are dependent on the motor speed. From [68] for most practical purposes, this kind of noise can be thought of as having a smooth spectrum without spectral lines. From [66], this noise may be modeled as white noise over the small CENELEC A-band. From the classification of [67], this kind of noise falls in the 2a category (i.e. random persistent oscillations).

***3. Single-event impulse noise***:
Main reason for this kind of noise is all kinds of switching phenomena. The on/off switching of a device equipped with a capacitor for power factor correction causes this capacitor to be suddenly connected to/disconnected from the RPC. This causes large transient voltages on the RPC, depending on the size of the capacitor. According to [66], it is probably fair to consider most of these noise impulses to be transient impulses as classified by category 2b in Section 4.2. However, the connection of large capacitor banks to the RPC leads to damped oscillations.

***4. Periodic noise, not synchronous to the power system frequency***:
This type of noise exhibits spectral lines at frequencies uncorrelated to the power system frequency. From [66], apart from florescent lighting, television receivers are indicated as the most common source of this kind of noise, with production of tones at multiples of the television horizontal scanning frequency (15,734 Hz for the NTSC standard in the USA; 15,625 Hz for the PAL standard used in most European countries). Many computer monitors also employ line frequencies other than the ones stated above. From the classification of Section 4.2, this type of noise falls in the category 2a i.e. persistent coherent oscillations.

From [10], some suggestions can be made to minimize the impact of the different noise categories stated above:

- Since x/x filters at the input of the receivers, with spectral nulls at the power system frequency, in order to combat noise of category 1.
- Forward Error Correction (FEC) codes combined with interleaving (to provide time diversity) should be implemented, to cope with noise of categories 1, 2 and 3.
- The television line frequency and its harmonics should be avoided when modulating the signal onto the channel.
- Some kind of frequency diversity (e.g. frequency hopping) combined with FEC should be implemented to cope with the unknown frequencies of e.g. computer monitors.

Reference [66] presents a summary of the findings regarding the intrabuilding background noise (i.e. the noise measured when no machine is active nearby), which in principal can be measured at any wall-socket inside a building. An assumption is also drawn, that the bulk of noise impulses occurring on the RPC last for more than 500 µs. At present, there are various publications discussing intrabuilding noise. However, only few publications exist that discusses the noise properties on the part of the RPC outside the consumer premises. One reason being, that the part of low voltage network is inaccessible without the cooperation of an energy company. In order to come to a better understanding of the qualitative and quantitative properties of RPC-noise outside the consumers premises, [66] presents results of extensive noise measurements on several locations in the low voltage network of the “Energie Bedrijf Amsterdam”, the Netherlands. From the testing, [66] concludes that in principal, four different noise types are present on the RPC-channel, namely:

a. *Background noise*:
The background noise at a certain location, at an arbitrary time for frequencies within the CENELEC A-band in a good approximation is distributed as:

$$N(f) = 10^{(K - 3.95\ 10^{-5} f)} \quad [W/Hz]$$

Where K is normally distributed with an average μ = -8.64 and a standard deviation σ of 0.5.

b. *Impulse noise*
c. *Noise synchronous to the power system frequency*
d. *Narrow-band noise*

Reference [65] presents results of tests performed at the Påtorp area (a specific low-voltage grid) located in Ronneby, Sweden. As a measure of the noise level, [65] estimates the power spectrum, R(*f*), which describes how the power of a signal is distributed in the frequency domain. Measurements of [65] suggests that the noise is roughly -110 dB (W/Hz) at 25 kHz, is non-white, and decays with increasing frequency.

## 4.3 Impedance and Transfer Function of a Residential Power Circuit

A good background of the publications providing a good insight in the RPC-impedance that can be expected at the AC-power outlets inside the houses is presented in [66].

- In [69] the minimum, mean and maximum curves are shown for the 60 Hz-based RPC in the USA. For CENELEC A-band frequencies maximum absolute impedances (i.e. $|Z_{RPC}|$ ) are shown to increase from 3 Ω at 20 kHz to 35 Ω at 100 kHz, mean values increase from 1.5 Ω to 13 Ω over the same frequency range and minimum values from well below 1 Ω to 3 Ω.

- In [70] similar results are reported for measurements performed on the European 50 Hz-based RPC. Separate curves are shown for measurements performed in German and Dutch RPC's. For the aggregate RPC, in the CENELEC A-band maximum absolute impedances are reported increasing from 20 Ω at 20 kHz to 80 Ω at 100 kHz. Mean values increase from 5 Ω to 17 Ω. Over the entire frequency range from 20 to 100 kHz, minimum absolute impedence values are indicated to be ~ 0 Ω.

- In [72] the three parts which make the RPC-impedance are identified and investigated separately for the frequency range from 5 to 20 kHz:

  - The impedance of the secondary side of the distribution transformer
  - The lines
  - The loads

- In [71] an experimental relation is presented for the absolute impedance of a Japanese RPC measured as a function of frequency, determined by using a least squared fit, equal to:

$$|Z| = 0.005 * f^{0.63} \quad [\Omega]$$

The measurements of [66] at Sloten, Amsterdam, Netherlands concluded that the exact behavior of the impedance as a function of frequency depends on the capacitive or inductive nature of the ensemble of loads and distribution transformers and can be quite different per location of measurement. It was also found that the network impedance of a meshed RPC network can be considered to be constant within an area of several hundreds of meters. RPC-impedance can change considerably as a function of time, but appears almost time-independent at most locations.

In [65] it is suggested that at conventional communications, impedance matching is attempted such as the use of 50 Ω cables and 50 Ω transceivers. However, the power-line network is not matched. The input (and output) impedance varies in time, with different loads and locations. It can be as low as milli Ω and as high as several thousands of Ω and is specially low at the substation. Except the access impedance, several other impedance mismatches might occur in the power-line channel e.g. cable-boxes do not match the cables and hence the signal gets attenuated. Use of filters helps in stabilizing the network. The cost of these filters is high however, and they must be installed in every household and perhaps also in every cable-box.

From [10], the overall impedance of a low voltage network results from:

● *Impedance of the distribution transformer*: This impedance increases with frequency

● *Characteristic impedance of the cable used*: A wide variety of cables is used, which can be modeled as a serial connection of inductors and resistors.

● *Impedance of the devices connected to the network*: This varies typically between 10 Ω and 1000 Ω.

With reference to the imaginary part of the transfer function i.e. the *phase shift* of a signal transmitted over the RPC, not much literature is available. The measurements of [66] conclude that for urban and suburban environments, the phase shift introduced by the RPC can be considered to be relatively stable in time. It is also suggested that virtually no time-variance is registered in the phase shift over an extended period of time. Variations with respect to the reference were never found to be larger than about ±10°. The results of [65] suggest that the transfer function is found to be frequency-selective.

## 4.4 Signal Attenuation

From [10], the signal attenuation for low voltage networks amounts to 100 dB/km, and for the medium voltage network to 10 dB/km. The large attenuation on especially low voltage networks may necessitate the frequent use of repeaters at a distance less then 1 km. A number of factors determine the signal attenuation, including:

● *Time Dependence*: There is strong day/night sensitivity.

● *Frequency Dependence*: From [10] for frequencies above 100 kHz, an increase of 0.25 dB/kHz is reported. Due to transmission line effects in long (>400 m) cable, signal attenuation can get very high at certain frequencies. From the findings of [65], the attenuation has been found to increase with frequency. Above 10 MHz it is hard to distinguish the received signal from the background noise, which limits the communication distance. The magnitude of the frequency response of the channel is not flat, except from decaying with increasing frequency, degradation in certain frequency bands occur, thus the channel is frequency-selective.

● *Distance Dependence*: From [10] for practical situations, a signal attenuation of 100 dB/km is often considered.

● *Signal Attenuation over Network Phases*: From [10] attenuation across phases can be as high as 40 dB. From the conclusions of [66], the signal attenuation for across-phase RPC channels is considerably higher than for corresponding in-phase channels.

From the conclusions of [73], which are based on the testing of Ascom Systec AG and RWE (German utility) performed at a low voltage powerline network in Leichlingen, Germany, assuming the tolerable attenuation is 40 dB for a given signal power, the achievable range is about 100 m at 20 MHz, 140 m at 10 MHz, 200 m at 5 MHz and 300 m at 2 MHz.

## 4.5 Signal-to-Noise Ratio

From [65], the signal-to-noise ratio (SNR) is a key parameter when estimating the performance of a communications system. The SNR is given as:

$$\text{SNR} = \frac{\text{Received power}}{\text{Noise power}}$$

This parameter is related to the performance of a communications system. The higher the SNR, the better is the communication.

The use of filters can improve the signal-to-noise ratio. By placing the filter in each household, blocking the noise generated indoors from entering the electricity grid, the noise level in the grid will decrease, however, the cost of implementing such filters is rather complex.

## 4.6 Coupling the signal onto the channel

From [10] there are two ways of connecting the PLC unit to the network:

● *Capacitive Coupling*: A capacitor is responsible for the actual coupling and the signal is modulated onto the network's voltage waveform.

● *Inductive Coupling*: An inductor is used to couple the signal onto the network's current waveform. Inductive coupling is known to be rather lossy, however, no physical connection to the network has to be made, which makes it safer to install than the capacitive coupling.

A phase coupling mechanism for power line communications with CEBus power line signal is highlighted in [32]. From [73] the homogeneity of power line network and the number of different feeders in substations and in-house access points have major influence on the coupling loss.

## 4.7 Medium access techniques for the powerline

Various channel access algorithms have been demonstrated for dedicated wiring. The algorithms are generally based on either a carrier sense technique or token passing mechanism. However, results from other transmission media are not transferable to the powerline because of the following reasons highlighted in [10]:

- On the powerline there is insufficient communications reliability to distinguish between noise and signal, which makes carrier sense exceptionally difficult. Nodes will back off when there are no contending devices transmitting on the powerline.

- Since the powerline characteristics can be remarkably different for each node, there is a strong possibility that a node will not necessarily listen to all the transmission on the powerline. In carrier sense, a node may thus incorrectly sense that the channel is quite and start transmitting in the middle of another transmission.

The above two arguments make carrier sense multiple access with collision detection (CSMA/CD) hard to implement for the powerline environment. The two other major channel access techniques, namely, *polling* and *token passing*, are much easier and reliable to implement in the powerline environment. These two techniques do not require collision detection and only the master or the node which holds the token can transmit data over the medium.

## 4.8 Low-level link protocols for powerline environment

From [10] it is suggested that only a certain amount of contiguous information can be sent over the powerline before it is almost a certainty that the transmission will be corrupted. This presents a requirement for the transmission of short data frames over the powerlines.

Since the application using powerline can be critical (for example, security systems, train control systems etc.) it is therefore necessary that the integrity of data frames should be ensured by using both the error-correcting and error-detecting codes. Forward error correction (FEC) should be used to minimize the number of retransmissions, and error detection should be used to determine if there is a need for retransmission. Also, each frame should be acknowledged by the receiver, before the transmission proceeds to the next frame (this however, may cause sever overhead on the transmission protocol).

## 4.9 Modulation techniques for the powerline communication channel

Powerline channel is a harsh environment. The characteristics of a powerline channel tend to vary in time, location and with load changes. Using powerlines for communication purpose requires sophisticated modulation schemes. Conventional modulation techniques such as ASK, PSK or FSK are normally ruled out by the hostile behavior of the powerline channel.

From [65] one possible solution to overcome the problems with such a channel is to use a robust modulation method. If the modulation method is able to handle unknown attenuation and unknown phase shifts, then the receiver can be simplified. The problem is to combine these requirements with the high bit rate needed in present day's computer communications and the bandwidth limitations on the power-line channel. A study of a set of modulation methods that may be a candidate to be used in powerline communications is presented in [65]. Also, a communication system for the powerline channel is suggested by combining the modulation methods with coding, frequency diversity, and the use of sub-channels (similar to Orthogonal Frequency Division Multiplexing), presenting a flexible structure that can be upgraded to future needs.

A detailed analysis on the performance of several modulation and coding techniques on the residential powerline carrier (RPLC) channel, is presented in [66]. The conclusions are:

- Modulation-techniques that resort to the higher part of the CENELEC A-band can generally be expected to show a superior performance to modulation-techniques that use the entire frequency band that is available.

- Narrow-band modulation techniques that operate close to the 95 kHz band-limit show very good performances in terms of bit-error rate (BER) as a function of distance that can be bridged. Unless a system is used that constantly looks for the best-carrier frequency, narrow-band systems better not be used for most applications. *M*-ary modulation techniques with an *M* that is not too high combine the good performance of narrow band modulation techniques in channels that exhibit impulsive noise with a good performance in channels that exhibit narrow band interferences.

- "Since spread spectrum systems use the lower A-band frequencies, which exhibit more noise, they can generally bridge distances that are a few hundred meters less than their binary- or *M*-ary counterparts. This is one of the main disadvantages of spread spectrum modulation on RPC-channels: a-priori knowledge concerning background noise distribution is not exploited. This, combined with a very moderate spreading gain (<20) leads to the conclusion that spread spectrum modulation techniques should not be used in case the distance that has to be bridged is to be maximized. Furthermore, the analysis showed that once a choice is made for spread spectrum modulation, fast frequency hopping with hard chip-decision should be preferred."

Modulation techniques based on Orthogonal Frequency Division Multiplexing (OFDM) have come into focus for the use on powerlines. OFDM is the heart of the HomePlug Powerline Alliance industry specification known as HomePlug 1.x (x being 0, 1). OFDM works by modulating digital information onto multiple carriers, up to 84 in this case, with each carrier occupying its own frequency from 4.3-20.9 MHz [13]. From [66], in OFDM the incoming bit-stream is demultiplexed in a number *N* of parallel bit-streams each one with a rate of 1/*N*-th of the original bit-rate. These parallel bit-streams are then modulated onto *N* orthogonal carriers (PSK is often used for this purpose). The advantages offered by this technique are various. For instance, since the bit-rate per channel is only 1/*N*-th of the original bandwidth, synchronization at the receiver is much easier and can in principle be based on the underlying 50 Hz/220 V. Furthermore, it is possible to spread out the *N* sub-channels over the entire frequency band that is available in order to get a FHSS-like robustness against type *d*-noise. From [13], the use of multiple carriers makes the most efficient use of the available spectrum, data rates being higher when multiple bits are sent on multiple channels at the same time. Each frequency is monitored for interference, impulse noise, or data loss, and those frequencies that pose a problem are eliminated. If something degrades the channel's signal-to-noise ratio, the data transfer is reduced, but communication does not stop. Forward error correction further enhances the reliability of each carrier. HomePlug supports four "traffic classes" or priority levels, which allow it to do simply quality of service at lowest network layers, producing a robust, reliable, and fast network system.

A comparison between FSK, OFDM and DS-SS for high data rate powerline communication in the frequency range of 4-20 MHz is presented in [74]. The results of [74] are presented as:

● *FSK*: FSK does not appear to be suitable for high-speed powerline communication, date rates over 500 kbps are almost impossible.

● *OFDM*: Apart from the complexity and overhead associated with OFDM, there is a very poor performance when large attenuation or jamming occurs in part of the channel. OFDM can be very efficient if the transmitter is allowed to learn the channel, data rates up to 10 Mbps are possible, but the channel is changing over time and between receivers.

● *DS-SS*: For [74], DS-SS is the preferred modulation technique. Spread spectrum transmits over the entire frequency band (in this case 4-20 MHz) and the receiver can collect the energy from those parts of the spectrum that has a positive signal-to-noise ratio. With DS-SS, the 1 Mbps speed is not a problem, while at 10 Mbps the spreading is not efficient enough, and at 5 Mbps the spreading appears to be efficient and robust communication is possible.

One of the problems with achieving high data rates on the powerline network is the fact that the attenuation increases with frequency. Above 20 MHz the signal is attenuated below the noise level at modest distances, while the noise levels are much lower at higher frequencies so the most suitable band for powerline communication is the 2-20 MHz, according to the findings of [74].

From [75], the Intellon enhanced OFDM, which is the base of PowerPacket technology, which in turn is the base of HomePlug standard, has the following benefits:

- Very good at mitigating the effects of time-dispersive channels (Multi-path reflections).
- Very good at mitigating the effects of in-band narrowband interference.
- Bandwidth efficient
- Scalable to very high data rates (100 Mbps and beyond – a function of available bandwidth and signal strength).
- Flexible and adaptive; different modulation, bit loading (ignoring bad carriers, coding), variable/adaptable bandwidth/data rate possible, etc.
- Has excellent co-channel interference (CCI) performance.
- Does not require channel equalization.
- Does not require phase lock of the local oscillators.

## 4.10 Conclusions

This chapter presented various techniques associated with communication over powerlines. Powerlines present a very harsh medium for transmission of data and information. Originally designed for the transmission of electric signals, the powerline behave significantly different from the dedicated network wiring designed specifically for the purpose. This chapter summarized the findings and solutions to-date of various testing and measurements performed at various live-networks in major European cities, and also presented the various problems associated with communication on the AC powerlines because of various factors such as the unpredictable noise and interference from various sources, high attenuation levels, widely varying impedance, multipath delay spread and others. Various channel characteristics including the ones presented in this chapter needs to be studied in depth before designing modulation techniques for transmission of information. The Intellon's OFDM technology presents a robust and scalable approach to the problem.

# 5 Powerline Communication Technologies

This Chapter is a result of the on-going study and research on the underlining technologies in the powerline networking arena. The technologies and standards used presently in the Power Line Communications are investigated in depth. These include LonWorks, X-10, OFDM, Passport, CEBus and the HomePlug standard. Then focus was on the technologies that are being deployed based on the standards. The advantages and benefits of using power line as the medium of data transmission at homes was also considered. The quality of service, data transmission rates, the limitations, the drawbacks and other important factors were taken into account. The description of technologies follows.

## 5.1 LonWorks (Local Operation Networks)

The LonWorks technology, developed by Echelon [19], and available as an open standard to all manufacturers, displaces the proprietary centralized systems with open, highly distributed, interoperable systems in the control system architectures. Every automatic control system (industrial or application) is comprised of the same basic components: sensors, actuators, application programs, communication networks, human-machine interfaces and network management tools. Rapid technology advancements demands changes in all types of system architectures, including the control systems. The LonWorks technology makes possible information-based control systems, rather than the old-style command-based control systems.

Figure 17 shows the centralized architecture that up until recently has been typical of most control systems in commercial and industrial applications. The figure shows typical tens of thousands of sensors and actuators (I/O points) that are wired to a sub-panel, which in turn is connected to the controller panel via a proprietary master/slave communication bus. The controller panel contains a high-performance microprocessor that runs a custom application program which implements the control logic for all the I/O ports connected to it. The system may have a proprietary HMI of may publish an interface to allow standard HMI tools to connect to the system [20]. The system typically resembles the legacy mainframes and minicomputer systems of past decades.

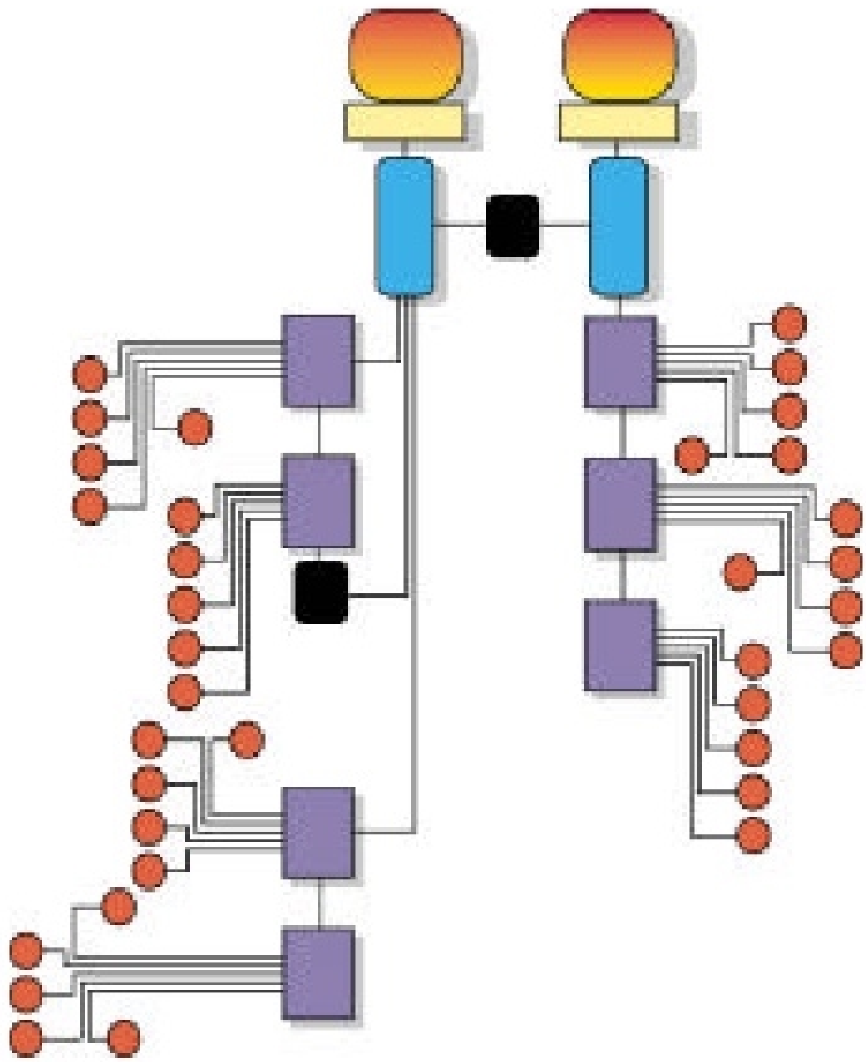


Fig. 17 Centralized Control Architecture Model [Courtesy: Echelon]

The highly distributed, peer-to-peer architecture made possible by LonWorks technology is shown in Figure 18. There are no centralized controllers or home-run wiring panels in this system. The LonWorks devices (also called as nodes), communicate with any other node in the system using a standard communication protocol on whatever physical medium is best (twisted pair, AC powerline, radio frequency, fiber optic cable, infrared). With each node having its own simple application program, the control logic is distributed throughout the system. Node application is customized by setting configuration parameters rather than by custom programming. Every sensor or actuator in the system can be a node. HMI and network management tools are available for multiple vendors and can have access to all points in the system through the common communication protocol.

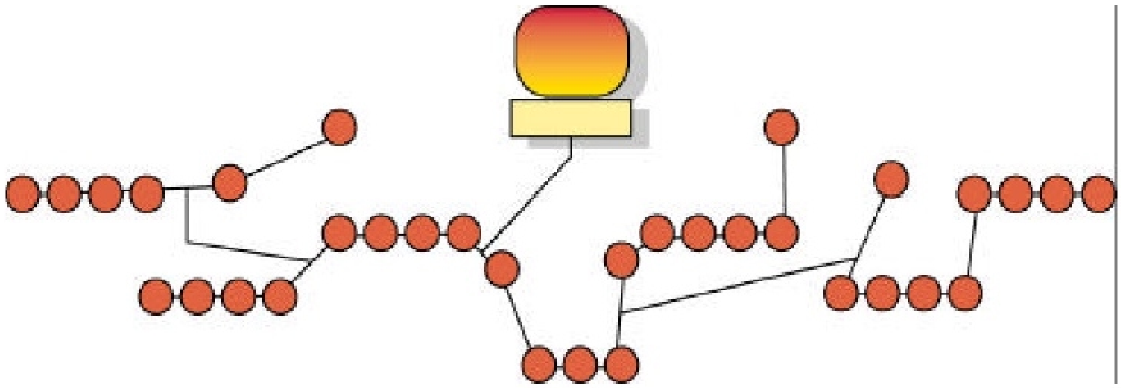


Fig. 3 LonWorks Distributed Control Architecture [Courtesy: Echelon]

LonWorks technology provides the concept of *network variables* (NVs), which makes it easy for manufacturers to design devices which system integrators can incorporate readily into the interoperable, information-based control systems. The benefits to the consumer (end-user or system integrator) of the LonWorks enabled flat control architecture are: compatibility, easy-to-use HMI and network-management tools, reduced wiring costs, short system design cycle, reliability, multi-vendor maintenance options, and the ease of implementing new functionality.

### 5.1.1 LonWorks Technology

This section highlights the key elements of LonWorks technology and the components comprising the LonWorks system, following a description of the salient features of LonTalk communication protocol and a discussion of the LonWorks Network Services (LNS).

The LonWorks technology is comprised of following major elements:

- Neuron Chip control processors and transceivers
- LonTalk communication protocol
- LonWorks Network Services (LNS)

*Neuron Chip* control processor is the physical core of every LonWorks device. It is a system-on-chip with multiple microprocessors, read-write and read-only memory (RAM and ROM), communication and I/O interface ports. The ROM contains an OS, the LonTalk communication protocol and an I/O function library. The chip has non-volatile RAM for configuration data and for the application program, both of which are downloaded over the communication network. Each Neuron Chip contains a unique-in-all-the-world 48-bit code, called the Neuron ID. Available in a large family with different speeds, memory type and capacity, and interfaces, the Neuron Chips are jointly designed by Echelon and its semiconductor partners Motorola and Toshiba. A *transceiver* is an electronic module that provides the physical interface between the communications port of the Neuron Chip and a physical medium, called a *channel*, which transports the digital communication packets to other devices. All devices connected to a specific channel must have compatible transceivers running at the same bit rate. Transceivers are available from Echelon and other manufacturers for a variety of media, including single twisted pair, power line, RF, infrared, fiber optics and coax. Bit rates depend on the media and transceiver design; up-to 1.25 Mbps can be achieved on a single twisted pair [20]. The Neuron Chip control processors and transceivers comprise the hardware components used in LonWorks devices, and are specifically designed to offer the most cost-effective solution available for network enabling and embedding intelligence into home control devices [15].

The *LonTalk communications protocol* is a layered, packet-based, serial peer-to-peer communications protocol. Adhering to the layered architectural requirements of the International Standards Organization (ISO), the LonTalk protocol is designed for the specific requirements of control systems, rather than data processing systems. Devices on a channel take turns transmitting packets. Each packet is a variable number of bytes in length and contains the application-level information together with addressing and other network information. Every device on a channel looks at every packet transmitted on the channel to determine if it is an addressee. If so, it processes the packet to see if it contains data for the node's application program or whether it is a network management packet. The data in an application packet is provided to the application program and, if appropriate, an acknowledgement message is sent to the sending device. A network management packet is processed appropriately with no involvement required from the application protocol. The LonTalk protocol is media-independent, allowing LonWorks systems to communicate over any physical transport media. The program implementation of the protocol called *LonTalk firmware* is contained in ROM in every Neuron Chip; providing a number of modifiable configuration parameters to make tradeoffs in performance, security, and reliability for a particular application; a portion of non-volatile RAM in the Neuron Chip is reserved for these parameters [20]. A comprehensive summary of the LonTalk protocol is given in [21] and a very detailed bits-and-bytes level discussion is available in [22]. The LonTalk communication protocol is permanently embedded in each LonWorks device. LonTalk has been approved as an open industry standard by the American National Standards Institute (ANSI)-EIA 709.1 [15].

*LonWorks Network Services* (LNS) is a client-server architecture that provides the foundation for interoperable LonWorks network tools. LNS enables the component-based software design of a new generation of tools that can work together to install, maintain, monitor, and control LonWorks networks. It also makes it easy to integrate control systems with other information systems. The architecture supports clients based on any platform; servers are currently based on Windows 95, Windows NT, and the Neuron Chip. An overview of the LonWorks Network Services is presented in [23]. The LNS is the basis for easy-to-use, interoperable network management and HMI tools; and provides a range of network services to appliances that are connected to the control system.

### 5.1.2 LonWorks System Components

A typical LonWorks system consists of three types of components:

- LonWorks devices
- Channels
- Network tools

Each LonWorks device, or *node*, attached to the network contains at least a Neuron Chip and a transceiver in a appropriate mechanical package, usually with a suitable power supply. Depending on device functionality, there may also be embedded sensors and actuators, I/O interfaces to external legacy sensors and actuators, or interfaces to host processors such as PC's. To accommodate complex applications, some version of Neuron Chips have a high-speed parallel interface allowing any microprocessor (for example, Motorola 68000 series) to execute the application program, while using the Neuron Chip, with a special microprocessor interface application, as its network communications processor. Alternatively, the open LonTalk protocol can be ported to run directly on any processor; and in that case the Neuron Chip is not required by all devices, rather all such devices are assigned a unique Neuron ID.

A *channel* is a specific physical communication medium to which a group of LonWorks devices are attached by transceivers specific to that channel. Each type of channel has different characteristics in terms of maximum number of attached devices, communication bit rates and physical distance limits. Table 6, taken from [20], summarizes the characteristics of several widely used channel types:

| Channel Type | Medium | Data Rate | Max. Devices | Max. Distance |
|---|---|---|---|---|
| TP/XF-1250 | Twisted pair, bus | 1.25 Mbps | 64 | 125m (bus length) |
| TP/XF-78 | Twisted pair, bus | 78 kbps | 64 | 1330m (bus length) |
| TP/FT-10 | Twisted pair, flexible topology | 78 kbps | 64 (upto 128 if link-powered) | 500m (node to node) |
| PL-20 | Power line | 5 kbps | No Limit | Determined by attenuation |

Table 6. Channel Characteristics

A complete reference of LonMark approved channels and transceivers, is available in [24]. Details on the activities and scope of LonMark Interoperability Association can be obtained from [25]. Network tools are software programs for network installation, configuration, monitoring, supervisory control, and maintenance. The may reside in a Neuron Chip or any other platform, such as hand-held computer or PC.

From [20], the components of a LonWorks System are shown in Figure 19. The figure illustrates the anatomy of several categories of LonWorks devices with specific product examples. In the figure, Neuron Chips and transceivers are labeled N and T respectively.

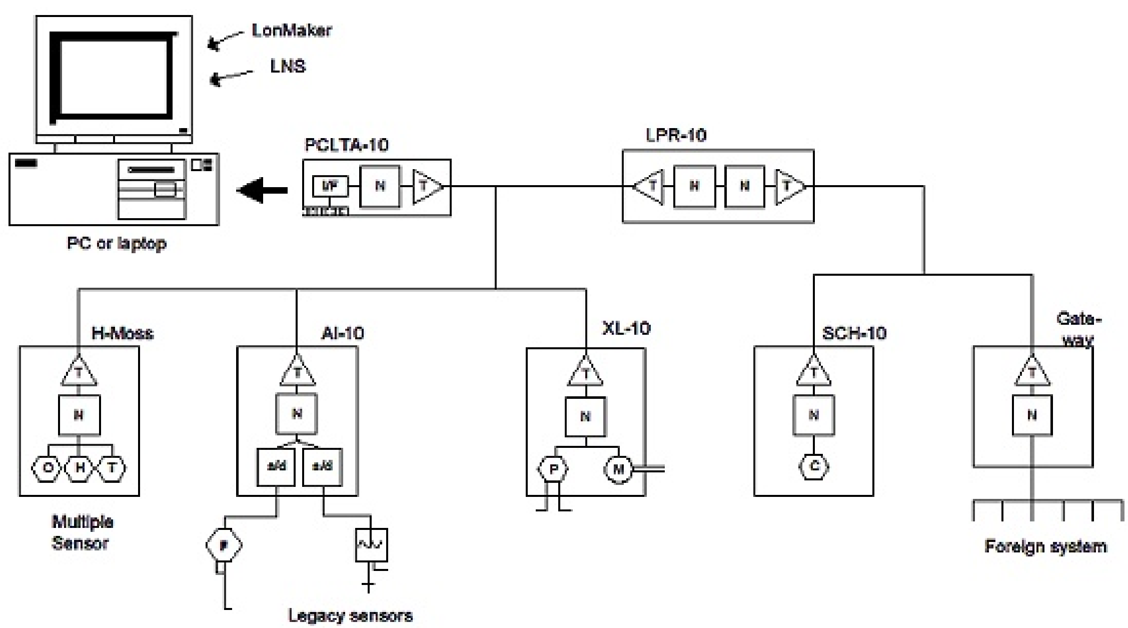



Fig. 19 Anatomy of some LonWorks devices [Courtesy: Echelon]

The role of *LonWorks control devices* is to sense and control the state of the components that comprise the physical system being controlled. The control devices may have any combination of embedded sensors and actuators or input/output interfaces to external legacy sensors and actuators. The application program in the device may not only send and receive values over the network but may also perform data processing (e.g. scaling, linearization) of the sensed variables and control logics such as PID loop control, data logging, and scheduling. From [20], the several control devices shown in Figure 19 are as follows:

- Echelon LonPoint AI-10 Module has two A/D convertors allowing up to two analog input legacy devices (4-20 ma or 0-10 volt interface) to be connected to the network.
- Hubbell H-Moss Multiple Sensor Module is a wall-mounted unit that contains three embedded sensors monitoring temperature (T), occupancy (O), and humidity (H).
- Honeywell XL-10 VAV Controller contains and embedded damper actuator motor (M) and differential air-pressure sensor (P). It obtains room temperature and setpoint values over the network and implements PID single loop control to maintain room comfort.
- Echelon LonPoint SCH-10 Scheduler module has an embedded real-time clock (C) and a highly configurable state machine logic for implementing scheduling and event-driven mode control for all or a portion of a LonWorks system.

### 5.1.3 Summary

LonWorks is an “open” technology and is accessible to all. A typical node in a LonWorks control network performs a simple task. Devices such as proximity sensors, switches, motion detectors, and sprinkler systems may all be nodes on a home network. LonWorks control networks can easily be integrated with the Internet. This built-in capability allows for seamless networking between IP-based devices and control devices. LonWorks powerline-based systems also support remote monitoring of home appliances through standard Web browsers.

## 5.2 Consumer Electronic Bus (CEBus)

The Consumer Electronic Bus (CEBus), is the Electronic Industry Association’s (EIA) open standard (EIA-600) describing a method of communication between electronic products in the home using five different media: Power Line, Twisted Pair, Coax, Broadcast RF, and InfraRed [26]. The CEBus is basically a local-area network for home automation. CEBus is a complete packet oriented, connectionless, peer-to-peer network utilizing Carrier Sense Multiple Access/Carrier Detect Contention Resolution (CSMA/CDCR) protocol. CEBus is a communications and product interoperability standard designed primarily for consumer products [27]. The first version of CEBus was releases as IS-60 (Interim Standard 60) in 1992 for industry review, and was revised in 1993 and 1994. After that it was released as EIA open standard (EIA-600).

The CEBus based products consist of two fundamental components: a transceiver and a microcontroller. Data packets are transmitted by the transceiver at about 10 Kbps [15]. The CEBus protocol uses a peer-to-peer communications model so that any node on the network has access to media at any time. The CEBus standard includes commands such as volume up, fast forward, rewind, pause, skip, and temperature up or down one degree. These commands are based on the application-to-application communication language called the CEBus Common Application Language (CAL).

From [28], “The CEBus Industry Council's (CIC) mission is to provide information to the design and development community information about CEBus and CEBus Home Plug & Play. The Council involves all applicable industries and organizations in the development of interoperable products which offer the homeowner a multiple of products to choose from that can communicate with each other and work as a system. These products can ask each other questions, answer question, and provide unsolicited status reports based on what they see and know about the home's environment. These messages are passed back and forth through the home's power lines, telephone wires, television cable, infrared signals and radio signals."

CEBus allows products to share information such as time, temperature, occupancy state, status of equipment, and so on. The data allows redundant product functions to be centralized, the removal of cumbersome user interface from many products, and easy delivery of outside service information directly to products. With CEBus, equipment can simply "place" information on the network where it is picked up by other devices that can use the same information to their advantage. Information can originate in the home or from service providers outside the home.

In a network, two ingredients are basic to successful communication: transparent movement of data between nodes and/or systems; and ensuring that the data arriving for the destination node and/or system is in a meaningful form that can be immediately recognized and processed. The CEBus standard defines only those functions required to facilitate communications; it does not describe the specific implementation, design, or technologies to be used. Those are left to the innovation of the system developer. However, a full range of multi-vendor interoperability issues are definitely addressed by the standard, including such items as connectors and signaling formats.

### 5.2.1 CEBus Technology

CEBus uses spread spectrum technology to overcome communication impediments found within the home's electrical powerline. Spread spectrum signaling works by spreading a transmitted signal over a range of frequencies, rather than using a single frequency. The CEBus powerline career spreads its signal over a range from 100 Hz to 400 Hz during each bit in the packet [15]. To avoid data collision, CEBus uses the CSMA/CDCR protocol. Similar to HomePNA, this media access control protocol requires an information appliance to wait until the line is clear, which means that no other packet can be transmitted before it can send a packet.

Each CEBus has two channels: a *control channel* for real-time, short-packet, control-oriented functions, and a *data channel* for intensive data transfer. To ensure reliable, tamper-proof, private communications, the CEBus standard includes such crucial network protocol features as error detection, automatic retry, end-to-end acknowledgement, and duplicate packet rejection, as well as authenticated service to prevent tampering, and encryption to ensure privacy. The CEBus control channel communication is standardized across all media, with a consistent packet format and signaling rate, and is used exclusively to control devices and resources of the network, including data channel allocations. Data channels typically provide selectable bandwidths that can support high data rates and are used to send data such as audio, video, or computer files over the network. The characteristic of a data channel can vary greatly depending upon the medium and connected device requirements. All data channel assignments and functions are managed by CEBus control messages sent via the control channel.

### 5.2.2 CEBus Protocol

CEBus uses a peer-to-peer connectionless service, CSMA/CDCR communication protocol (Carrier Sense Multiple Access with Collision Detection and Collision Resolution) [27]. The OSI Protocol stack consists of a physical layer, a data link layer, a network layer, and a application layer, as shown in Figure 20 below.

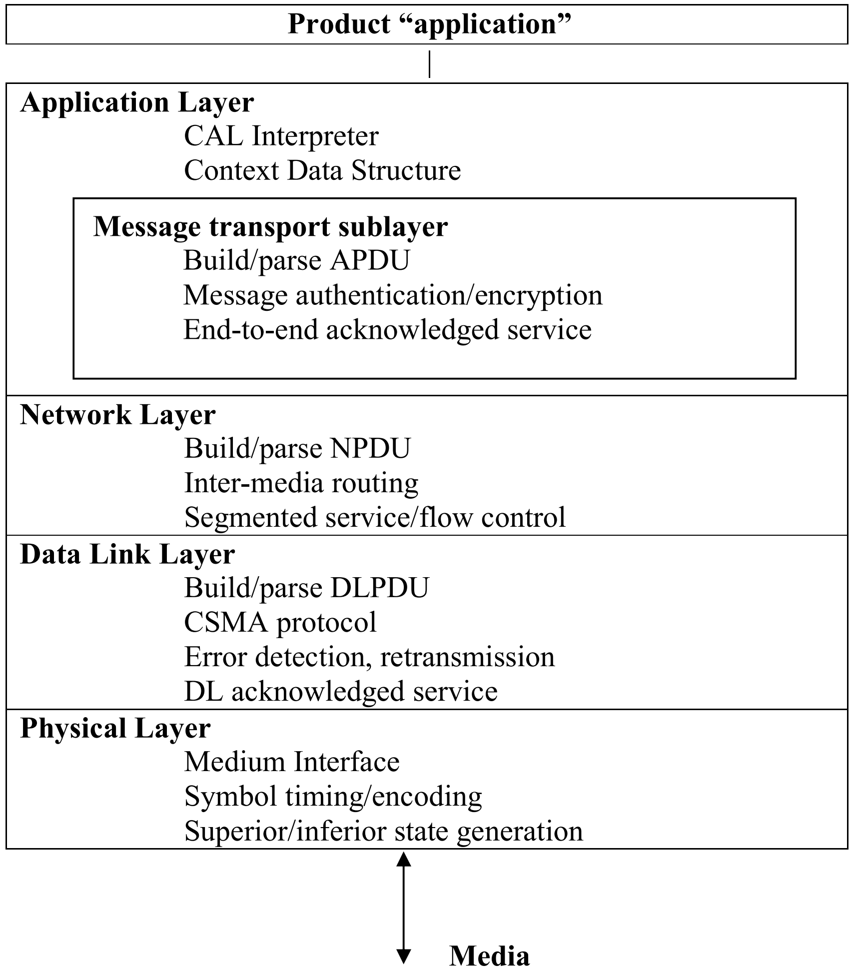



Fig 20 CEBus protocol ”stack”

Many transport layer functions (segmented service, end-to-end acknowledgement) are incorporated into the application and network layers. Besides the protocol functions defined by the traditional OSI model, the CEBus standard defines the physical characteristics of each of the allowed media and an application language interpreter. The Common Application Language (CAL) provides a data structure model of how each function of a product operates. CAL also provides management of network resources, node status functions and address configuration.

### 5.2.3 CEBus Packet Structure

Figure 21 illustrates the breakdown of elements of a CEBus packet into logical groups with size information. A CEBus packet frame can be broken down into several parts: The Link Protocol Data Unit (LPDU), the Network Protocol Data Unit (NPDU), the Application Protocol Data Unit (APDU) and the CAL message.

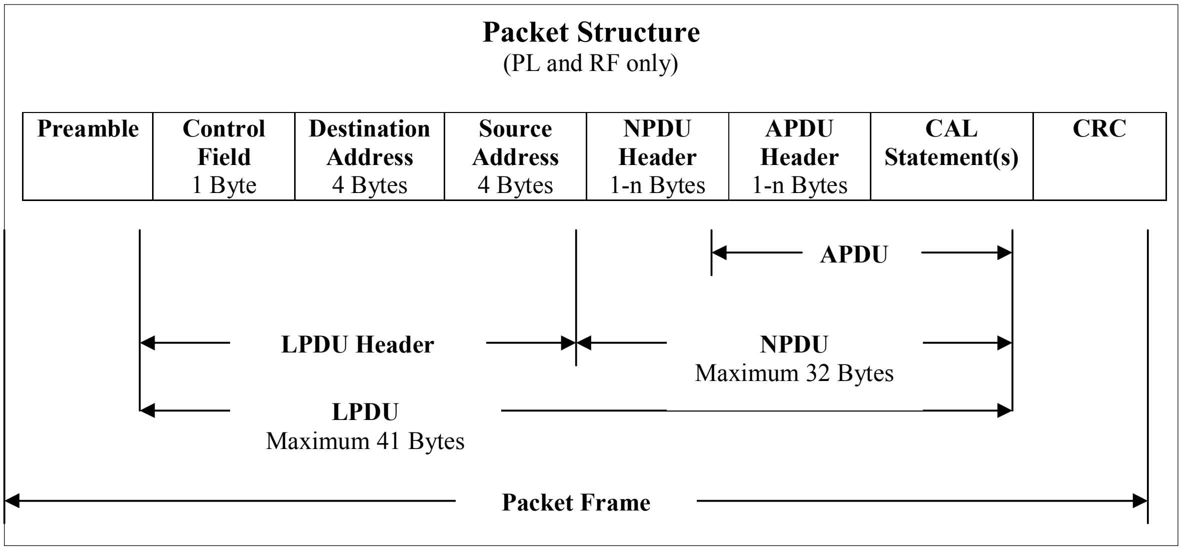



Fig. 21 CEBus Packet Structure [Courtesy: Intellon Corporation]

The CEBus packet structure reflects the contribution of each protocol layer. The APDU, generated by the message transport sublayer, contains the CAL message and the necessary application layer acknowledgement service and security service (authentication and encryption) header information. The NPDU, generated by the network layer, contains the APDU and the necessary network routing and message segmentation header information. The LPDU header contains the Control Field and the source and destination addresses. The Control Field specifies the packet type, packet priority, and service class to the Data Link Layer (DLL). The remaining parts of packet are the preamble and the frame check sequence (FCS) or the Cyclic Redundancy Check (CRC). The CRC is a packet-level error detection field appended by the data link layer. Packets vary in size from approximately 50 bits (the smallest packet) to about 350 bits (the largest packet), depending on the size of the CAL message and the content of the layer headers.

All CEBus nodes have a unique address pair: a system address and a node address. The system address is the same for all nodes in the home, while each node address in a given system is unique. The purpose of a system address is to logically isolate the nodes in one house from the nodes in another house, particularly on medium networks that span multiple homes (PL, RF). Messages from a node in one system network cannot be received by nodes in another system network.

The generation of a CEBus packet is a two-step process. First the data from the host is converted to symbols. These symbols are then converted to waveforms to be transmitted.

### 5.2.4 Spread Spectrum Carrier Technology

Most of the material for this topic is based on [29]. The encoding and signaling method used by CEBus power line (PL) physical layer is discussed here. Each CEBus packet consists of a preamble, packet body, and CRC. Each of these components is discussed in relationship to symbol encoding. This information becomes useful when identifying CEBus signals on the power line.

Intellon's spread-spectrum power line technology was chosen by EIA as a result of an industry wide competitive selection. Spread-spectrum, by its very nature, has wide bandwidth which makes it immune to a long range of impairments. This is due to the fact that only a portion of Intellon's spread-spectrum signal is required for detection. The signal may suffer from many different types of impairments and still provide error free communication.

Spread Spectrum Carrier (SSC) Technology is a method of spread spectrum communications suitable for carrier sense multiple access (CSMA) networks. Spread-spectrum systems have been used historically for secure communications and/or to overcome narrow-band impairments in the communications medium. The initial time period required for synchronization with the carrier, makes spread spectrum receivers inappropriate for CSMA networks. Spread Spectrum Carrier Technology is a method by which a series of short, self-synchronizing, frequency swept “chirps” act as a carrier. The chirps are always of the same known pattern and detectable by all the nodes on the network. The chirps ranges in frequency from 100 to 400 kHz over a duration of 100 μs, per the EIA-600(CEBus) Power Line Physical Layer and Medium Specification. The chirps is swept from approximately 200 kHz to 400 KHz and then from 100 kHz to 200 kHz. Figure 22 illustrates the CEBus powerline chirp. Each chirp represents the shortest communication symbol time, defined as a Unit Symbol Time (UST).

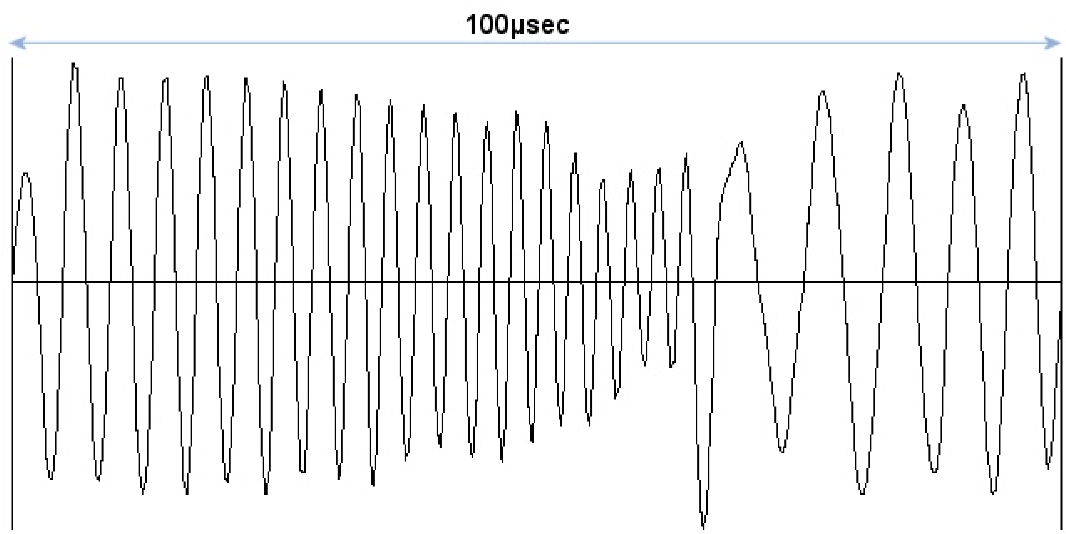



Fig. 22 Spread Spectrum Carrier Chirp

From [30], as in traditional direct sequence systems, the chirp effectively spreads the signaling energy over a broad frequency range. In the case of the EIA’s CEBus Standard the signal is spread over a frequency range of 100 kHz to 400 kHz, with an effective bit rate of 10 Kb/s, while systems developed in Europe spread the signal over a frequency range of 20 kHz to 80 kHz, while lowering the effective communication bit rate to 2 Kb/s, thus, preserving the processing gain. While theoretically the signal could be generated by simply sweeping the pulse frequency from 100 kHz to 400 kHz, or 20 kHz to 80 kHz, the practical implementation as developed by Intellon Corporation, begins and ends the frequency sweep at 200 kHz with a transition from 400 to 100 kHz in the middle. The two major reasons for doing this, was to simplify the filtering required to limit the harmonic energy generated by the signal, and to allow a smooth transition between data bits. An overview of Spread Spectrum technology is also highlighted in [31].

### 5.2.5 Summary

Many CEBus complaint products for home automation are being developed including lighting and appliance controllers, wireless security systems (utilizing SSC RF Signaling), thermostats, HVAC controllers, audio/video equipment control, etc. In addition to the consumer level products that are being used, many utility providers are installing energy management systems at their customer's premises to perform meter reading, load control, and provide services such as security monitoring. There are also many commercial applications being implemented, using the CEBus PL and RF SSC signaling technology, that are not concerned about CEBus compliance. In at least one European city, public lighting is being controlled with SSC PL communications utilizing the 20 to 80 kHz chirp signal [30]. For CEBus communications over the electric distribution network, reference [32] highlights the phase coupling mechanism for power line communications. There have been two serious impediments to the growth of the power-line carrier (PLC) communications industry in particular, and the home and building automation markets in general; line noise, which plays havoc with communications reliability, and the lack of a standard communication network protocol [33]. These stumbling blocks have been removed to a greater extent; the first, by the development of spread-spectrum PLC technology, which all but eliminates the noise impediment, and the second, by the industry wide adoption of the EIA's CEBus standard. Reference [34] outlines methods of communication over a powerline namely X-10 and CEBus and also introduces spread spectrum technology as to increase speed to 100-150 times faster than the X-10 system. Detailed information on the CEBus standard, development tools, training, existing products and literature are available from [28].

## 5.3 Passport and Plug-in PLX

Intelogis Inc., Draper, Utah (founded in 1997 and renamed to Inari Inc. in 2000) developed one of the first powerline technologies, called Passport, which is sometimes also referred to as the original powerline technology. The Intelogis or Inari's websites does not appear to work anymore and there was no further information available at the time of writing this thesis, that whether Inari still exists. This section is given as a reference to discuss the Intelogis Passport powerline technology. Most of the material in this section is based on the findings of [35].

Passport relies on frequency-shift keying (FSK) to send data back and forth over the home electrical wiring. FSK uses two frequencies, one for 1's and the other for 0's, to send digital information between the computers on the network. The frequencies used are in a narrow band above the level of line noise occurrence. A flaw of this somewhat fragile method is that anything that impinges on either frequency can disrupt the data flow, causing the transmitting computer to have to resend the data. This can affect the performance of the network, including network slowdown. Included with the Intelogis Passport kit were line-conditioning power strips which would be inserted between the wall outlet and the user computer equipment to help reduce the amount of electrical-line noise. Based on 110-volt electrical system (which made the technology unsuitable to countries outside of North America), the Intelogis powerline network uses computer's parallel port for physical connections. It also requires the installation of software for its modules to work. Intelogis Passport technology uses a client/server network architecture ( which is a centralized administrative system providing information to all of the other devices), and the first computer on which software is installed becomes the Application Server (which in essence is controlling the data flow over the network and directing each device towards finding other devices). Some of the disadvantages associated with the Intelogis Passport technology are highlighted below:

- Slow connection speeds ( 50 kbps up to 350 kbps)
- Home power usage affects performance
- Printer features can get limited
- Only works with Microsoft Windows operating system
- Powerline Device (Module) size appears to be rather large
- Only works on 110-V standard lines

- All data needs to be encrypted for a secure network
- Older wiring degrades performance

Taking a different track to power-line communications, Intelogis technology transmits data in a frequency band above the noise region. Dubbed as Plug-in PLX technology [38], it uses a combination of datagram-sensing multiple access (DSMA) and centralized token passing (CTP). DSMA acts in a similar fashion to the multi-node contention resolution of an Ethernet network. A node, when entering the network for the first time, detects the carrier of the other packets on the line, sending its own packet only if it is clear to do so. Once all the nodes are known to each other, the dynamic centrally distributed token passing scheme is instituted which avoids multi-node contention and collision and thus raises the effective throughput. Intelogis claimed that its technology permits simultaneous transfer of small control packets and entertainment data (for example, MP3), without interfering with each other. From the findings of [38], Plug-in PLX conforms to the CEBus CAL.

## 5.4 X-10

X-10 (also referred to as X10) is a communications protocol that allows compatible home networking products to talk to each other via the existing home electrical wiring. The X-10 code format was first introduced in 1978 by X-10 Inc., for the Sears Home Control System and the Radio Shack Plug 'n' Power System [36]. The 25 years old X-10 technology was initially developed to integrate with low cost lighting and appliance control devices.

X-10 enables the X-10 compatible devices, which are electrical components directly plugged into wall outlets, to communicate with each other. But these devices are susceptible to damage by voltage spikes. Additionally, signal attenuation and line noises generated by household appliances or external sources can transiently interfere with X-10 communications. With the powerline subnet being shared among neighboring houses, X-10 commands from one house and interfere with devices in another house. As a result, reliability remains a major issue in X-10 powerline networking [37]. Complex and unanticipated faults are unavoidable in X-10 networking, and the faults manifest themselves as anomalous behavior on the powerline in terms of illegal sequences of X-10 commands. The X-10 protocol is under-specified with respect to when exactly modules get to be addressed and unaddressed (i.e., when the modules move from unaddressed state to an addressed state and vice versa). Only experimentation with various command sequences could lead to the formulation of rules governing the addressing of X-10 modules and development of a model for the legal X-10 command sequences. Reference [37] considers the X-10 powerline communication protocol and defines a model-based fault detection system that achieves completeness of coverage for X-10 faults.

X-10 originally started out as unidirectional only; however capability for bidirectional communication has also been added to it. The vast majority of X-10 communication remains unidirectional only [15]. X-10 controllers send signals over existing AC wiring to receiver modules. The X-10 modules are adapters connected to outlets and controlling simple devices. X-10 transmission rate is limited to only 60 bps [15] which makes it unsuitable for carrying internet type traffic around the house. By using X-10 it is possible to control lights and virtually any other electrical device from anywhere in the house with no additional wiring.

The X-10 technology and resource forum designs, develops, manufactures, and markets products that are based on this standard. X10 Ltd. which designs its own chips for its devices, manufacture products for companies including IBM, Thomson (GE and RCA brands), Philips (Magnavox brand), Radio Shack, Leviton, Honeywell, Stanley, Ademco, and ADT among others. IBM, for one, relies on X-10 technology in its Home Director product [38]. According to X-10 group, more than 100 million units have been shipped by the company [15]. These home automation devices are called “powerline carrier” (PLC) devices and are often installed by builders who want to offer home automation as an additional selling feature. The home automation line consists of “controllers” that automatically send signals over existing electrical wiring to receiver “modules”, which in turn control lights, appliances, heating and air conditioning units, etc.

### 5.4.1 X-10 Transmission Theory

Most of the material for this section is based on [36]. X-10 transmissions are synchronized to the zero crossing point of the AC power line. The design goal should be to transmit as close to the zero crossing point as possible but certainly within 200 microseconds of the zero crossing point. The X10 powerhouse power line interface models PL513 and TW523 provide a 60 Hz square wave with a maximum delay of 100 µsec from the zero crossing point of the AC power line. The maximum delay between signal envelope input and 120 kHz output bursts is 50 µsec. Therefore it should be arranged that outputs to the PL513 and TW523 be within 50 µsec of this 60 Hz zero crossing reference square wave.

A binary 1 is represented by a 1 millisecond burst of 120 kHz at the zero crossing point and a binary 0 by the absence of 120 kHz. The PL513 and TW523 modulate their inputs (from the O.E.M) with 120 kHz, therefore only the 1 ms “envelope” need to be applied to these inputs. These 1 millisecond bursts should actually be transmitted three times to coincide with the zero crossing points of all three phases in a three phase distribution system. Figure 23 below shows the timing relationship of these bursts relative to zero crossing.

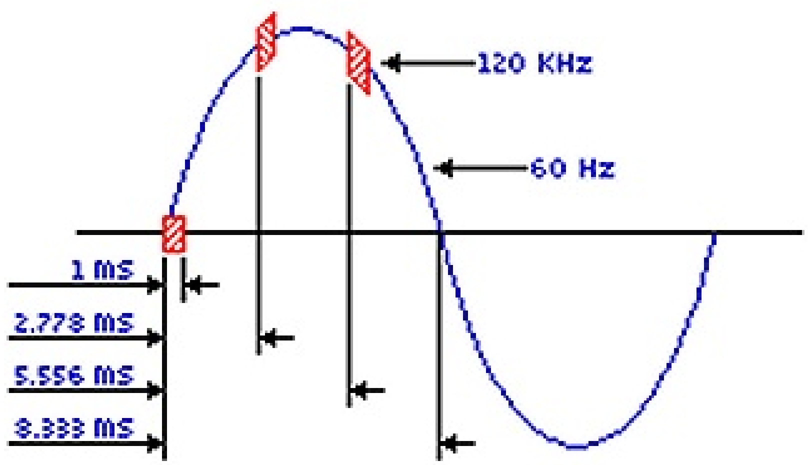



Fig. 23 Timing relationship of X-10 signals

A complete code transmission encompasses eleven cycles of the power line. The first two cycles represent a Start Code. The next four cycles represent the House Code and the last five cycles represent either the Number Code (1 thru 16) or a Function Code (On, Off, etc.). This complete block, (Start Code, House Code, Key Code) should always be transmitted in groups of 2 with 3 power line cycles between each group of 2 codes. Bright and dim are exceptions to this rule and should be transmitted continuously (at least twice) with no gaps between codes. Figure 24 explains this concept.

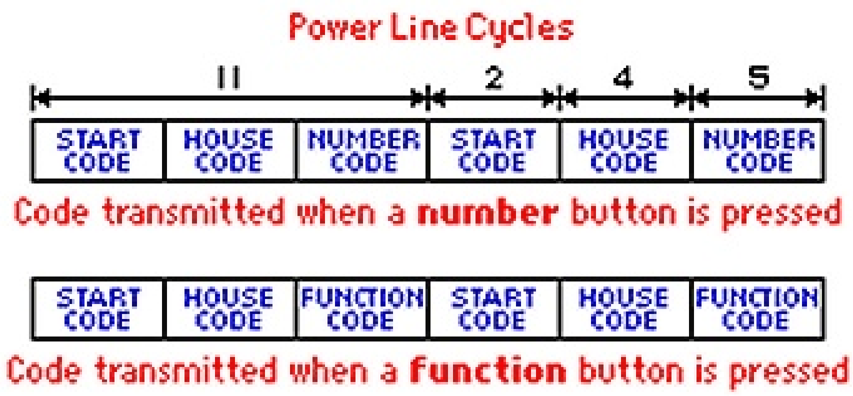



Fig. 24 Power line cycles for X-10 code transmission

The control capabilities of X-10 are depicted in the Figure 25 below.

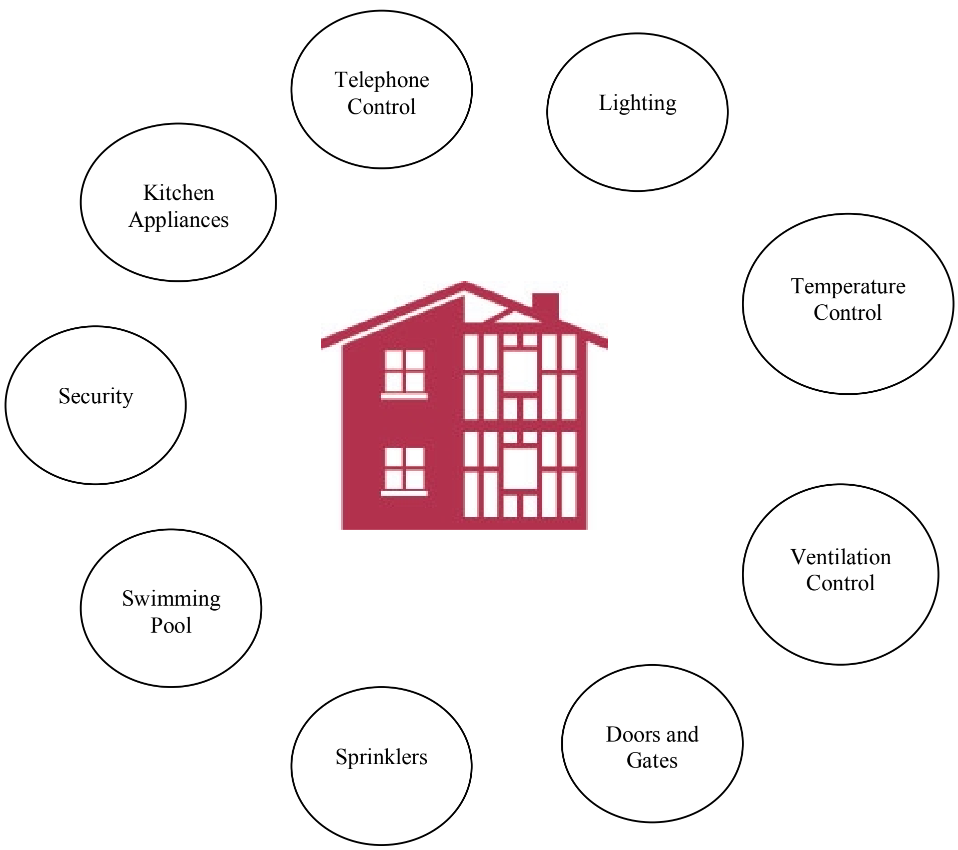



Fig. 25 X-10 Control Capabilities

### 5.4.2 Summary

The main disadvantage of the legacy X-10 technology is the fact that it has very limited capability in terms of both speed and intelligence. X-10 is a technology relegated to control application only due to its low data rate and rudimentary functionality [15]. Another disadvantage with the X-10 power line carrier (PLC) signaling "language" is that it operates on 110V AC power cycle [39]. However, the ultimate goal of X-10 technology is to innovate itself into a higher-speed protocol that facilitates communication between home PCs and controlled home appliances.

## 5.5 PowerPacket

Intellon Corporation's PowerPacket™ technology which is the basis of the HomePlug Powerline Alliance industry specification, is a carefully crafted version of the Orthogonal Frequency Division Multiplexing (OFDM). PowerPacket is the brand name for Intellon's high-speed powerline communications technology that now provides a 14 Mbps data rate over existing powerlines in the home. PowerPacket is a complete solution that encompasses the physical (PHY) and media access (MAC) layers of the networking model. It supports advanced services such as voice over IP (VoIP), Quality of Service (QoS) and streaming media [41], which will provide new multimedia and telephony applications to the consumer. 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 [40]. 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 yields a very high data rate.

### 5.5.1 PowerPacket Technology

PowerPacket physical layer (PHY) uses the orthogonal frequency division multiplexing (OFDM) as the basic transmission technique. It is currently widely used in xDSL 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 [40].

From [40], the high-speed data stream to be transmitted is processed as multiple parallel bit streams by OFDM, with each having 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 different phase modulation. Figure 26 illustrates the 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.

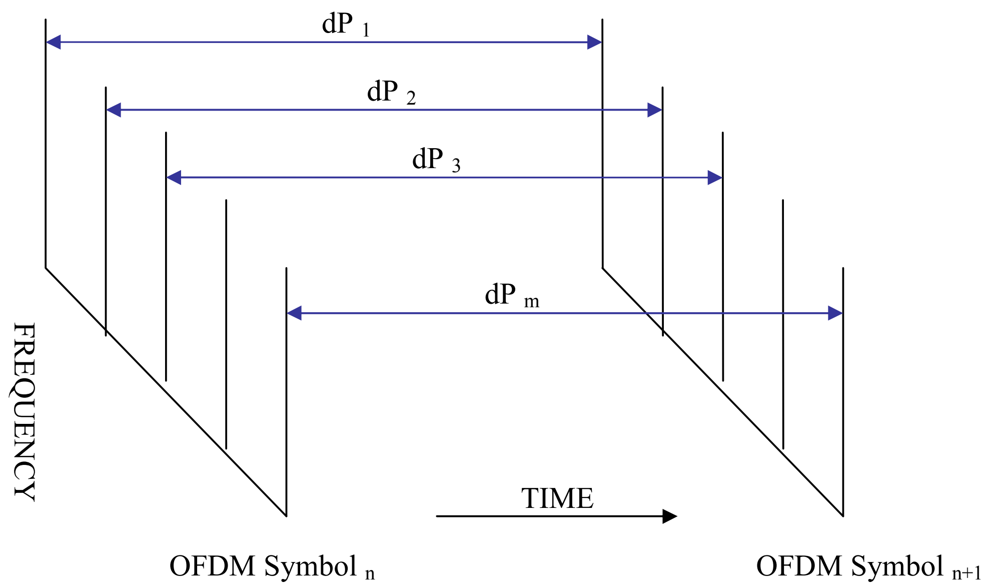



Fig. 26 PowerPacket Differential Modulation [Courtesy: Intellon]

OFDM waveforms are being typically generated using an inverse Fast Fourier Transform (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 FFT is a time domain signal, called the OFDM signal. Since an FFT is reversible, the data can be recovered via a forward FFT, converting back to the frequency domain. Figure 27 below illustrates the conversion process between the frequency domain and the time domain.

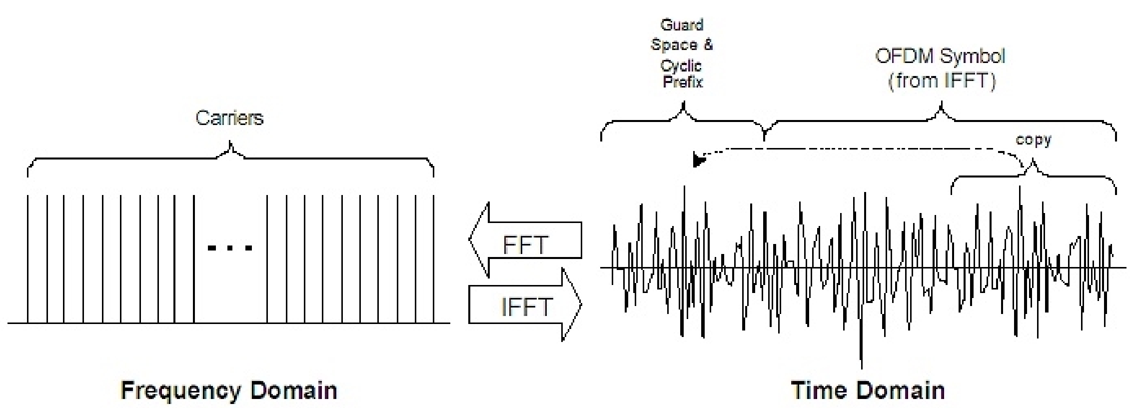



Fig. 27 Symbol Creation by IFFT [Courtesy: Intellon]

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

Considering the frame format, the PowerPacket transmission frame consists of a start-of-frame delimiter, a payload, and an end-of-frame delimiter, as illustrated in Figure 28 below. The frame 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. The payload portion of a frame is rate adaptive according to the channel quality between the transmitter and receiver. Rate adaption occurs in three ways: by not using same 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. The PowerPacket PHY occupies the band from 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 [41]. The HomePlug 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 [42].

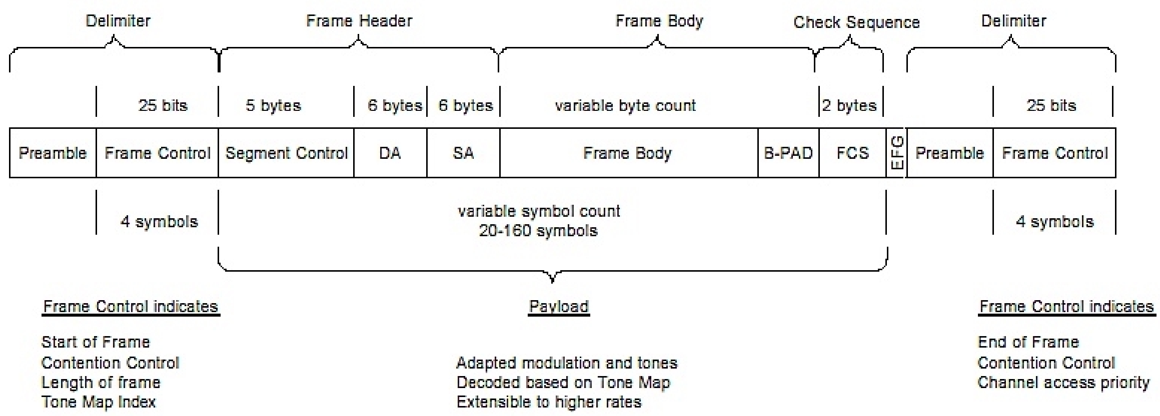



Fig. 28 PowerPacket Frame Format [Courtesy: Intellon]

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 the IEEE 802.11 specification. The PowerPacket MAC protocol uses a classic, listen-before-talk strategy and transmission after a randomly selected delay to avoid collisions [41]. This virtual carrier sense (VCS) mechanism and contention resolution helps minimize the number of collisions [42]. Addition of several features enables the protocol to support priority classes, provide fairness, and allows the control of latency.

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) since a high priority frame may be forced to wait for a long, slow transmission to complete. To overcome this problem, PowerPacket requires the 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 [41] such as voice-over-IP (VoIP) or streaming media [42].

PowerPacket's privacy mechanism creates a logical network with all nodes in the network sharing a common encryption key. Encryption of all frames is performed at the MAC layer by a 56-bit data encryption standard (DES) algorithm using cipher block chaining. The key management systems include features that enable the distribution of keys to nodes that lack an I/O capability.

### 5.5.2 Summary

Intellon's PowerPacket technology serves as the basis for the HomePlug Powerline Alliance standard. Using the enhanced OFDM, the rate-adaptive design allows PowerPacket to maintain an Ethernet-class connection throughout the power-line network without losing any data. From [35], some of the advantages of PowerPacket include the following:

- Fast, with 14 Mbps data rate
- Avoids disruptions in the powerline, maintaining the network's connections and speeds
- Printer features are not limited
- Compatibility with different Operating Systems (OS)
- Embedded circuitry in the device enables only the standard power cord to access an AC outlet
- Works independently from the line voltage and frequency of current
- 56-bit DES encryption is included
- Tests show none or negligible signal degradation due to older wiring

PowerPacket devices connect via a USB or Ethernet cord to the computer or other devices and on the other end to the AC outlet. PowerPacket uses a peer-to-peer network architecture (which eliminates the need for consulting a central system first).

The latest generation of PowerPacket is rated at 14 Mbps, which is faster than existing phone-line and wireless solutions. However, as broadband access and Internet-based content including streaming audio and video and voice-over-IP (VoIP) become more common, speed requirements will continue to rise. Along these lines, the Intellon's OFDM approach to power-line networking is highly scalable, eventually allowing the technology to surpass 100 Mbps [35]. The exact methods of scaling the PowerPacket technology to higher speeds are proprietary by Intellon [40], however, the suggested areas of focus are modulation techniques, protocol enhancements, and circuit design optimization.

## 5.6 Cogency's HomePlug Technology

Established in 1997 and based in Toronto, Canada, Cogency Semiconductor Inc. [43] addresses the technical challenges to using powerline for data communications by providing integrated circuits, offering a robust, cost-effective, high-speed technology solution for networking, entertainment and computer products. Cogency's HomePlug technology combines OFDM, signal coding, and error correction techniques.

The information provided in this topic is based on [44]. Cogency's technology for powerline networking includes a physical layer (PHY) and Medium Access Control (MAC) layer. The PHY layer implements the modulation techniques, the coding, and basic packet formats. The PHY uses packet-based OFDM as the transmission technique. The MAC uses a CSMA/CA protocol to mediate access between multiple clients.

The Cogency MAC/PHY provides per packet equalization and efficient access to the shared powerline medium. Additionally a proprietary resolution signaling scheme enables latency-sensitive applications such as voice-over-IP (VoIP) and multi-player gaming.

The Cogency MAC/PHY uses OFDM technology for signal transmission at a high data rate with few bit errors. OFDM modulation generates a set of tones in the frequency domain. Resistance to deep, narrow fades is provided by using many carriers. The loss of few tones can be compensated for with the Forward Error Correction (FEC) coding which redundantly encodes data across all active tones. Automatic channel adaptation allows the system to respond to current conditions on the powerline. The tones are modulated using either differential BPSK (76 bits per OFDM symbol) or QPSK (152 bits per OFDM symbol). For harsh channels or when channel adaptation has not been performed, the payload data is sent using ROBust OFDM (ROBO) mode. ROBO mode uses all available tones with differential BPSK modulation on each tone, as well as heavy error correction and interleaving. ROBO mode is useful for very harsh channels or when establishing initial contact with another device to negotiate the optimum communication scheme. Convolutional or Reed-Solomon coding are used for payload data. Convolutional coding rates of ½ can be punctured to achieve a rate of ¾. A combination of coding rate and modulation is used to adjust to varying channel conditions. Product encoding is used for frame control fields, which ensures that all devices on the network are able to detect and decode this information. Channel adaptation is used to specify modulation or coding schemes for payload data. If significant fading occurs, specific tones can be dropped from the transmission. Data packets can be transmitted in two modes: to all stations or to one specific station. Data is encoded on all carriers when transmitting frame control symbols. Reliability of transmission is ensured by the MAC/PHY layer's acknowledgment of Unicast transmission by sending a response delimiter (ACK) to indicate a successful transmission. A NACK signal is sent to indicate that the packet was received but with errors. The MAC/PHY uses Automatic Repeat request (ARQ) to guarantee reliability. Receipt of a NACK (or no response) results in the packet being resent. The MAC/PHY layer can determine the state of powerline by monitoring the frame delimiters. This is known as "carrier sense". For reduction of collisions that occur with random access to the channel, Cogency uses a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol enhanced with priority signaling. Prioritized access to the channel is achieved by using the Priority Resolution Period.

Cogency's HomePlug technology provides a robust solution to the powerline networking, providing reliable data transmission for the home networking environment. The Cogency MAC/PHY layer adapts automatically to changing conditions on the powerline providing a reliable channel under the noisiest conditions. Multipath distortion effects are taken care of with the OFDM technology. Privacy management using 56-bit encryption techniques provides privacy, while priority contention control ensures timely access for latency-sensitive applications. Cogency's HomePlug technology provides Ethernet-class data networking and supports VoIP, QoS, and streaming media applications.

## 5.7 Conclusions

Powerline Carrier (PLC) Communication Systems is a relatively recent and rapidly evolving technology, aimed at the utilization of the electricity powerlines for the transmission of data. Lack of collective information and a collective study of all the existing technologies in the powerline home networking area, is the main driving factor for this Chapter and the thesis. This Chapter presented an in-depth technical analysis of all the existing technologies associated with the powerline carrier (PLC) communication systems. Powerline is inherently the most attractive medium for home networking due to its universal existence in homes, the abundance of AC outlets and the simplicity of the power plug. In comparison, the phone line suffers from too few connection points and wireless from congestion at 2.4 GHz [45] as well as interference. The potential for powerline to act as a backbone for home networking is great, provided that the powerline is able to provide reliability, security and robustness to meet the requirements of the most demanding applications.

As many companies have developed their own (and sometimes proprietary) systems for dealing with the powerline networking, there was a need for standardization, which is covered in Section 1.3 of this thesis. The four driving needs for a home network are home automation, home computer, audio and video distribution, and an access network. CEBus aimed at control, makes HomePlug the ideal choice for home networking scenario. CEBus, X-10, and LonWorks core technologies are more suited to home control and automation systems. HomePlug certified products deliver data at 14 Mbps and the flexibility of Intellon's enhanced OFDM (which is the basis of HomePlug specification) allows scalability to very high data rates (100 Mbps and beyond).

# 6 Powerline Networking Products

This Chapter gives a technical overview of the available powerline equipment (modules) in the market, which can be an interesting trade for the Telecommunication Systems Laboratory (TS Lab) Demonstrator at the KTH/IT University, Kista, Sweden, as discussed in Section 1.2 earlier. A short description of available powerline modules is given with the focus being on home-automation products mainly used for the small office home office (SOHO) and home area networking (HAN) networking scenarios. Table 7 provided at the end of this Chapter, summarizes the product comparison highlighting the salient features.

At the time of submission of the Project Plan for this thesis [94], the main idea for this market survey was to compare different available products in the market used in powerline networking, and then suggest one or two modules to the Supervisor, so that the modules can be purchased and then made available for the TS Lab Demonstrator purpose. However, the market survey phase was already started in a sense of comparing different product specifications and contacting the companies for further details. Thus, one very good advancement for the project was that Phonex Broadband Corporation, USA agreed to sponsor the TS Lab Demonstrator and have been kind enough to supply a set of the NeverWire14 series of powerline modules. Another progress was made with GigaFast Ethernet Inc., USA who also agreed in principle to sponsor the TS Lab Demonstrator and provided of a set of their HomePlug powerline modules.

The purpose of this Chapter is to document the powerline products available in the market that were being considered for TS Lab Demonstrator purpose, along with specifications comparison chart included at the end of this Chapter. The reference material used in this Chapter is mostly based on the Internet Homepages of the companies and on contacts made with different companies regarding clarification of some questions. Also worthwhile to mention is that this paper focuses on the finished products or modules that are ready to be used by the end-user, rather than silicon chips. Thus the silicon chip products are not listed or compared here (an example of not listed chip products is the 'Ready Wire Powerline Home Communications Chip' by Phonex Broadband). The standard used as a basis of comparison in this paper is HomePlug [see Section 1.3.3 for details on HomePlug], and all the companies listed under HomePlug-certified Products are being listed. Another consideration that is used as selection criteria is the operating input voltage for the products. Since the input power voltage cycle in Sweden is 220VAC 50Hz, therefore the products operating at only 110VAC 60Hz are not considered in depth for TS Lab Demonstrator scenario (note that the addition of an external voltage converter can however make the 110V products work at 220V).

The following sections list the HomePlug-certified powerline modules available in the market from the vendors or online retailers.

## 6.1 GigaFast Range of Products

Founded in 1997 and located in California, Los Angeles and Taipei (Taiwan), GigaFast Ethernet is a leading manufacturer of networking products for home-based and small to medium-sized businesses. GigaFast Inc. [76] currently provides following three products for the HomePlug powerline networking.

**PE901-UI** (see Figure 29) is the GigaFast HomePlug USB Adapter. The Plug and Play USB Chipset allows the HomePlug USB Adapter to be easily installed onto any Microsoft Windows based machine. The device can be installed with a simple power plug to the wall outlet and a USB plug into the computer. A quick detection plus driver installation brings the HomePlug connection online.

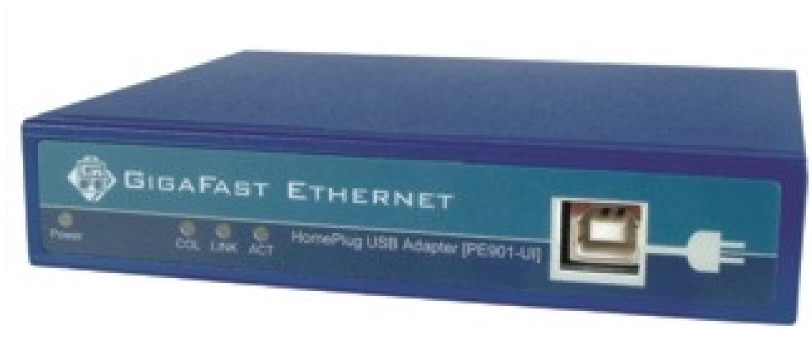



Fig. 29 GigaFast PE901-UI HomePlug USB Adapter

**PE902-EB** (see Figure 30) is the GigaFast HomePlug Ethernet Bridge. The installation of the Ethernet Bridge only requires that a 10/100Mbps Network Adapter is installed on the computer. This makes the HomePlug Ethernet Bridge compatible with any device including Mac, Windows, and Unix machines.


Fig. 30 PE902-EB GigaFast HomePlug Ethernet Bridge

**PE909-UI** (see Figure 31) is the GigaFast HomePlug USB Adapter. The Plug and Play USB Chipset allows the HomePlug USB Adapter to be easily installed onto Microsoft Windows based machine. The device can be installed with a simple power plug to the wall outlet and a USB plug into the computer. A quick detection plus driver installation brings the HomePlug connection online.

Fig. 31 PE909-UI GigaFast HomePlug USB Adapter

The difference between **PE901-UI** and **PE909-UI** includes appearance as well the ability of **PE909-UI** to be powered by USB power.

For security, all GigaFast HomePlug devices are equipped with 56-bit DES encryption. The private home power grid plus encryption makes HomePlug significantly more secure than competing technologies. All GigaFast HomePlug products operate on the HomePlug Powerline Specification 1.0 standard, providing up to 14Mbps bandwidth over home AC wiring allowing multiple home desktops and notebooks to be networked to share Internet connectors, printers, files, and play games without any additional wiring.

## 6.2 Phonex Broadband Range of Products

Phonex Broadband Corporation [77] has been designing, manufacturing, and marketing technologies that transmit telephone, data, audio, and video reliably over electrical wiring for over 12 years. Phonex chipsets are currently in over 7 million nodes throughout the world. Phonex Broadband products address the entire spectrum of application needs within the residential environment. Telephony, high-speed data, audio, video, set-top-boxes, DSL, Cable Modems, gaming consoles, and any technology with a modem can be networked without the burden of new wiring and costly installation delays. Phonex is proud of its history of being first in the USA market with voice and data technology over the power lines; Phonex was also first in Canada, Mexico, South America, Europe, Australia, and Asia. Phonex has announced the very first 14 Mbps Ethernet-compatible product over the powerline, with many more announcements to follow.

Excluding the ReadyWire, Phonex Broadband currently offers following four products for the HomePlug powerline networking.

**NeverWire 14** (see Figure 32) Powerline Ethernet Bridge comes in two models **QX-201** and **QX-202**. Phonex Broadband's QX-202 NeverWire 14 uses the existing home A/C wiring to pass digital signals between Ethernet enabled devices, without running new wire. This facilitates sharing a single high-speed Internet modem among multiple computers, sharing data files, streaming audio/video as well as playing interactive computer games between PCs. Some of the salient specifications of NeverWire 14 are 14 Mbps maximum bit rate, comparable to Ethernet speeds, Ethernet interface, supports up to 16 nodes per network, customer installable external device, requires no computer disassembly, one button 56 bit DES encryption/decryption ensures security and privacy, Phonex proprietary protocol facilitates upgrades and service diagnostics, HUB/PC switching allows the NeverWire 14 to connect directly to cable modems or PCs, MAC compatible (no software required).

Fig. 32 Phonex NeverWire 14 Powerline Ethernet Bridge

**NeverWire Combo** (see Figure 33) can be used to network any Ethernet-enabled or USB-ready device - computers, printers, routers, DSL modems, cable modems and more. Salient specifications include 14 Mbps maximum rate (Ethernet mode), 56-bit DES encryption/decryption security to ensure privacy, Universal power supply designed for worldwide operation, IEEE 802.3 RJ-45 Ethernet jack,USB 1.1 Series B jack, HomePlug 1.0 Compliant.

Fig. 33 Phonex NeverWire Combo

**Wireless Jack for Modems** (see Figure 34) comes in two models PX-441 and PX-442 and is being designed to turn any electrical outlet into a phone jack that can be used to connect computer modems, video set-top-boxes, Internet appliances, fax machines, and other data oriented devices to the phone line. Other salient specifications include MDU compatibility, fully recoverable and reusable, 65,000 security codes for maximum privacy, 911 emergency interrupt feature compatibility.

Fig. 34 Phonex Wireless Jack for Modems

**NeverWire USB** (see Figure 35) can be used to network any host controller USB device - computers, game consoles and more. Specifications include 12 Mbps maximum rate, 56-bit DES encryption/decryption security to ensure privacy, Universal power supply designed for worldwide operation, USB 1.1 Series B jack, HomePlug 1.0 Compliant.

Fig. 35 Phonex NeverWire USB

## 6.3 Siemens Range of Products

Efficient Networks Inc. [78], a Siemens Company provides a range of powerline products under the brand name SpeedStream.

Siemens currently offers the following five products for powerline networking scenario.

- SpeedStream Powerline Wireless DSL/Cable Router
- SpeedStream Powerline DSL/Cable Router
- SpeedStream Powerline 802.11b Wireless Access Point
- SpeedStream Powerline USB Adapter
- SpeedStream Powerline Ethernet Adapter

However, from the technical specification data sheets it was revealed that all the above mentioned products require 120VAC 60Hz power cycle for operation. This makes the products unsuitable for implementation in the Swedish 220VAC 50Hz power availability. Therefore these products are not considered for TS Lab Demonstrator purpose.

## 6.4 Linksys Range of Products

Founded in 1988, Linksys Inc. [79] has been ranked as an Inc. 500 Fastest Growing Private Company in the United States for 5 consecutive years. For over a decade, Linksys has defined leading edge, easy-to-use, value-priced broadband, wireless, Ethernet, phoneline, powerline and gigabit solutions for desktop and notebooks for home and corporate LANs.

Linksys currently offers the following two products in the powerline networking family.

- Instant PowerLine USB Adapter (PLUSB10)
- Instant PowerLine Etherfast 10/100 Bridge (PLEBR10)

However, based on correspondence with Linksys Technical Support, it was revealed that “Linksys powerline products only work with 110V and are currently not available in other countries outside the US”. This makes the products unsuitable for implementation in the Swedish 220VAC 50Hz environment. Therefore these products are not considered for TS Lab Demonstrator purpose.

## 6.5 NETGEAR Range of Products

Founded in 1996, Headquartered in the heart of Silicon Valley, USA, NETGEAR [80] designs and develops products that enable home and business customers to share broadband Internet access, network office peripherals, and enjoy multimedia entertainment among multiple personal computers and other Internet-enabled devices.

Currently NETGEAR offers the following two products in the powerline networking family.

- Powerline Ethernet Adapter (XE602)
- Powerline USB Adapter (XA601)

However, from the technical specification data sheets it was revealed that both the above mentioned products require 85 to 135v @ 60Hz, Internal power input for operation. This makes the products unsuitable for implementation in the Swedish 220VAC 50Hz power availability. Therefore these products are not considered for TS Lab Demonstrator purpose.

## 6.6 Asoka Range of Products

Asoka USA Corporation [81] is a global manufacturer that specializes in Powerline home networking and gaming products. Boasting more than 20 years of experience in designing, developing and manufacturing computer and gaming products from her parent company, Asoka, Inc. of Taiwan, Asoka USA is focused on efficiently providing quality and affordable home networking and gaming products, as well as delivering excellent support and service

Asoka offers six different products for the powerline networking scenario. The following four products require input power to be 110VAC and are thus not considered in depth:

- PlugLink™ USB Wall Mount PL9720-USB
- PlugLink™ Ethernet Wall Mount PL9620-ETH
- PlugLink™ Ethernet Bridge PL9610 ETH
- PlugLink™ USB Adapter PL9710 USB

The following two products by Asoka require input voltage to be 8VDC@1.2A and are therefore studied in detail:

**PlugLink PL Wireless Access Point - PL9510-WAP** (see Figure 36) allows to extend the Powerline network into a Wireless network as well. Instantaneously, the existing Powerline network can be broadened beyond just the inside of home or office and range of wireless network can be increased from a mere 100 feet to over 3,300 feet. The Asoka PlugLink PL Wireless Access Point offers a convenient way to create a simple network through the existing electrical wiring of a home or office with the additional ability to provide access to the network without wires. Salient Specifications include an all-in-one wireless solution for any powerline-ready network, fully compatible with IEEE 802.11b Standard, supports up to 11 Mbps on the wireless connectivity and up to 14 Mbps on the powerline connectivity, built-in 128-bit WEP encryption ensures a secure wireless network, built-in 56-bit DES Encryption provides security on a powerline network, easy set-up and installation.


Fig. 36 Asoka PlugLink Wireless Access Point

**PlugLink™ PL Cable/DSL Router - PL9510 –BBR** (see Figure 37) which is the cutting-edge combination of a router, Powerline network, and a 4-port switch, acts as the Internet gateway on the home Local Area Network (LAN) and it can be configured to regulate internal users' access to the Internet and serve as an Internet firewall against unwanted outside intruders. The Asoka PlugLink PL

Cable/DSL Router offers a myriad of features that provide a comprehensive network solution for homes and small offices. For offices, the PL Cable/DSL Router offers functions such as firewall, network address translation (NAT), DHCP server, and IPSEC VPN pass-thru, allowing working safely and securely at the office. For homes, especially those with children, the PL Cable/DSL Router offers special features that give parents the option to block out websites with inappropriate content, so that they can feel completely at ease with younger family members using the Internet. Key Specifications include connection to a broadband modem and a powerline backbone, uses just one IP address to access the Internet over entire network, creates a firewall with NAT to protect PCs from unwanted outside intruders, easy set-up through web browser, ability to act as a DHCP Server for the network, ability to block specific internal users' internet access, can dramatically speed up data transmissions with built-in internal switch.


Fig. 37 Asoka PlugLink PL Cable/DSL Router

The above mentioned two products of Asoka are although good for the powerline scenario, however they are mostly dealing with providing gateway connectivity to the network or to extend an existing network. Therefore for the TS Lab Demonstrator, these are not recommended.

## 6.7 IOGEAR Range of Products

IOGEAR, Inc. [82], headquartered in Irvine, CA, is a leading connectivity and peripheral manufacturer that provides complete KVM (Keyboard, Video, Mouse), FireWire, USB (Universal Serial Bus) 1.1 / 2.0, Bluetooth and HomePlug solutions, targeting home users, mobile users and small to medium sized businesses.

IOGEAR presently offers two products for HomePlug Networking.

**HomePlug to Ethernet Bridge (GHPB01)** is compliant to HomePlug Powerline Specifications 1.0 and offers up to 14 Mbps bandwidth, and is less prone to interference. The installation of this unit only requires that a 10/100Base-T network adapter is installed on the computer. The operating input voltage of 110VAC makes this model unsuitable for TS Lab Demonstrator.

**HomePlug to USB Adapter (GHPU01)** (see Figure 38) is compliant to Homeplug Powerline Specification 1.0 and offers up to 12 Mbps bandwidth while being highly resistant to interference. Other salient features include up to 990 feet (300 meters) distance through power lines, low risk of interference by other RF sources, 56-bit DES encryption assuring data security, encryption done by hardware with no sacrifice on bandwidth. The operating voltage input for this model is 110V-220V which makes it suitable for consideration for TS Lab Scenario.


Fig. 38 IOGEAR HomePlug to USB Adapter

## 6.8 ST&T Range of Products

ST&T Electric Corp. [83] founded in 1990, is located at the Yung-Kang Industrial park of Tainan County, Taiwan. ST&T divided its service into two companies- ST&T Electric Corp. and ST&T Biotech Inc. ST&T delivers its powerline products with the trademark iPower Point™ and presently offers the following three products for the Powerline Networking.

**Powerline Ethernet Bridge (**Models **M51** and **M52**) (see Figure 39) can be used to bridge any Ethernet device to the powerline network. By leveraging the performance of the Ethernet protocol and pervasiveness of its use, the Powerline Switch/Bridge Adapter allows users to quickly connect PCs, routers, Internet Gateway such ad DSL cable modems and routers, and other Ethernet-enabled products together over the existing powerline in the home. Other salient features include 56 bit data encryption with key management, support for 10BaseT Ethernet, physical layer data rate up to 14 Mbps over the powerline and input power voltage of 100 ～ 240 VAC, 50/60 Hz.

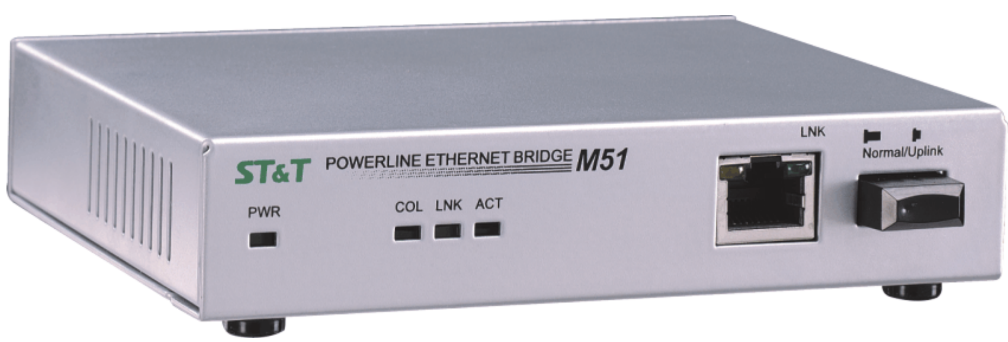



Fig. 39 ST&T Powerline Ethernet Bridge M51


Fig. 40 ST&T Powerline Ethernet Bridge M53

Except for appearance, no other salient feature was discovered between models **M51** and **M53** (see Figure 39 and Figure 40 for comparison).

**Powerline USB Adapter (**Models **U21**, **U22** and **U23)** allows users to quickly connect PCs, routers, Internet Gateways such as DSL cable modems and routers and other USB-enabled devices together over the existing powerlines in the home and enables users to build a strong and simple-to-use home network by leveraging the most pervasive home networking medium - power jacks. The USB Adapter plugs into USB-equipped notebook or desktop PCs, and the other end plugs directly into a power jack outlet on the wall. Other salient features include 56 bit data encryption with key management, support for 10BaseT Ethernet, physical layer data rate up to 14 Mbps over the powerline and input power voltage of 100 ～ 240 VAC, 50/60 Hz.


Fig. 41 ST&T Powerline USB Adapter U21


Fig. 42 ST&T Powerline USB Adapter U22


Fig. 43 ST&T Powerline USB Adapter U23

Except for appearance, no other salient feature was discovered between models **U21**, **U22** and **U23** (see Figure 41, Figure 42 and Figure 43 for comparison).

**Powerline PCI Adapter P11** (see Figure 44) also referred to as Powerline NIC Adapter presents a new and innovative solution for data communications. By using the powerline technology, powerline home network enables multiple PCs and entertainment devices to seamlessly share the broadband Internet. The high bit rate of Powerline NIC Adapter allows for shared Internet access at both current dial-up modem speeds, and those offered by broadband cable modem, xDSL and satellite modems with a HomePlug certified powerline network adapter. Other salient features include 56 bit data encryption with key management, support for 10BaseT Ethernet, physical layer data rate up to 14 Mbps over the powerline and input power voltage of 100 ~ 240 VAC, 50/60 Hz.

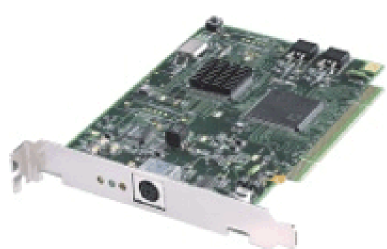


Fig. 44 ST&T Powerline PCI Adapter P11

## 6.9 Telkonet Range of Products

Maryland, USA based company Telkonet Inc. [84] offers the following two products for the commercial powerline communications industry:

**"Plug Plus Internet" Gateway** is a modular, self-contained unit that accepts data from an existing network on one port and distributes it via the second. The most common configuration of the gateway is 10BaseT Ethernet (ETH) on one side and power line carrier (PLC) on the other. The intelligent backbone of the Gateway is a fast communications processor running a series of proprietary applications under Linux. Other useful configurations of the Gateway are PLC-PLC to bridge data around a physical block to the signal (e.g. from old to new sections of a building that do not share common wiring). Another useful configuration is PLC to wireless access point (WAP) to provide immediate line-of-sight wireless access in a large office.

The PLC signal generated by the Gateway can be directly coupled into low voltage wiring via the power cord of the Gateway itself. In addition, the PLC signal may be routed to a remote injection point via an inexpensive coaxial cable. This allows the Telkonet solution to couple into the medium voltage and multi-phase environments found in commercial buildings.

A suite of software applications running on the Gateway can be roughly classified as performing communications functions or system management functions. For example, the gateway enhances the communications capability of the basic PLC by enforcing a logical star configuration in the power line network. Such a configuration immediately expands the maximum reachable distance by a factor of two in all directions resulting in an 8-fold improvement in the covered volume within a building. As an example of the supported management functions, the gateway provides for remote management of the network via a Telnet (command line) interface and remote updating of its own firmware.

The gateway is optimized to network with dozens of "Plug Plus Internet" Modems and provides scalable, robust solution for the commercial market.

**"Plug Plus Internet" Modem** is a small, self-contained unit with a standard 110V plug on one side and an Ethernet RJ-45 connector on the other. This intelligent Modem in conjunction with the gateway provides the enhanced communications and management functions required by enterprise customers.

No further specifications or product illustrations were available from Telkonet website [84].

## 6.10 Corinex Global Range of Products

Founded in 1989 and based in Vancouver, Canada, Corinex Global Corporation [85] is a developer and manufacturer of innovative connectivity products for the expansion of the accessibility and distribution of high speed data, audio, video and voice signals to and within premises and a provider of system integration services to industries world wide.

Corinex presently offers three products for powerline networking scenario and has some very interesting potential products to be released in the near future.

**Corinex Intelligent PowerNet™ Ethernet Adapter** (see Figure 45) uses digital power line technology enabling 14 Mbps data rate at distances of up to 200m for indoor solution. Technical features include multiprotocol communication (TCP/IP, NetBEUI, IPX/SPX), 56 Bit DES link encryption with key management for secured communication, Orthogonal Frequency Division Multiplexing (OFDM) with sophisticated signal processing techniques for high data reliability in noisy media conditions, Intelligent channel adaptation maximizing throughput under harsh channel conditions, integrated Quality of Service (QoS) features such as four-level prioritized random access, contention-free access, and segment bursting, implementation of a scheme with prioritization and repeat request for reliable delivery of Ethernet packets via packet encapsulation and physical connection of the PowerNet PCI Card to power line medium through a power line coupler. Operating input power range is 110V/220V AC. The Intelligent PowerNet Kit comes with Drivers for most of operating systems (Win9x/NT/2000/XP, Linux, OS2, Unix).


Fig. 45 Corinex Intelligent PowerNet Ethernet Adapter

**Corinex Intelligent PowerNet USB Adapter** (see Figure 46) uses digital power line technology enabling 14 Mbps data rate at distances of up to 200m for indoor solution. Technical features include multiprotocol communication (TCP/IP, NetBEUI, IPX/SPX), 56 Bit DES link encryption with key management for secured communication, Orthogonal Frequency Division Multiplexing (OFDM) with sophisticated signal processing techniques for high data reliability in noisy media conditions, Intelligent channel adaptation maximizing throughput under harsh channel conditions, integrated Quality of Service (QoS) features such as four-level prioritized random access, contention-free access, and segment bursting, implementation of a scheme with prioritization and repeat request for reliable delivery of Ethernet packets via packet encapsulation and physical connection of the PowerNet PCI Card to power line medium through a power line coupler. Operating input power range is 110V/220V AC. The Intelligent PowerNet Kit comes with Drivers for most of operating systems (Win9x/NT/2000/XP, Linux, OS2, Unix).


Fig. 46 Corinex Intelligent PowerNet USB Adapter

**Corinex Intelligent PowerNet PCI Card** (see Figure 47) uses digital power line technology enabling 14 Mbps data rate at distances of up to 200m for indoor solution. Technical features include multiprotocol communication (TCP/IP, NetBEUI, IPX/SPX), 56 Bit DES link encryption with key management for secured communication, Orthogonal Frequency Division Multiplexing (OFDM) with sophisticated signal processing techniques for high data reliability in noisy media conditions, Intelligent channel adaptation maximizing throughput under harsh channel conditions, integrated Quality of Service (QoS) features such as four-level prioritized random access, contention-free access, and segment bursting, implementation of a scheme with prioritization and repeat request for reliable delivery of Ethernet packets via packet encapsulation and physical connection of the PowerNet PCI Card to power line medium through a power line coupler. Operating input power range is 110V/220V AC. The Intelligent PowerNet Kit comes with Drivers for most of operating systems (Win9x/NT/2000/XP, Linux, OS2, Unix).


Fig. 47 Corinex Intelligent PowerNet PCI Card

## 6.11 Product Comparison Chart

Table 7 presents a comparative analysis of some of the physical and technical features of selected above mentioned products and vendors.

| Vendor | Product Name | Power Source | Standards | LED Status Lamps | Port | Nodes per network | Retail Price[1] (excluding shipping) US$ |
|---|---|---|---|---|---|---|---|
| Phonex Broadband | QX-201 NeverWire 14 | 220VAC | HomePlug 1.1 | 5 | 1 ETH | 16 | 99.99 |
| | QX-202 NeverWire 14 | 220VAC | HomePlug 1.1 | 5 | 1 ETH | 16 | 189.99 (twin pack) |
| | NeverWire Combo | | HomePlug 1.0 | 2 | 1 USB<br>1 ETH | 16 | N/A |
| | NeverWire USB | | HomePlug 1.0 | 3 | 1 USB | 16 | N/A |
| GigaFast | PE902-EB | Internal Power Adapter | HomePlug 1.0 | 4 | 1 ETH | Any<br>(Max. 2 units in bridge mode) | 87.95 |
| | PE901-UI | Internal Power Adapter | HomePlug 1.0 | 4 | 1 USB | N/A | 82.05 |
| Asoka | PL9920-BBR PlugLink PL Cable/DSL Router | 8VDC | HomePlug 1.01 | 14 | 1 10BaseT<br>4 10/100 | 16 | 139.99 |
| ST&T | M53 Powerline Ethernet Bridge | 100~240 VAC | HomePlug 1.0<br>IEEE 802.3<br>IEEE 802.3U | 4 | 1 ETH | 12 | N/A |
| | U23 Powerline USB Adapter | 100~240 VAC | HomePlug 1.0<br>IEEE 802.3<br>IEEE 802.3U | 3 | 1 USB | 12 | N/A |
| Corinex Global | Intelligent PowerNet Ethernet Adapter | 110/220 VAC | HomePlug 1.0.1 | 5 | 1 ETH | 5 | N/A |
| | Intelligent PowerNet Ethernet Adapter | 110/220 VAC | HomePlug 1.0.1 | 5 | 1 USB | 5 | N/A |

Table 7. Product Comparison Chart

[1] Retail Price is quoted from vendor's site or direct link provided from vendor's site available at March 2003

## 6.12 Conclusions

This Chapter presented the HomePlug-certified products with an overview of their technical and salient features. A comparison was also presented of selected products. The purpose of Chapter is two-fold. On one side it lists all the available products to-date for the powerline networking scenario, and the main purpose is also kept in mind for selecting some potential interesting products for the Telecommunications Systems Laboratory (TS Lab) Demonstrator purpose.

As mentioned in introduction of this Chapter, Phonex Broadband Corporation and GigaFast Ethernet have already supplied their set of powerline modules. These modules were used for the TS Lab Demonstrator and thus the rest of products can be employed in future for large scale deployment purpose.

HomePlug appears to be a promising standard and with the ongoing development and investment by leading companies, powerline technology has a very applicable future with suspected penetration into a vast majority of households and small office (SOHO) market around the globe.

# 7 Powerline Network Demonstration

This Chapter focuses on the evaluation and results of different tests being performed to demonstrate the powerline networking concept. The tests were performed in Sweden and final demonstration of the powerline equipment would be given at the time of final thesis presentation. The original planned idea was to do the testing only at the Telecommunication Systems Laboratory (TS Lab) at the Department of Microelectronics and Information Technology, IMIT, KTH/IT-University, Kista, Sweden. However, the testing was also performed in a normal household in addition to the TS Lab.

## 7.1 Modules/Products used in the testing

This section lists the salient features of HomePlug-certified powerline modules that were being used for the tests. These modules were supplied by their manufacturing companies (or vendors) to the author, for the purpose of testing and demonstration. A full list of all the currently available products in the market, in the powerline networking family is listed earlier in Chapter 6 of this thesis.

### 7.1.1 GigaFast HomePlug modules

**PE901-UI** (see Figure 48) is the GigaFast HomePlug USB Adapter. The Plug and Play USB Chipset allows the HomePlug USB Adapter to be easily installed onto any Microsoft Windows based machine. The device can be installed with a simple power plug to the wall outlet and a USB plug into the computer. A quick detection plus driver installation brings the HomePlug connection online.

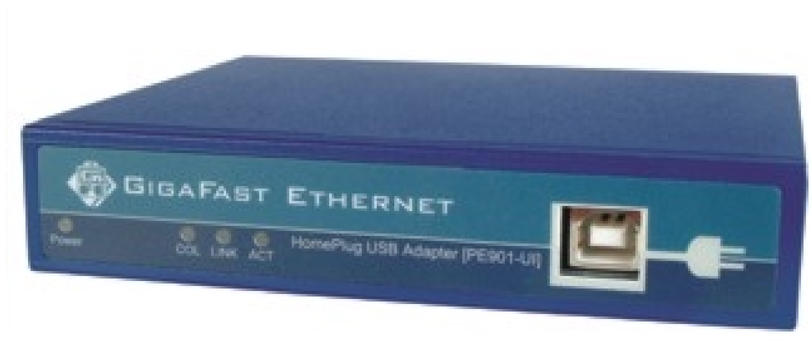



Fig. 48 GigaFast PE901-UI HomePlug USB Adapter

**PE902-EB** (see Figure 49) is the GigaFast HomePlug Ethernet Bridge. The installation of the Ethernet Bridge only requires that a 10/100Mbps Network Adapter is installed on the computer. This makes the HomePlug Ethernet Bridge compatible with any device including Mac, Windows, and Unix machines.

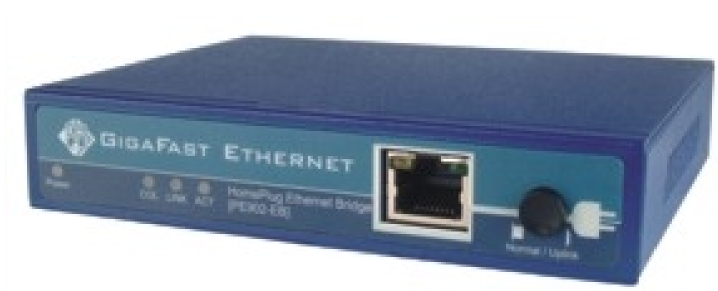



Fig. 49 PE902-EB GigaFast HomePlug Ethernet Bridge

### 7.1.2 Phonex Broadband HomePlug module

**NeverWire 14** (see Figure 50) Powerline Ethernet Bridge comes in two models **QX-201** and **QX-202**. The QX-201 model was provided by Phonex Broadband. Phonex Broadband's NeverWire 14 uses the existing home A/C wiring to pass digital signals between Ethernet enabled devices, without running new wire. This facilitates sharing a single high-speed Internet modem among multiple computers, sharing data files, streaming audio/video as well as playing interactive computer games between PCs. Some of the salient specifications of NeverWire 14 are 14 Mbps maximum bit rate, comparable to Ethernet speeds, Ethernet interface, supports up to 16 nodes per network, customer installable external device, requires no computer disassembly, one button 56 bit DES encryption/decryption ensures security and privacy, Phonex proprietary protocol facilitates upgrades and service diagnostics, HUB/PC switching allows the NeverWire 14 to connect directly to cable modems or PCs, MAC compatible (no software required).

Fig. 50 Phonex NeverWire 14 Powerline Ethernet Bridge

The total available modules for the testing/evaluation/demonstration were four in number. Two units of NeverWire 14 (**QX-201**), one unit of GigaFast HomePlug Ethernet Bridge (**PE902-EB**) and one unit of GigaFast HomePlug USB Adapter (**PE901-UI**) were the ones being used.

The performance of modules was evaluated using different scenarios as highlighted in the following sections.

## 7.2 Networking using 2 modules of same manufacturer

In this scenario the pair of NeverWire 14 modules was used. Although no special software is required to install the modules, however for the purpose of diagnosis, a special utility software called “Phonex Broadband Console software” and also termed as “Phonex Network Administration Console (NAC)” was used which can be downloaded free of charge from the Phonex website listed in [95].

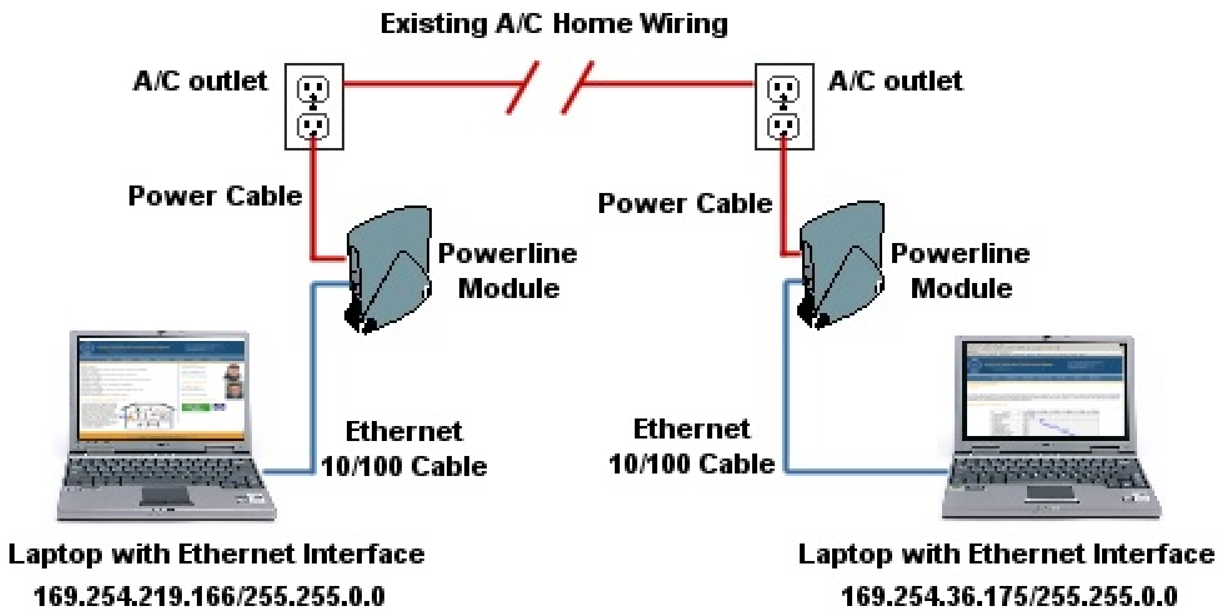



Fig. 51 Powerline networking setup using the NeverWire14 modules

Figure 51 shows the test network set-up, which consists of the NeverWire14 pair of modules connected to the Ethernet 10/100 Interface of Laptop and to the A/C power outlet. The average distance between the A/C outlets (hidden inside the wall) was about 3 meters. Operating system running on both Laptops was Microsoft Windows 2000 Professional. Each of the Laptop's Ethernet interface was set to obtain an IP address automatically. When the powerline modules were plugged to the Laptop, the IP addresses 169.254.219.166 Host Mask 255.255.0.0 and 169.254.36.175 Host Mask 255.255.0.0 were assigned to the Laptops automatically by the OS (i.e. since this test network only comprised of two Laptops, the private IP address was not configured on either of the Laptops). This test was done at an average home in Stockholm, Sweden with power-load of two lamps of 100W each, 1 Refrigerator and laptops running. The performance variation was negligible with additional load introduction of electric oven and television. Two files of total 1.41 Gb (729 Mb + 718 Mb) were transferred @10 Mbps speed using direct Windows networking connection without any additional file transfer application. The time taken for transfer was recorded as 38 minutes. Apart from the operating system, there was no other major application running on the laptops at the time of file transfer.

The Console administration utility by Phonex was used to further investigate different parameters. Figure 52 illustrates the utility java console.

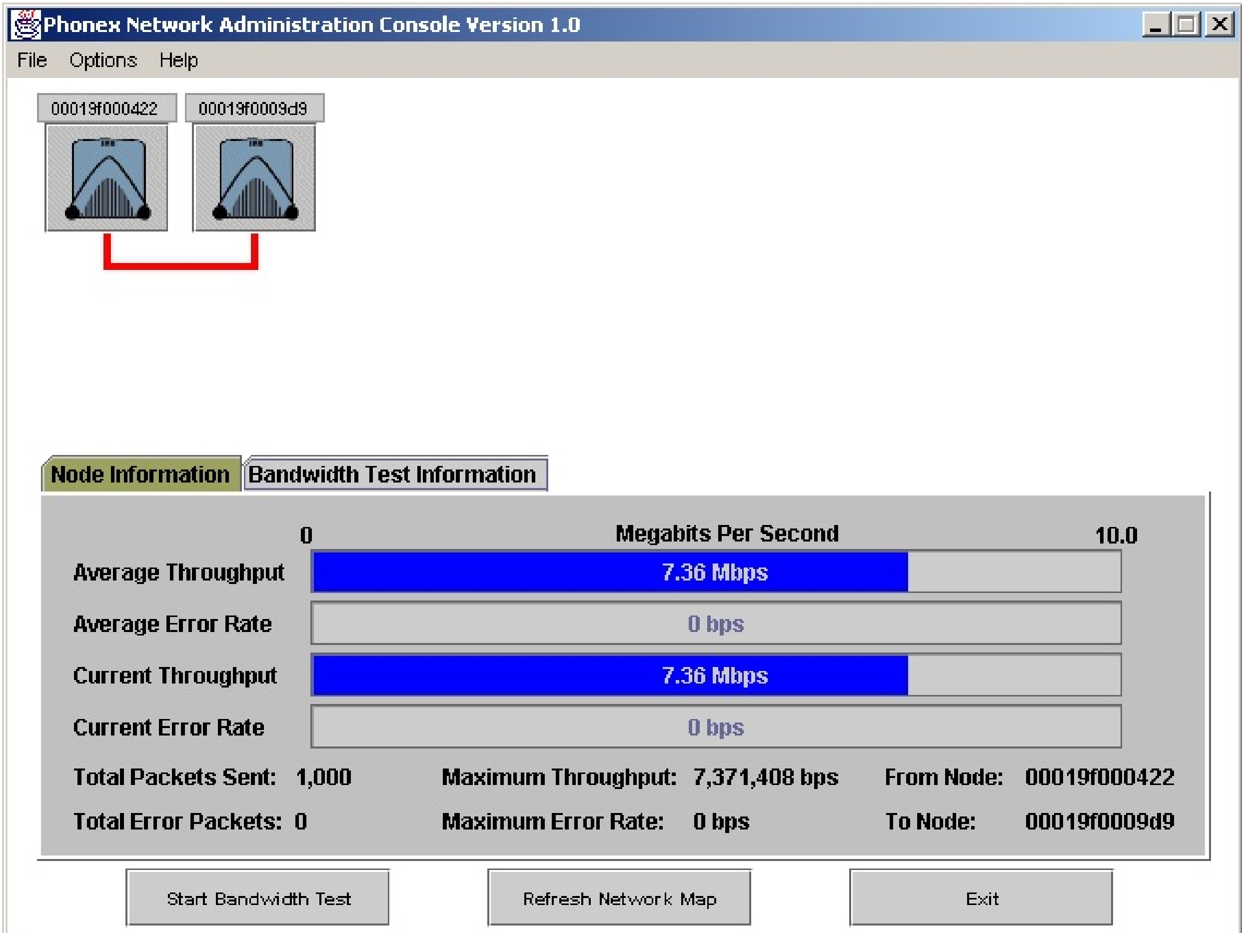



Fig. 52 Phonex Broadband Network Administration Console

The bandwidth test in Figure 52 was performed with a file transfer in progress among the nodes. Parameters reported by the utility were:

Average Throughput: 7.36 Mbps

Average Error Rate: 0bps

Total Packets Sent: 1000 (this parameter is adjustable; Packet Size: 1518 bytes each)

Maximum Throughput: 7.37 Mbps

The Phonex NAC needed a gateway configuration at the laptop running the NAC. Gateway was the IP address of the system running the console. The NAC also gives useful information about the Nodes being detected by the utility. Figure 53 illustrates the NAC with Node Information. A discussion with GigaFast Tech Support revealed that the Phonex NAC utility "requires java Virtual Machine which doesn't come with Windows XP." However, the Java Virtual Machine can easily be downloaded from the relevant site [92] (note: the Java Runtime Environment [JRE] installs the Sun Java Virtual Machine). The author also found this interesting article at [93] on settlement agreement of Microsoft Corporation with Sun Microsystems Inc. regarding the discontinuation of Microsoft from the development and distribution of Microsoft virtual machine (VM).

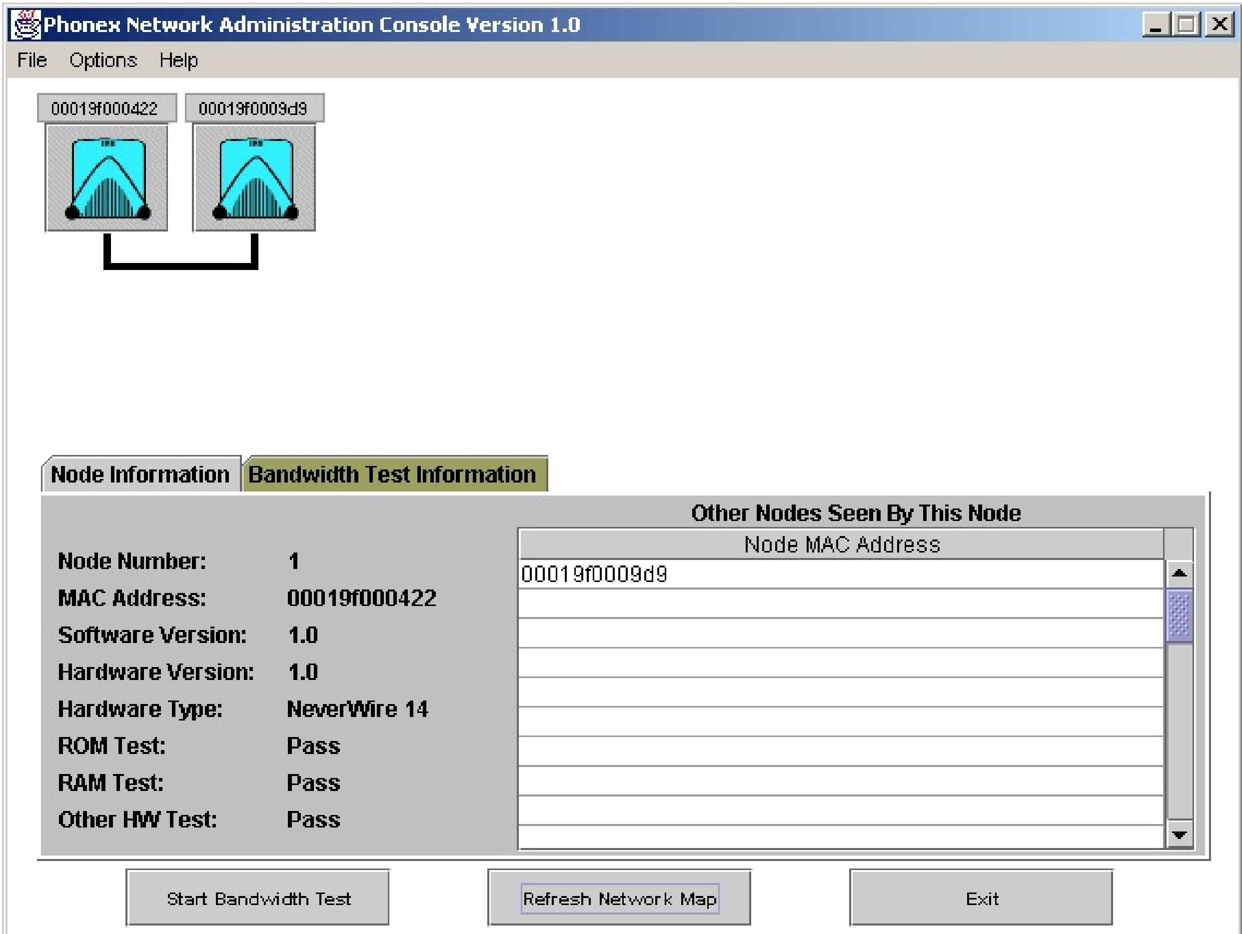



Fig. 53 Phonex NAC with Node Information

The average throughput seemed to increase when then test was performed again with no file transfer in progress between the nodes. The number of packets sent for the test was also increased from 1000 to 5000. Figure 54 illustrates the results.

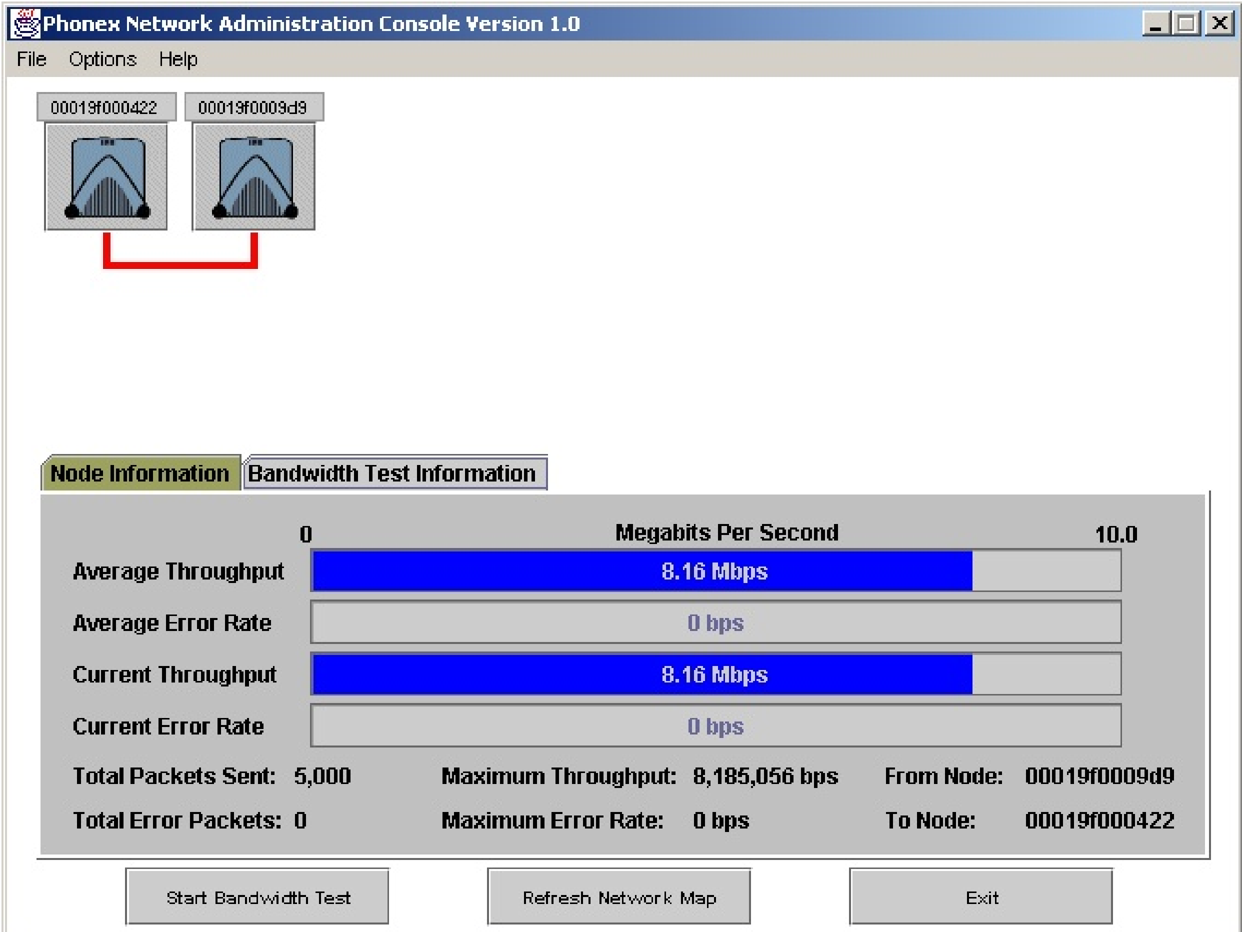



Fig. 54 Phonex NAC with no file transfer among the nodes

The results of the test were:

Average Throughput: 8.16 Mbps

Average Error Rate: 0 bps

Total Packets Sent: 5000 (Packet size: 1518 bytes each)

Maximum Throughput: 8.18 Mbps

The above results using the NeverWire14 modules are just one of the outputs taken from variety of tests performed at various locations in the TS Lab.

## 7.3 Networking using 2 modules of different manufacturer

In this scenario one **QX-201** and one **PE902-EB** were used. The Phonex Broadband's diagnostics utility was not able to detect the GigaFast PE902-EB module. A discussion with GigaFast revealed:

> *"PE909-UI, wall-mount USB does not have the diagnosis utility. PE902-EBx, Ethernet Bridge second generation, does not have the ability either. PE903-EB, Ethernet Bridge, MAC compatible version of HomePlug. It is not shipping yet, but it will have the utility .. It will be available in about 2 months, or earlier. We do not have the ETA yet .. Also, in the future, we will have both*

*Ethernet bridges available (PE902-EBxand PE903-EB), will not discontinue PE902-EBx, because for regular home users, this product gives enough support. (PE903-EB is more advanced).”*

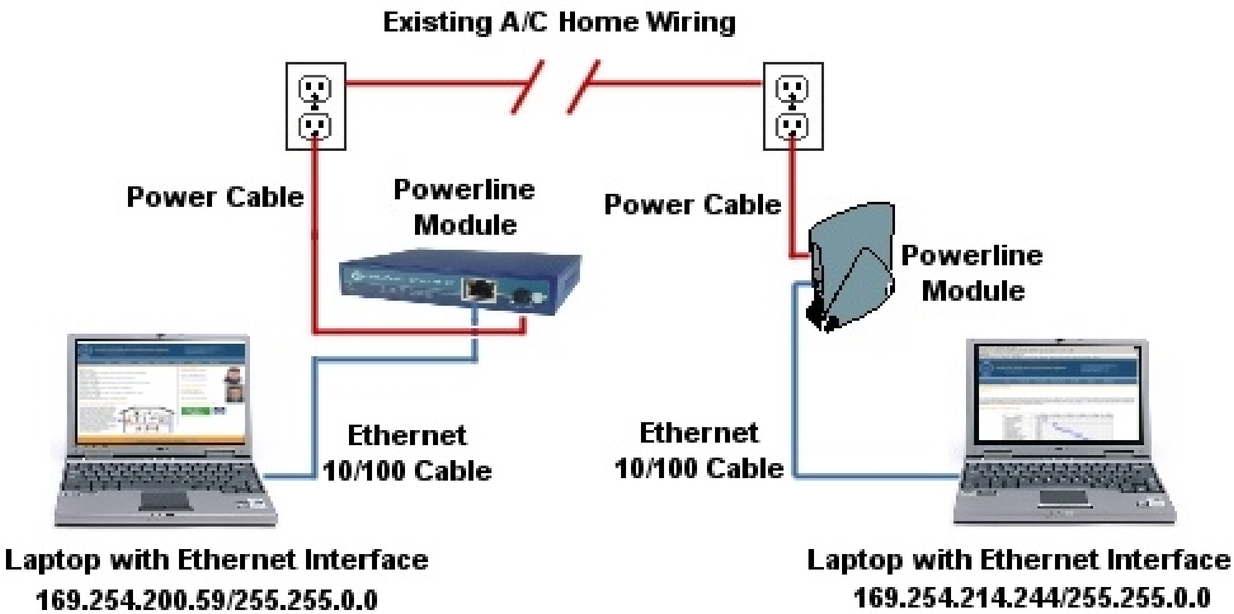



Fig. 55 Powerline network setup using GigaFast and Phonex Modules

Figure 55 shows the test set-up, which consists of the NeverWire14 modules networked with the GigaFast Ethernet Bridge. Both modules are connected to the Ethernet 10/100 Interface of Laptop and to the A/C power outlet. The average distance between the A/C outlets (hidden inside the wall) was about 3 to 4 meters. An interesting variation in this test was that although both manufacturers recommend on not using the extension cords and plug the modules directly to the A/C outlet, the author used extension cords on both the ends. The Operating system running on both Laptops was Microsoft Windows 2000 Professional. Each of the Laptop’s Ethernet interface was set to obtain an IP address automatically. The GigaFast module requires a utility software installation (provided on a CD by the manufacturer along with the module) and also the system on which the GigaFast utility software is installed needs a restart. When the powerline modules were plugged to the Laptop, the IP addresses 169.254.200.59 Host Mask 255.255.0.0 (GigaFast) and 169.254.214.244 Host Mask 255.255.0.0 (Phonex) were assigned to the Laptops automatically by the OS (i.e. since this test network only comprised of two Laptops, the private IP address was not configured on either of the Laptops). This test was done at the TS Lab, Kista Sweden with average power load equivalent to a small office/home office (SOHO) scenario. The performance variation was negligible with additional load introduction of three computers. One file of 693 Mb was transferred @10 Mbps speed using direct windows networking connection without any additional file transfer application. The time taken for transfer was recorded as 20 minutes. Apart from the operating system, there was no other major application running on the laptops at the time of file transfer. Phonex NAC was not able to detect the GigaFast module, therefore the Throughput and other parameters could not be diagnosed using the Phonex NAC.

From [90], Figure 56 below shows throughput results of some of the powerline networking products.

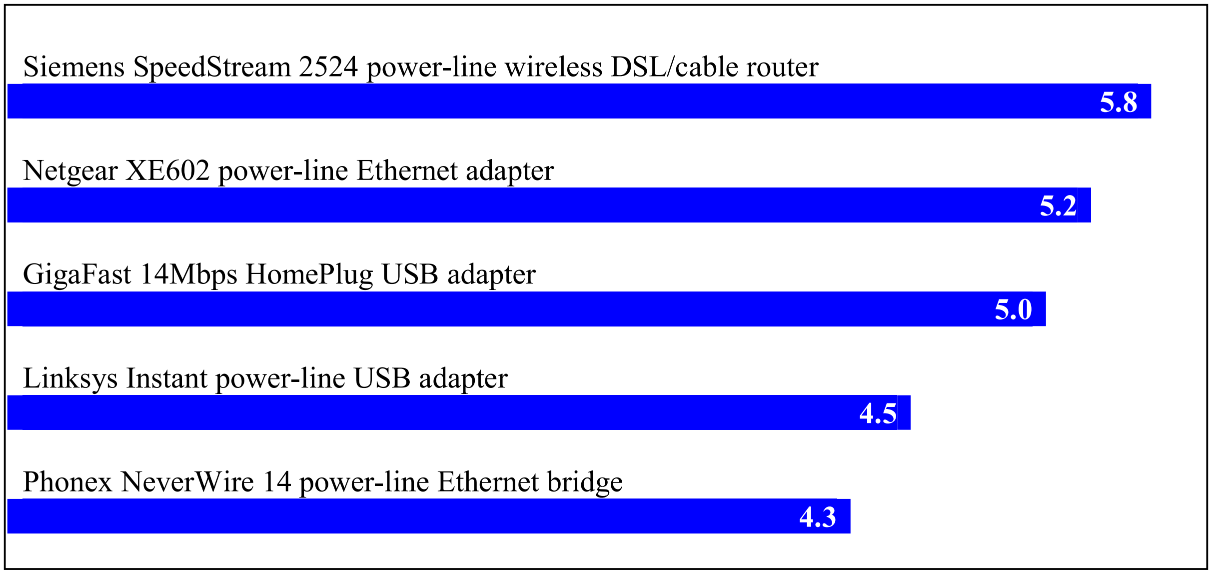



Fig. 56 Chariot power-line throughput tests (Measured in Mbps)

A field performance comparison of IEEE 802.11b and HomePlug 1.0 is presented in [91]. The overall results yields that the powerline network outperforms the wireless network for reliable connection service and throughput performance. Table 8 below highlights the results found by [91]:

| Transmitter Location | Receiver Location | Tx to Rx Distance | 802.11b T'put (Mbps) | | Powerline T'put (Mbps) | |
|---|---|---|---|---|---|---|
| | | | WSFTP | TTCP | WSFTP | TTCP |
| Laptop-1 | Laptop-2 | 2 ft | 3.2 | 4.9 | 4.2 | 5.2 |
| Study Room | Dining Room | 23 | 3.6 | 4.7 | 4.5 | 5.3 |
| Home Office | Kitchen | ~ 35 | 2.5 | 4.1 | 4.0 | 4.5 |
| Kitchen | Home Office | ~ 35 | 2.4 | 1.6 | 3.1 | 3.1 |
| Bedroom C | Home Office | ~ 70 | No Conn. | No Conn. | 1.9 | 1.8 |
| Home Office | Bedroom C | ~ 70 | No Conn. | No Conn. | 4.1 | 3.9 |
| Pool Area | Home Office | ~ 60 | No Conn. | No Conn. | 2.0 | 1.6 |
| Home Office | Pool Area | ~ 60 | No Conn. | No Conn. | 2.4 | 2.8 |

Table 8. Field test throughtput performance results of IEEE 802.11b and HomePlug 1.0 [91]

## 7.4 Conclusions

This Chapter presented the results of the various tests performed at TS Lab to demonstrate the concept of powerline networking. The CEA Data Networking Subcommittee, R7.3 started working on a high-speed PLC standard at the end of 1999 [88] [89]. Quoting from [87]: "CEA members have assembled an extensive set of field and laboratory tests to determine exactly how each technology will perform.. in various scenarios under widely varying conditions of impedance, noise and size of home. These tests will ultimately reveal the strengths and weaknesses of each technology."

Due to limited time, resources and scope, the tests included in this Chapter were restricted to just demonstrate the concept of powerline carrier communications at the TS Lab with the available modules. A future extension of this might be to perform a large scale field test with modules from different vendors and to observe various characteristics of powerline medium including signal attenuation, frequency selective and impulse noises, signal time dispersion, mutual existence of PLC and wireless services and their influence on each other etc. involving significant more users and a wide area. The results from this test were found satisfactory to install the modules at the TS Lab. A future suggestion is to develop a software that is capable of functionality similar to the Phonex Broadband's NAC and also included in the module should be features like instant messaging, voice and video conferencing etc., and the compatibility of the software to work with all HomePlug complaint devices.

# 8 Laboratory Exercises to Understand Powerline Networking

This chapter is provided as a comprehensive laboratory instructions paper which can be handed to the students to perform the exercises.

In these labs we will look at some of the underlying concepts in the powerline networking technology. These lab exercises are produced as part of the thesis work and should be used and read in conjunction with this thesis. These exercises will give the students an idea of how to perform the networking of computers using powerline networking technology and also how to setup an integrated network with powerline equipment used in conjunction with the wireless equipment. As more equipment is made available to the Telecommunications Systems Lab (TS Lab) at the IT-University, Kista, Sweden, the exercises can be expanded to use the wireless access points with the powerline technology.

## 8.1 Lab 1 Building A Simple Network Using Same Vendor Powerline Nodes

The simple network setup for this lab is demonstrated in Figure 8.1.

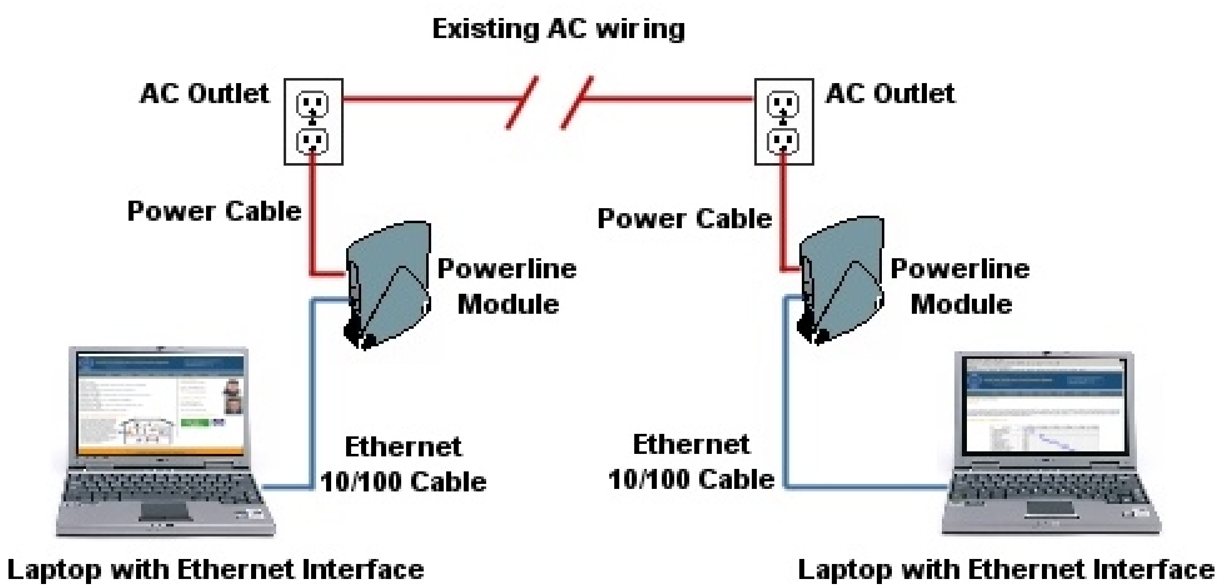



Fig. 8.1 Lab 1 Network Setup

In order to build the above network, the following logical steps are needed:

**Step 1**. For Windows Networking to work properly, in System Properties, Network Identification Tab, make sure all the computers connected to the network have the “same” Workgroup name.
**Step 2**. For this lab, the powerline nodes used for network should be from the same vendor (for example, Phonex Broadband or GigaFast Ethernet modules etc.).
**Step 3**. In the Network Properties for the Ethernet Adapter, make sure the TCP/IP properties for the Adapter are set to “Obtain an IP address automatically.”
**Step 4**. Make sure the AC powerline that you will be using is in fact internally connected to each other. Ask the lab assistant for this or simply use the hit-and-trial mechanism to find out two AC power outlets that are linked.
**Step 5**. Connect the powerline nodes to the computers and AC power outlets.

**Step 6**. Use the "ping" command from the Windows Command Prompt to see if you can reach other computers. "ipconfig /all" command also discloses relevant information.
**Step 7**. Note the IP addresses assigned to the computers automatically by the OS.

## 8.2 Lab 2 Building A Network With Different Vendor Powerline Nodes

In this lab we will make a network using various nodes from different providers to demonstrate the compatibility of HomePlug equipment. The Lab setup is shown in Figure 8.2.

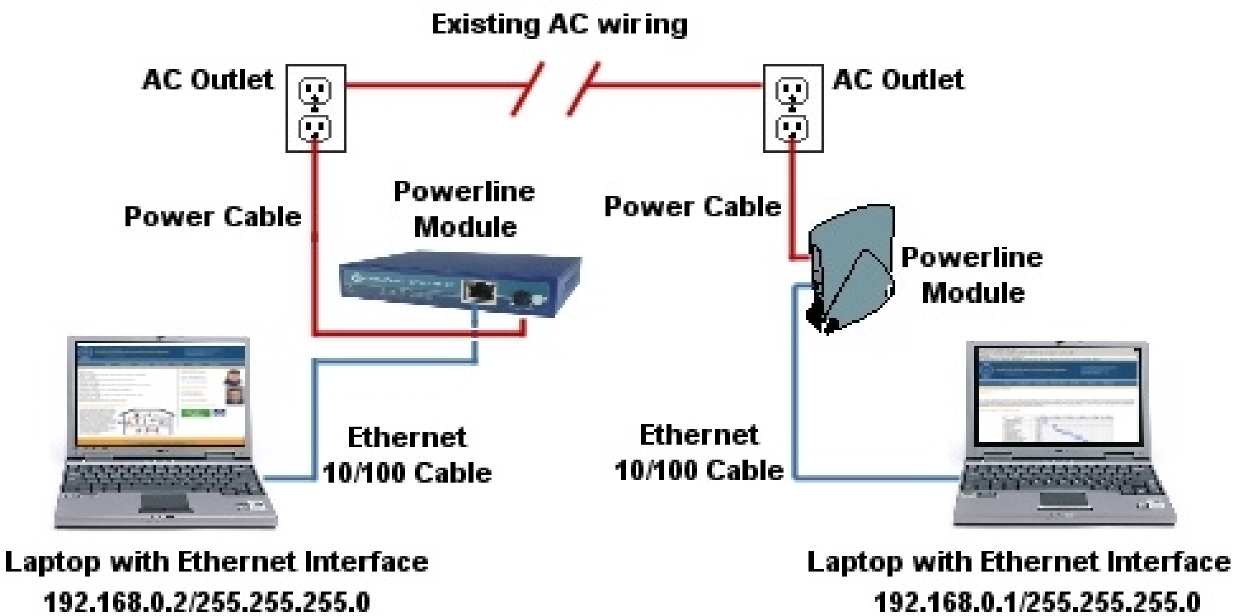



Fig. 8.2 Powerline Network to demonstrate HomePlug compatibility

Repeat Steps 1 to 5 of Lab 1. Also the following additional steps are needed:

**Step 6**. If software installation is needed for a particular module, install the recommended software and then restart the system if required.
**Step 7**. Use the "ping" command from Windows Command Prompt to see if all computers on the network are accessible.
**Step 8**. Note the IP addresses assigned to the computers automatically by the OS.

***Assignment***: Repeat Lab 1 and Lab 2 with assigning private IP addresses to the Ethernet Adapter of the Laptop instead of obtaining the IP address automatically by the OS. Then use the "ping" utility to check for the network availability. The Internet Assigned Numbers Authority (IANA) has reserved the following three blocks of the IP address space for private internets:

10.0.0.0 - 10.255.255.255 (10/8 prefix)

172.16.0.0 - 172.31.255.255 (172.16/12 prefix)

192.168.0.0 - 192.168.255.255 (192.168/16 prefix)

## 8.3 Lab 3 Internetworking The Lab Network With Internet

In this Lab we will connect the powerline network with the Internet. This Lab will extend the concept of peer-to-peer networking to connecting the intranet with Internet. Figure 8.3 demonstrates the Lab Setup.

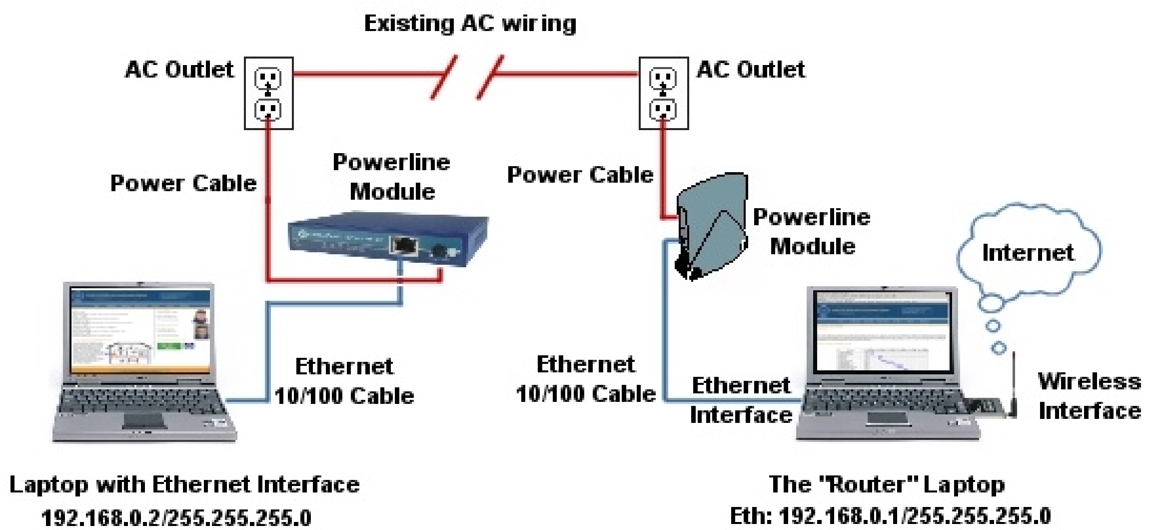



Fig. 8.3 Powerline Lab Network connected to Internet

**Step 1**. Connect the Laptops with powerline nodes.
**Step 2.** Connect the powerline nodes to the AC outlets & make sure the AC wiring is linked internally.
**Step 3**. Set the laptops Ethernet interfaces to obtain an IP address automatically.

***Note***: After performing Step 5 the windows networking will assign the IP address 192.168.0.1 to the "Router" Laptop's Lab Network Interface (i.e. the Ethernet Interface connected to Powerline Network), and then it will automatically assign all internal network addresses acting as a DHCP server.

**Step 4**. Connect a wireless adapter to the Laptop acting as "Router" (see Fig. 3) and providing Internet Gateway to the other computers. Login to wireless Internet using the KTH University Wireless Network.
**Step 5**. In the "Router" Laptop, go to the wireless network interface properties and "enable sharing" which will allow the lab network to be connected to the Internet.

With the Internet connection sharing feature of Network and Dial-up Connections, you can use Windows 2000 to connect your home network or small office network to the Internet. The Internet connection sharing feature is intended for use in a small office or home office where network configuration and the Internet connection are managed by the computer running Windows 2000 where the shared connection resides. It is assumed that on its network, this computer is the only Internet connection, the only gateway to the Internet, and that it sets up all internal network addresses. For further help on the topic, try using the "Help" feature of Windows and search for "Internet connection sharing".

**Step 6**. You should now be able to use the Internet via the "Router" laptops wireless interface, from all the Laptops connected to the powerline networking.

## 8.4 End of Lab Exercises

After the completion of above labs, the students should call over a lab instructor to explain the network setup and the suggestions they can think of to make the network more scalable.

The Power Line Communication Systems use the existing AC electrical wiring as the network medium to provide high speed network access points almost anywhere there is an AC outlet. In most cases, building a home network using the existing AC electrical wiring is easier than trying to run wires, more secure and more reliable than radio wireless systems like 802.11b, and relatively inexpensive as well. For most home and small office applications, this is an excellent solution to the networking problems.

# 9 Conclusions and Suggestions for Future Research

Since the developments and research on the subject had been relatively new and information scattered, the lack of collective information had been the primary initiative behind this thesis. This thesis serves as a general and technical reference on the "Powerline Carrier (PLC) Communication Systems" with the presentation of a comprehensive and detailed analysis on the standards, characteristics, technologies, products and development associated and currently being deployed in the powerline networking technology.

The usage of powerline communications over the low-voltage electrical power supply networks gives an alternative for the telecommunication access area. Initially powerlines were used for controlling appliances, however with the recent technology advancements the powerlines are now able to compete successfully with other relatively stable home networking technologies like wireless and phoneline. The transmission of bandwidth intensive information and multimedia over powerlines is no more a theoretical concept and with current available data speeds of 14 Mbps (and much greater speeds promised for the near future), powerline represents a potential candidate for the preferred choice in home networking and automation scenarios. Maximum throughput for Phonex NeverWire series of products was found to be 8.18 Mbps and other comparative results showed the performance of powerline networking superceding those of wireless or other home networking technologies. The suggested laboratory exercises will help the students or researchers to test the equipment functionality and throughput more efficiently.

The channel characteristics and transmission impairment study was based on the findings of other researches made in various European cities, based on practical field trials. Due to the lack of funding or support from any energy provider for this thesis, it was not possible to perform the field trials or simulations on the energy network directly. The market survey presents HomePlug certified products related to powerline networking with the survey results specifically targeted towards deployment of a demonstrator at the TS Lab at Kista, Sweden. The products not suitable for Swedish RPC (i.e. operating on 110V 60 Hz) were not listed in the product specifications. Availability of only two vendor's modules was also a drawback in comparing the throughput and performance functionality of various powerline modules, however results from other related field trials were also studied and presented.

The powerline technology is getting stabilized now and attracting many industry leading vendors and developers. The arguments that favor the selection of powerline as the networking medium for SOHO scenarios are: First, with exceptionally large growth in the number of household computers and other electronic devices, there is a more-than-ever need for a centralized system for information sharing and management of resources. Secondly, in developed countries the powerlines have already been successfully tested on a large scale for meter reading, control and even data transmissions. The first stage of testing is now successful and vendors are shipping products at relatively cheaper prices than other competing home networking technologies. The electric utilities can take advantage of this emerging technology and provide other services to their consumers like broadband Internet access etc. along with the traditional electric power, as well as the utilities are now also able to automate the meter reading, signaling and other controls via the powerlines. The third advantage of using powerlines for data transmission is directed towards the scenario when the normal telephone lines or other links are not able to reach the consumer premises (due to certain factors including cost to lay the cable, weather or natural obstacles etc.); in that case the electric powerlines are already in place. All the utility needs to do is adapt to the powerline networking environment and start offering services to the consumers.

This is particularly useful solution for the undeveloped or developing Asian countries like Pakistan, India, Bangladesh, etc. where the potential of communications over powerlines is tremendous.

With respect to future research, exact and large scale real-time analysis of line characteristics and response is needed on certain potential areas with the availability of full resources (including the testing, measurement, performance analyzers, etc.) to establish verified and authentic results. The lack of centralized standardization and regulation is another major factor which should be overcome to facilitate the deployment. The need for an open source comprehensive channel characteristics analyzer and plotter equipment (hardware and software), is present. There is also a need for a vendor-neutral open source powerline network analysis software similar to the Phonex Network Administration Console (preferably developed in Java or other multi-platform language) that measures and records certain network characteristics (including throughput, error, signal attenuation, frequency selective and impulse noises, signal time dispersion, among others) in real-time and outputs them graphically. Also included in the module should be features like instant messaging, voice and video conferencing etc., and the compatibility of the software to work with all HomePlug complaint devices. Another potential research topic is the design and production of open-source simulator(s) (preferably in Java or other multi-platform language) which is capable of performing complex simulations on the low voltage and medium voltage electric power distribution grids with the output of results in certain user readable formats. A full scale research is also seemed important on the real-time testing, measurement and comparison of results of a powerline network deployed at a European and American RPC with mutual existence of PLC and wireless (and/or other home networking) services and their influence on each other etc. involving significant more users and a wide area and suggestions made on the basis of the pilot network formed and tested at various major practical locations.

# 10 Abbreviations

For the purpose of this thesis, the following abbreviations apply:

| | |
|---|---|
| AC | Alternating Current |
| ARQ | Automatic Repeat Request |
| BHN | Broadband Home Networks |
| BPSK | Binary Phase-Shift Keying |
| CSMA/CA | Carrier Sense Multiple Access/Collision Avoidance |
| CSMA/CD | Carrier Sense Multiple Access/Collision Detection |
| DLC | Distribution line communication systems (refers to low voltage part of the electric power distribution network) |
| DS | Direct Sequence |
| DS-SS | Direct Sequence Spread Spectrum |
| FEC | Forward Error Correction |
| FH | Frequency Hopping |
| FSK | Frequency-Shift Keying |
| HAN | Home Area Networking |
| HMI | Human Machine Interface |
| HVAC | Heating Ventilation and Air Conditioning |
| KTH | Royal Institute of Technology, Stockholm, Sweden |
| MPSK | *M*-ary Phase-Shift Keying |
| MP3 | Moving Picture Expert Group (MPEG) Layer 3 |
| OEM | Original Equipment Manufacturer |
| OFDM | Orthogonal Frequency Division Multiplexing |
| PC | Personal Computer (Most commonly referred to x86 Intel machines) |
| PL | Power Line |
| PLC | Powerline Carrier Communication |
| PLT | Powerline Telecommunications (ETSI Project) |
| RF | Radio Frequency |
| ROBO | ROBust OFDM |
| RPC | Residential Power Circuit (refers to low voltage part of the electric power distribution network) |
| QAM | Quadrature Amplitude Modulation |
| QPSK | Quadrature Phase-Shift Keying |
| SOHO | Small Office Home Office |
| TS Lab | Telecommunication Systems Laboratory, IMIT, IT-University, Kista, Sweden |
| xDSL | Digital Subscriber Line (DSL) and x is the service designator (e.g., ADSL, VDSL) |

# 11 Appendices

PhonexBroadband

# NeverWire 14

## Powerline Ethernet Bridge

### YOU ARE ALREADY WIRED FOR A MULTIMEDIA NETWORK!

Need a speedy internet connection in the kids' room?
How about the kitchen? Or maybe out on the deck?

It's as easy as 1-2-3 with NeverWire 14 and your existing broadband internet connection. ***Works right out of the box!***

1. ***Plug your existing DSL, cable or other broadband modem into the first NeverWire 14.***
2. ***Plug the NeverWire 14 into any power outlet.***
3. ***Plug your second NeverWire 14 into any other power outlet in your home-and plug in your computer!***

No tearing into walls to install cable! No software required! Just reliable broadband internet access from any room in your home or small office, from the world leader in powerline technology. Phonex Broadband has sold over 9 million powerline products.

You can even move your NeverWire 14 from room to room-wherever you need internet access.

Think of all the places you can enjoy your speedy broadband internet connection courtesy of the NeverWire 14. Emailing from your deck. Searching for recipes from your kitchen counter. Shopping for tools from your garage.

Concerned about security? NeverWire 14's **exclusive** one-touch security button makes it easy to protect your privacy-no passwords to remember, no software required. It's all in the **exclusive** dual processor design. And the diagnostic LED light lets you know that security is working and your privacy protected.

You can also use the NeverWire 14 to network any ethernet-enabled device-computers, printers, routers, DSL modems, cable modems and more.

NeverWire 14 comes with a no-questions-asked money-back guarantee from Phonex Broadband, the world leader in powerline technology, with over 9 million powerline technology products sold. If you are not satisfied with the NeverWire 14 for any reason, we will refund your money within 30 days. No hassles!

INTERNATIONAL CES INNOVATIONS BEST OF INNOVATIONS 2002™

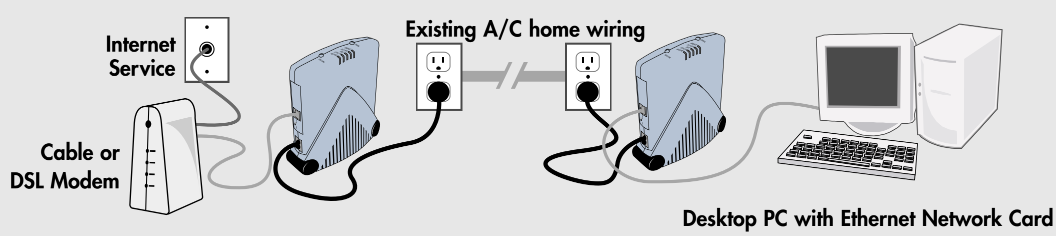
*For home networking*

PC WORLD WORLD CLASS 2002

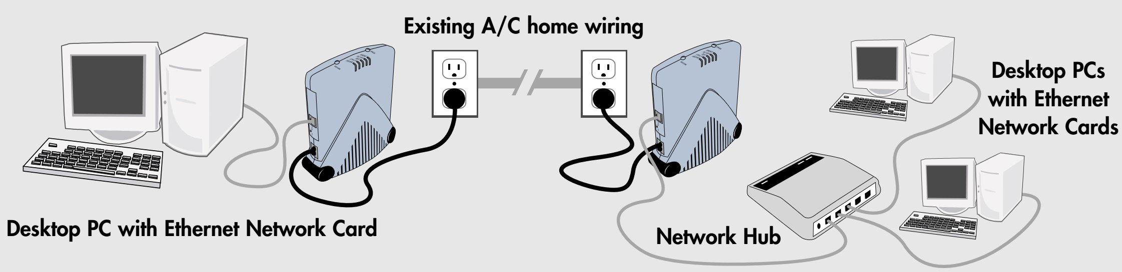
*HomePlug Powerline Alliance Most Promising Newcomer July 2002*

### EASY INSTALLATION FOR A VARIETY OF HOME OR SMALL OFFICE NETWORK SOLUTIONS

*Extend your high-speed Internet access anywhere in your home or small office:*




*Network computers together and share files at high-speed network transfer rates:*



## SPECIFICATIONS FOR THE NEVERWIRE 14 MODEL QX-201

***No software installation, configuration or drivers to load.***
- ***Exclusive*** - Devices are fully configured right out of the box for an Ethernet network of any size or complexity.
- NeverWire 14 devices automatically detect and setup a Powerline connection without user intervention.
- Easy installation: plug in Ethernet cable, plug power cord into outlet. Repeat for second device.

***Hub/PC cross-over switch for easy connection to hubs, switches, routers, or any Ethernet device***

***Exclusive - "Secure" button for Push Button Encryption (see User's Guide)***
- Industry standard encryption engine (56 bit DES)
- Homeplug default encryption ship standard out of the box.
- Private encryption key set with the press of "Secure" button on each device (see User's Guide)
- ***Exclusive*** - "Secure" button can be used to set private encryption, default encryption or disable encryption (see User's Guide)

***Exclusive - "Diags" button for Push Button Troubleshooting (see User's Guide)***
- Performs self test to check internal components of the device for any failure, result indicated on "Test" LED
- Performs Network Connection Check to detect connection with other devices on home Powerline network, result indicated on "Test" LED

***Exclusive - 5 LED lights to indicate encryption, self test, network connection check and other valuable information - labeled clearly on the NeverWire 14 device.***
- "Secure" LED indicates default encryption (flashing), private encryption (solid) or no encryption (off).
- "Eth L/A" LED indicates Ethernet traffic (flashing).
- "Test" LED indicates both self test and powerline connection check (see User's Guide for details)
- "PLC R/A" LED indicates power to device.
- "Bridge" LED indicates when more than one Ethernet device is connected to an individual NeverWire unit.

***14 MB maximum rate***

***IEEE 802.3 Ethernet interface - 1 port***

***220v auto-switching power supply***

***Ordinary power cord carries Powerline data signal to power outlet.***

***Homeplug 1.1 Compliant***

***Unique dual processor design***

***Network management***
- Supports up to 16 NeverWire devices communicating on a single network
- Supports more than 16 NeverWire devices present on a single network
- Supports unlimited Ethernet devices connected to each NeverWire device

***Phonex Network Protocol facilitates upgrades and service diagnostics***

***Requires Ethernet adapter in PC (common on most PCs and Cable/DSL broadband modems)***

## PHONEX BROADBAND CORPORATION

Founded in 1988, Phonex Broadband Corporation, based in Midvale, Utah, is a privately held company recognized as the world's leading developer of powerline carrier technology. Phonex Broadband's patented technology enables phones and telecom devices to communicate reliably using standard electrical wiring. Phonex Broadband products are designed to let you add a phone, modem or computer extension anywhere one is needed, without the inconvenience associated with wireline installations. Phonex Broadband has already installed over 9 million units worldwide.

## CONTACT

Phonex Broadband Corporation
6952 High Tech Drive
Midvale, Utah, U.S.A. 84047
Toll Free: 1.800.257.0601
Fax: 1.801.566.0880
Email: sales@phonex.com
Web: www.phonex.com

GIGAFAST ETHERNET

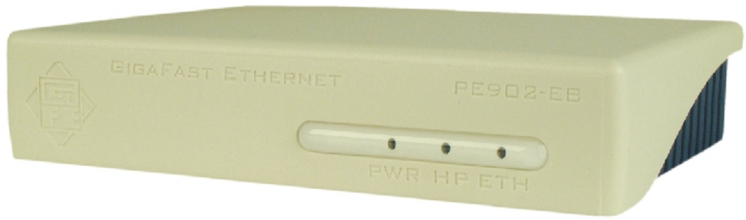
PE902-EBx

# 14Mbps HomePlug™ Ethernet Bridge

HomePlug 14 Mbps CERTIFIED

## Features:

- **Up to 14 Mbps bandwidth over standard home power lines**
- **Estimated range of 300m in wall power lines**
- **No problems passing through circuit breakers**




**More Reliable than Wireless !**

HomePlug™ Ethernet Bridge

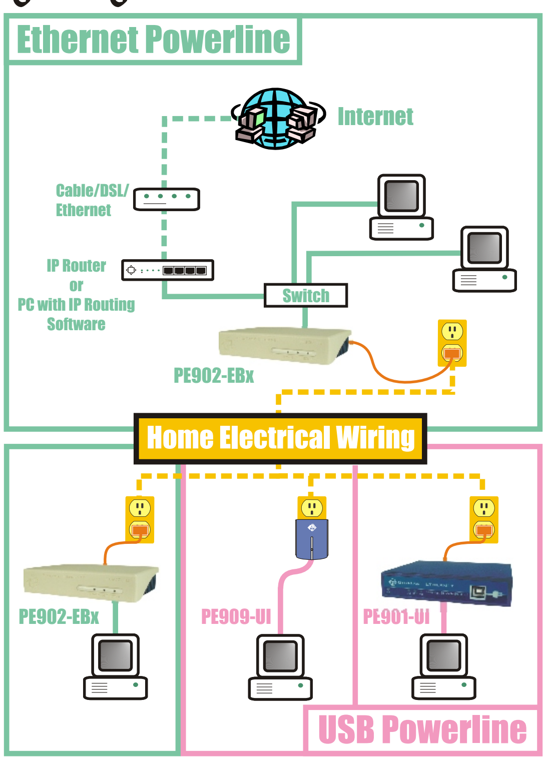
The GigaFast HomePlug Ethernet Bridge operates on the HomePlug Powerline Specification 1.0 standard, providing up to 14Mbps bandwidth over home AC wiring. Since the home power lines are the most pervasive medium in households with multiple outlets in every room, the HomePlug Ethernet Bridge allows multiple home desktops and notebooks to be networked to share Internet connections, printers, files, and play games without any additional wiring.

The installation of the Ethernet Bridge only requires that a 10/100Mbps Network Adapter is installed on the computer. This makes the HomePlug Ethernet Bridge compatible with any device including Mac, Windows, and Unix machines.

For security, all GigaFast HomePlug devices are equipped with 56-bit DES encryption. The private home power grid plus encryption makes HomePlug significantly more secure than competing technologies.

The GigaFast HomePlug Ethernet Bridge is the best solution for No-New-Wires home networking. With easy Plug and Play installation, no need for new wires, and the reliability of GigaFast Ethernet's products, the GigaFast HomePlug Ethernet Bridge is the best solution for high speed networking.

## Usage Diagram:




**What is a HomePlug node?**

**The PE902-EB can operate in two modes: Node and Bridge. As a node, only one computer can be connected to the PE902-EB, and software drivers must be installed on the computer. As a bridge, a switch or router is connected to the PE902-EB and other computers are connected to the switch or router. This mode does NOT require software driver installation.**

| | |
|---|---|
| *Computer Interface* | IEEE802.3 |
| *Network Interface* | HomePlug Powerline |
| *Cabling* | 10BASE-T: Cat 3, 4, or 5 UTP Cable |
| *Installation* | Plug-and-Play |
| *LED Indicators* | Link, ACT (Activity), Col (Collision), Power |
| *Certifications* | HomePlug Powerline Specification 1.0 |
| *Power Supply* | Internal Power Adapter |
| *Operating Temperature* | 0° ~ 40°C |
| *Humidity* | 5% ~ 90% |
| *Housing* | Plastic |
| *Dimensions* | 4.5 x 3.0 x 1.0 inches |
| *Driver Support* | Microsoft Windows 98, 2K, ME and XP |
| *Warranty* | 3 Years Limited & Free Technical Support (US Only) |

HomePlug™

# 12 References

[1] EN 50 065-1, "Signalling on low voltage electrical installations in the frequency range 3 kHz to 148.5 kHz; Part 1: General requirements, frequency bands and electromagnetic disturbances", CENELEC, Brussels, 1991

[2] CENELEC, European Committee for Electrotechnical Standardization, http://www.cenelec.org/Cenelec/CENELEC+in+action/Horizontal+areas/ICT/SC205A.htm, accessed July 2003

[3] IEEE Standards Online Power Systems Communication Standards, http://standards.ieee.org/catalog/olis/psystcomm.html, accessed August 2003

[4] Dr. Michael Propp, "The Use of Existing Electrical Powerlines for High Speed Communications to the Home", http://ksgwww.harvard.edu/iip/doeconf/propp.html, accessed March 2003

[5] IEC – International Electrotechnical Commission, http://www.iec.ch, accessed August 2003

[6] Stefan Ramseier et al., "MV and LV Powerline Communications: New Proposed IEC Standards", 0-7803-5515-6/99, IEEE,1999

[7] PLC Forum, http://www.plcforum.com, accessed August 2003

[8] ETSI – Telecom Standards, http://www.etsi.org, accessed August 2003

[9] Regis J. Bud Bates et al., "Voice and Data Communications Handbook", ISBN-0-07-213188-8, Osborne/McGraw-Hill, 2001

[10] Fredrik Roos, "Powerline Communication in Train Control Systems", Master Thesis, KTH, Stockholm, 2000

[11] Understanding Telecommunications, http://www.ericsson.com/support/telecom/, Ericsson, STF, Studentlitteratur, 2002

[12] ABCs of Spread Spectrum, http://www.sss-mag.com/ss.html, accessed July 2003

[13] Owen Rubin, "Plug Into Home Networks", IEEE Spectrum, June 2002, pp 60-62

[14] "Intellon High Speed Power Line Communications", White Paper, Intellon Corporation, July 1999

[15] Amit Dhir et al., "Home Networking Using No New Wires Phoneline and Powerline Interconnection Technologies", White Paper, WP133 v1.0, Xilinx Inc., March 2001

[16] "Powerline Telecommunications (PLT); Coexistence of Access and In-House Powerline Systems", Technical Specification, ETSI TS 101 867 v1.1.1 (2000-11)

[17] ”Powerline Telecommunications (PLT); Reference Network Architecture Model; PLT Phase 1”, Technical Specification, ETSI TS 101 896 V1.1.1 (2001-02)

[18] “Powerline Telecommunications (PLT); Quality of Service (QoS) requirements for in-house systems”, Technical Report, ETSI TR 102 049 V1.1.1 (2002-05)

[19] Echelon Corporation, http://www.echelon.com/, accessed June 2003

[20] “LonWorks Technology Overview”, Technical Document, Echelon Corporation

[21] “LonTalk Protocol”, Echelon Engineering Bulletin 005-0017-01, 27 pages, Echelon Corporation

[22] “LonTalk Protocol Specification”, Echelon Manual 078-0125, 114 pages, Echelon Corporation

[23] “LonWorks Network Services (LNS) Architecture Strategic Overview”, Echelon Corporation

[24] “LonMark Layer 1-6 Interoperability Guidelines”, 078-0014-01, Echelon Corporation

[25] LonMark Interoperability Association, http://www.lonmark.org/, accessed July 2003

[26] Peter House, “CEBus for the Masses”, Technical Article #0593, Intellon Corporation

[27] Grayson Evans, “The CEBus Communication Standard”, Part 1 & 2, Intellon Corporation

[28] Frameset for CEBus Users Group, http://www.cebus.org/, accessed July 2003

[29] “CEBus Power Line Encoding and Signaling”, White Paper #0027, Intellon Corporation

[30] Denny Radford, “New Spread Spectrum Technologies Enable Low Cost Control Applications For Residential And Commercial Use”, Intellon Corporation

[31] Vander Mey, J.E., "Spread Spectrum Communications for the CEBUS Powerline", Consumer Electronics, 1990. ICCE 90. IEEE 1990 Intl. conf., June 6-8, 1990, pp. 240 -241

[32] “Phase Coupling for Power Line Communications”, Application Note #0050, Intellon Corporation

[33] Danny Radford, “Spread-Spectrum Data Leap Through AC Power Wiring”, Intellon Corporation

[34] M.H. Shwedi, A.Z.Khan, "A Power Line Data Communication Interface Using Spread Spectrum Technology In Home Automation", IEEE Transactions on Power Deliver, Vol. 11., July 1996

[35] Jeff Tyson, “How Power-line Networking Works”, http://www.howstuffworks.com, accessed June 2003

[36] Dave Rye, “The X-10 POWERHOUSE Power Line Interface Model # PL513 and Two-Way Power Line Interface Model # TW523”, Technical Note, Revision 2.4, X-10 (USA) Inc.

[37] Anish Arora, Rajesh Jagannathan, Yi-King Wang, "Model-based Fault Detection in Powerline Networking", Proceedings of the International Parallel and Distributed Processing Symposium (IPDPS'02), IEEE, 2002

[38] Micheal J. Riezenman, "Networks for Homes", IEEE Spectrum, Vol. 36, December 1999

[39] X10 Technology, http://www.x10.com/technology.htm, accessed July 2003

[40] PowerPacket™ Primer, Rev 2.0, http://www.intellon.com, Intellon Corporation

[41] Intellon: PowerPacket FAQs, http://www.intellon.com/support/powerpackfaqs.html, accessed July 2003

[42] Steve Gardner, Brian Markwalter et al., "HomePlug Standard Brings Networking to the Home", "http://www.commsdesign.com/main/2000/12/0012feat5.htm", accessed March 2003

[43] Cogency Semiconductor Inc., http://www.cogency.com, accessed July 2003

[44] "Data Communications over Power Lines", White Paper, Cogency Semiconductor Inc.

[45] Michael Propp et al., "The Powerline as the High-Speed Backbone of a Home Network", Technical Document, Adaptive Networks Inc.

[46] HomePlug Powerline Alliance, http://www.homeplug.org, accessed July 2003

[47] HomePlug-certified Products, http://www.homeplug.com/products/, accessed July 2003

[48] Gary Arlen, "Extending the Power of Broadband", White Paper, Ucentric Systems LLC, 2000

[49] Powerline System Overview, http://www.abb.de/plc, ABB New Ventures GmbH, accessed March 2003

[50] Dave Marples, Stan Moyer, "In-Home Networking", Guest Tutorial, IEEE Communications Magazine, Vol. 40 No. 4, April 2002

[51] Sandy Teger et al., "End-User Perspectives on Home Networking", IEEE Communications Magazine, Vol. 40 No. 4, April 2002

[52] Cable Testing Standards, http://www.cabletesting.com/CableTesting/Standards/Overview.htm, accessed August 2003

[53] HomePNA – Home Phoneline Networking Alliance, http://www.homepna.org/, accessed August 2003

[54] Consumer Electronics Association, R7 Home Network Committee, http://www.ce.org/standards/committees/view_committee_details.asp?DivisionID=13&CommitteeID=10052947, accessed August 2003

[55] HomeCNA | Standards & Protocols, http://www.caba.org/standard/homecna.html, accessed August 2003

[56] Johan De Vriendt et al., ”Mobile Network Evolution: A Revolution on the Move”, IEEE Communications Magazine, Vol. 40 No. 4, April 2002

[57] IEEE Standards “Get IEEE 802” ™: Wireless (IEEE 802.11), http://standards.ieee.org/getieee802/802.11.html, accessed August 2003

[58] HomeRF Resource Center, http://www.palowireless.com/homerf/, accessed August 2003

[59] The Official Bluetooth Wireless Info Site, http://www.bluetooth.com/, accessed August 2003

[60] Bluetooth Wireless Technology, http://www.ericsson.com/technology/tech_articles/Bluetooth.shtml, accessed August 2003

[61] HiperLAN2 Global Forum, http://www.hiperlan2.com/, accessed August 2003

[62] UWB Ultra Wideband Resource Center, http://www.palowireless.com/uwb/, accessed August 2003

[63] Khurram Hussain Zuberi, “Broadband Wireless Access Systems”, http://www.it.kth.se/~iw01_zkh/deliverables/Broadband_Wireless_Access_Systems.pdf, Project Report, June 2003

[64] PowerLine Networking, http://www.linksys.com/edu/page13.asp, accessed July 2003

[65] Lars Selander, “Power-Line Communications - Channel Properties and Communication Strategies”, Ph.D. Thesis, Lund University, 1999

[66] Olaf Hooijen, “Aspects of Residential Power Line Communications”, Ph.D. Thesis, Shaker Verlag GmbH, ISBN 3-8265-3429-8, 1998

[67] L.M. Millanta et al., ”A Classification of the Power-Line Voltage Disturbances for an Exhaustive Desription and Measurement”, Proceedings of the IEEE National Symposium on Electromagnetic Compatibility, Denver, CO, USA, pp. 332-226, May 1989

[68] R.M. Vines et al., “Noise on the residential power distribution circuits”, IEEE Transactions on Electromagnetic Compatibility, Vol. 26. No. 4, pp. 161-168, November 1984

[69] J.R.Nicholson et al., “RF Impedance of Power Lines and Line Stabilization Networks in Conducted Intereference Measurments”, IEEE Transactions on Electromagnetic Compatibility, Vol. 15, pp. 84-86, May 1973

[70] J.A Malack et al., ”RF Impedance of United States and European Power Lines”, IEEE Transactions on Electromagnetic Compatibility, Vol. 18, No. 1, pp. 36-38, February 1976

[71] M. Tanaka, "High Frequency Noise Power Spectrum, Impedance and Transmission Loss of Power Line in Japan on Intrabuilding Power Line Communications", IEEE Transactions on Consumer Electronics, Vol. 34, No. 2, pp. 321-326, May 1988

[72] R.M. Vines et al., "Impedance of the Residential Power-Distribution Circuit", IEEE Transactions on Electromagnetic Compatibility, Vol. 27, No. 1, pp. 6-12, February 1985

[73] Weilin Liu et al., "Nature of Power Line Medium and Design Aspects for Broadband PLC System", 0-7803-5977-1/00, IEEE, 2000

[74] Dan Raphaeli, Evgeni Bassin, "A Comparison between OFDM, Single Carrier, and Spread Spectrum for high Data Rate PLC", http://www.itrancomm.com/White_OFDM_4_99.html, Itran Communications, April 1999

[75] OFDM Communications Primer, White Paper #0032, Rev. 5, http://www.intellon.com, Intellon Corporation, March 1999

[76] GigaFast Ethernet, http://www.gigafast.com/products/homeplug.htm, accessed March 2003

[77] Phonex Broadband, http://www.phonex.com/prd_overview.htm, accessed March 2003

[78] SpeedStream.com, http://www.speedstream.com/products_powerline.html, accessed March 2003

[79] Linksys, http://www.linksys.com/products/, accessed March 2003

[80] NETGEAR, http://www.netgear.com/products/homewiring/powerline.asp?view=hm, accessed March 2003

[81] Asoka USA, http://www.asokausa.com/products/, accessed March 2003

[82] IOGEAR: Expand Your Connectivity, http://www.iogear.com/products/productselect.php?Category=SOHO%20Networking, accessed March 2003

[83] ST&T Group - iPower Point Powerline Network, http://www.stt.com.tw/products_plc.htm, accessed March 2003

[84] Telkonet Communications, http://www.telkonet.com/, accessed March 2003

[85] Corinex Global, http://www.corinex.com/web/doccx.nsf/(w)/products?Open, accessed March 2003

[86] Khurram Hussain Zuberi, Product Specifications Paper, http://www.it.kth.se/~iw01_zkh/deliverables.html, March 2003

[87] Bill Rose, "Home Networks: A Standard Perspective", IEEE Communications Magazine, December 2001

[88] R7-Consumer Electronic Association (CEA) Standards & Protocols, http://www.caba.org/standard/cea.html, accessed May 2003

[89] Consumer Electronics Association TechHome Guide to Home Networks, http://www.ce.org/publications/books_references/techhome/home/network_structure/standards/no_new_wires.asp, accessed May 2003

[90] CNet Labs Test, Siemens SpeedStream 2524 Powerline Wireless DSL/Cable Router, http://reviews.cnet.com/4505-3334_7-20786387-4.html, accessed August 2003

[91] M.K. Lee, S. Katar et al., "Field Performance Comparison of IEEE 802.11b and HomePlug 1.0", Proceedings of the 27th Annual IEEE Conference on Local Computer Networks, LCN'02, IEEE, 2002

[92] Java 2 Platform Standard Edition, http://java.sun.com/j2se/1.4.1/download.html, accessed September 2003

[93] Customer Fact Sheet on Removal of Java from Windows, http://www.microsoft.com/windowsxp/pro/evaluation/news/jre.asp, accessed September 2003

[94] Khurram Hussain Zuberi, Project Plan - PLC Communication Systems Thesis, http://www.it.kth.se/~iw01_zkh/deliverables.html, January 2003

[95] Phonex Network Administration Control, http://www.phonex.com/downloads/nw14.html