Power Line Communications: An Overview – Part I

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Abstract

We give an overview of the Power Line Communications (PLC) technology, its importance, its standards and an overview of the HomePlug standards associated with it. This is done is two parts due to publication constraints. In this part, we will concentrate on the PLC applications and the technical issues regarding it. We will also see the layers and methods that are needed to make it work.

Keywords: ***Latest technology, Power Line Communications, PLC, Standards, HomePlug 1.0, HomePlug AV.***

1. Introduction

Power lines were originally devised to transmit electric power from a small number of sources (the generators) to a large number of sinks (the consumers) in the frequency range of 50-60 Hz. It is a fact that power transmission towers and lines are some of the most robust structures ever built. Historically, the PLC technology has very limited applications but now we are witnessing the possibility of it being acclaimed universally as a prime mode of long-haul data communication.

With the inevitable arrival of broadband access, the demand for sending digital voice, video and Internet data within the home increases continuously. While retrofitting the houses and neighborhoods with special wires is one option, it is expensive and time consuming. PLC Technology allows the use of the existing and widespread power distribution infrastructure to provide high speed networking capabilities along with many other benefits.

Section 2 gives a brief application history and the shining prospects of PLC technology. Section 3 discusses the technical issues in PLC, its layers and protocols. The second part of this overview will focus on the standards and the HomePlug standards.

2. A Treatise on PLC Applications

2.1. A Bit of History

Initially, the first application involving data transmissions over power lines were primarily done only to protect sections of the power distribution system in case of faults. (In fact, power line protection remains one of the primary functions of power line communications.) In such an event, the fast exchange of information is necessary between power plants, substations and distribution centers so as to minimize their detrimental effects. The robustness of the power lines and their ready connectivity and availability make this technique an optimal solution.

Narrowband power line communications started soon after the beginning of wide-spread electrical power supply. Around the year 1922 the first carrier frequency systems began to operate over high-tension lines in the frequency range 15 to 500 kHz for telemetry purposes, and this continues to the present time [1]. Consumer products such as baby alarms have been available at least since 1940. [2]

Historically, also, a primary motivation for power line communications has been to do load management in future. The currently employed ripple control systems have the disadvantage of requiring several megawatts for information transmission. A second important motivation has been to facilitate meter reading from a distance. An English study has shown that a meter reader achieves an average information rate of only about 1 bit/s [3]. The Tokyo Electric Power Co was running experiments in the 1970's which reported successful bi-directional operation with several hundred units [4].

Considering that data transmission over power lines has been around for quite some time, one might wonder why it is receiving such renewed attention recently especially considering the data rate for protection and telemetering purposes is at most a few kb/sec and is not comparable to the Mb/sec data that needs to be supported for multimedia applications? The answer is a combination of effects that took place during the mid thru late 1990s, namely, the explosive

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growth of the Internet and the gigantic leaps in VLSI (Very Large Integrated Circuits) and DSP (Digital Signal Processing) technology. Then was the telecommunications market deregulation, first in the US and then in Europe and Asia. All these events have made power line communications a viable technology for numerous other applications.

2.1.1. Home Automation. Power line communications technology can use the household electrical power wiring as a transmission medium. This is a technique used in home automation for remote control of lighting and appliances and sensors for alarm systems etc without installation of additional control wiring. This is primarily based on the X10 Industrial Standard and has been in development since 1975. A detailed article on this standard and its application can be found in [5].

2.1.2. Home Networking and Internet Access (Broadband over Power Lines, BPL). It follows that we can use the low voltage power network as a Local Area Network (LAN) for conveniently connecting many different computers in the same building. With multiple outlets in every room, residential power lines are already the most pervasive network in the home. Using this existing infrastructure to provide high speed networking capabilities provides several benefits. First of all, there is no need for expensive rewiring of the house. Secondly, almost all devices that need to be networked are already connected to the AC wiring. Thus, home networking becomes as simple as plugging the device in the AC outlet.

The market for PLC for consumers is thus two-fold: to the home, or "last mile" access; and in the home, or "last inch" access. [6]

The development of the "last inch" by Home-networking companies in the form wireless network adapters and power-line adapters is gradually leading to widespread home networking; i.e., a wide array of devices connected inside the home in an intra-home network. This "in-home networking" could transform all power outlets in the household into broadband connections for PCs, telephones and their accessories, as well as other 'enabled' electric appliances.

Figure 1 illustrates the concept of "last inch" or in-home networking, while Figure 2 illustrates the "last mile" concept.

Broadband over power lines (BPL), also known as power-line internet or Powerband, is the use of PLC technology to provide broadband Internet access through ordinary power lines. A computer (or any other device) would need only to plug a BPL "modem" into any outlet in an equipped building to have high-speed Internet access.

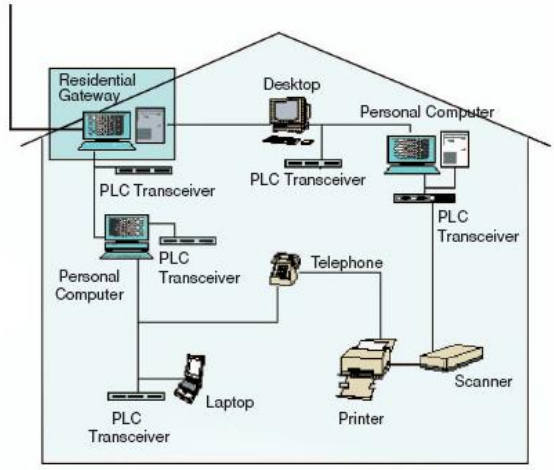

Figure 1: The "last-inch" networking through PLC.

However, due to several issues hampering the implementation and usefulness of BPL, one possible alternative is to use BPL as the backhaul for wireless communications, by for instance hanging Wi-Fi access points or cellphone base stations on utility poles, thus allowing end-users within a certain range to connect with equipment they already have. In the near future, BPL might also be used as a backhaul for WiMAX networks.

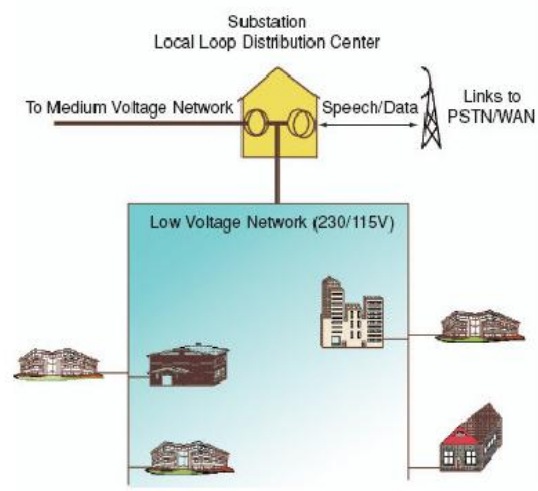

Figure 2: The "last-mile" broadband access to homes and offices through the local power distribution center.

Much higher speed transmissions using microwave frequencies transmitted via a newly discovered surface wave propagation mechanism called E-Line have been demonstrated using only a single power line conductor. These systems have shown the potential for symmetric and full duplex communication well in excess of 1 Gbit/s in each direction [7].

Multiple WiFi channels with simultaneous analog television in the 2.4 and 5.3 GHz unlicensed bands have been demonstrated operating over a single medium voltage line. Furthermore, because it can operate anywhere in the 100 MHz - 10 GHz region, this technology can completely avoid the interference issues associated with utilizing shared spectrum while offering the greater flexibility for modulation and protocols found for any other type of microwave system.

At present there is no universal standard for power line communication for this purpose. However, HomePlug Powerline Alliance has defined enduring standards, the detailed exposition of which is in Sections 5 and 6.

2.1.3. Narrowband PLC - Radio Broadcasting. PLC for radio transmission was and is widely used in Germany (Drahtfunk), Switzerland (Telefonrundspruch), Norway (Linjesender), USSR and some other countries. In all cases the radio program was fed by special transformers into the lines. In order to prevent uncontrolled propagation, filters for the carrier frequencies of the PLC systems were installed in substations and at line branches. The narrowband powerline communications channel presents many technical challenges. A mathematical channel model and a survey of work can be found in [8].

2.1.4. Automotive. Power-line technology enables in-vehicle network communication of Data, Voice, Music and Video signals by digital means over Direct Current (DC) battery power-line. Advanced digital communication techniques tailored to overcome hostile and noisy environment are implemented in a small size silicon device. One power line can be used for multiple independent networks.

Prototypes are successfully operational in vehicles using automotive compatible protocols such as CAN-bus, LIN-bus over power line (DC-LIN) and DC-bus developed by Yamar. Automotive applications include Mechatronics (e.g. Climate controls, Door modules, Immobilizers, Obstacle detectors), Telematics and Multimedia.

2.1.5. Further Reading on Specific Applications. Nowadays, we are seeing novel applications being developed using PLC and there is a wealth of literature available on the topic. The demand for home automation systems / intelligent homes has fueled much research and practical intelligent homes have been designed, as in [9]. Cavdar has presented a solution to remote detection of illegal electricity usage in [10]. The quality of power can also be measured using PLC [11].

3. Issues in PLC

3.1. The Powerline Channel as Transmission Medium

3.1.1. Design. First off, the power line carrier was not specifically designed for data transmission and provides a harsh environment for it. Varying impedance, considerable noise that is not white in nature and high levels of frequency-dependent attenuation are the main issues.

3.1.2. Varying Channel Model. For successful communication, the communication channel must be first modeled and analyzed accordingly. The channel between any two outlets in a home has the transfer function of an extremely complicated line network. Power line networks are usually made of a variety of conductor types, joined almost at random, and terminating into loads of varying impedance. Over such a transmission medium, the amplitude and phase response may vary widely with frequency. While the signal may arrive at the receiver with very little loss over some frequencies, it may be completely indistinguishable over other frequencies. Worse, the channel transfer function itself is time varying since plugging in or switching off of devices connected to the network would change the network topology. Hence, the channel may be described as random and time varying with a frequency dependent signal to noise ratio (SNR) over the transmission bandwidth.

A detailed discussion of modeling with mathematical treatment for a Power Line Channel is given in [12]. The signal propagation modeling in PLC networks is given in [13].

3.1.3. High Dependence of Transmitter and Receiver Location. The location of the transmitter or the receiver (in this case the power outlet) could also have a serious effect on transmission error rates. For example, a receiver close to a noise source would have a poor signal to noise ratio (SNR) compared to one further away from the noise source. The noise sources could be home devices plugged into the network.

3.1.4. Reflection, Multi-path Fading and Attenuation. Just like a wireless channel, signal propagation does not take place between the transmitter and the receiver along a line-of-sight path. As a result, additional echoes must be considered. This echoing occurs because a number of propagation paths

exist between the transmitter and the receiver. Reflection of the signal often occurs due to the various impedance mismatches in the electric network. Each multi-path would have a certain weight factor attributed to it to account for the reflection and transmission losses. All reflection and transmission parameters in a power line channel may be assumed to be less than one. The number of dominant multi-paths to be considered (N) is often not more than five or six since additional multi-paths are usually too weak to be of any significance. This is because the more transitions and reflections that occur along a path, the smaller its weighting factor would be. It has been observed from channel measurements that at higher frequencies the channel attenuation increases.

3.1.5. Noise. Noise in power lines is a significant problem for data transmission. This is because it rarely has properties similar to the easily analyzed white Gaussian noise of the receiver with which we are much familiar with. Typical sources of noise are brush motors, fluorescent and halogen lamps, switching power supplies and dimmer switches. Apart from these, ingress sources such as amateur radio transmission can render certain frequencies unfit for communication. The noise in power lines can be impulsive or frequency selective in nature and, sometimes, both. Due to high attenuation over the power line, the noise is also location dependent.

Recent studies have indicated that the noise in PLC systems can be typified into four categories.

i. Colored noise: This type of noise has relatively low power spectral density (psd) which decreases with increasing frequency. It is considered to be the sum of all low power noise sources and may be time varying.

ii. Narrowband background noise: This noise is mainly due to amplitude modulated sinusoidal signals. This kind of interference is from broadcast stations in the medium and short wave bands. The interference level varies during different times of the day.

iii. Impulse noise that is synchronous with the generator's actual supply frequency: This type of impulse noise usually repeats at multiples of the supply frequency of 60/50Hz. It has a short duration of about a few microseconds and a power spectral density that decreases with increasing frequency. The noise is caused from power supplies operating synchronously to the main's frequency.

iv. Impulse noise asynchronous with the main's frequency: This is the most detrimental type of noise for data transmission. Its duration varies from a few microseconds to milliseconds and has a random inter-arrival time. The psd of such impulse noise may be as much as 50dB above the background noise spectrum. Hence, it is capable of wiping out blocks of data symbols during high data transmission at certain frequencies. It is caused from switching transients in the system network.

With this discussion we are ready to generalize a PLC system into a model as shown in block diagram form in figure 3.

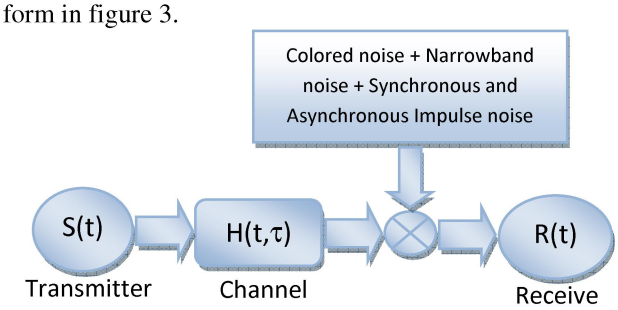

Figure 3: General block diagram for PLC systems.

3.2. Layers, Access Methods and Protocols.

The communication in power lines can be divided into two main layers: The *Physical Layer* and the *Medium Access Control (MAC) Layer*.

The Physical Layer defines the modulation techniques to transmit data over the power lines while the MAC protocol specifies as resource sharing strategy i.e. the access of multiple users to the network transmission capacity based on a fixed resource sharing protocol. Communicating at the PLC Physical Layer demands robust modulation techniques like Frequency Shift Keying (FSK), Code-Division Multiple Access (CDMA) and Orthogonal Frequency Division Multiplexing (OFDM). For low cost, low data rate applications, such as power line protection and telemetering, FSK is seen as a good solution. For data rates up to 1Mbps, the CDMA technique may provide an effective solution. However, for high data applications beyond that, OFDM is the technology of choice for PLC. For MAC, there are generally two categories of access schemes.

3.2.1. Fixed Access. It assigns each user a predetermined or fixed channel capacity irrespective of whether the user needs to transmit data at that time. Such schemes are not suitable for traffic in bursts, such as data transmission that is provided by PLC.

3.2.2. Dynamic Access. These protocols may be classified into two separate categories: Contention based protocols where collisions occur and Arbitration protocols which are collision free.

Contention protocols may not be able to guarantee a quality of service (QoS), especially for time critical applications, since collisions might occur and data might have to be retransmitted. Arbitration based

protocols are more capable of guaranteeing a certain QoS. However, contention based protocols may actually provide higher data rates in applications which do not have stringent QoS requirements (e.g., Internet applications). This is because they require much less overhead compared to arbitration protocols (polling, reservation, token passing).

The widely studied protocols for MAC Layer in PLC are.

3.2.3. Polling. It is a primary/secondary access method in which the primary station asks the secondary station if it has any data to send. Arbitration based polling can handle heavy traffic and does provide QoS guarantees.

3.2.4. Aloha. It is a random access protocol in which a user accesses a channel as soon as it has data to send.

3.2.5. Token passing schemes. These schemes, e.g. token ring, token bus, are efficient under heavy symmetric loads. However, they can be expensive to implement and can cause serious problems with lost tokens on noisy unreliable channels such as PLs.

3.2.6. Carrier Sense Multiple Access (CSMA). CSMA with overload detection has been proposed for PLC. CSMA is a contention based access method in which each station listens to the line before transmitting data. CSMA is efficient under light to medium traffic loads and for many low-duty-cycle bursty terminals (e.g. Internet browsing).

i. Collision Detection (CSMA/CD) senses the channel for a collision after transmitting. When it senses a collision, it waits a random amount of time before retransmitting again. But on power lines the wide variation of the received signal and noise levels make collision detection difficult and unreliable.

ii. Collision Avoidance (CSMA/CA). As in the CSMA/CD method, each device listens to the signal level to determine when the channel is idle. Unlike CSMA/CD, it then waits for a random amount of time before trying to send a packet. Packet size is kept small due to the PLC's hostile channel characteristics. Though this means more overhead, overall data rate is improved since it means less retransmission.

CSMA/CA is used in HomePlug Standards and we will talk about it in more detail in part II of this paper. For further details of all of the other protocols, see [14].

4. Conclusion

In this overview, we have seen the evolution and potential of PLC technology and have gained some idea of the structure of the standards involved with it. We will discuss the more important technical issues related to the standards in Part II.

5. Acknowledgment

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