A Power Line Communication Network Infrastructure for The Smart Home

Yu-Ju Lin, Haniph A. Latchman and Minkyu Lee
Electrical and Computer Engineering Department
University of Florida
Gainesville, FL 32611
and
Srinivas Kata
Intellon Corportion
Ocala, Florida

Abstract

Low voltage electrical wiring in homes has largely been dismissed as too noisy and unpredictable to support high speed communication signals. However, recent advances in communication and modulation methodologies as well as in adaptive digital signal processing and error detection and correction have spawned novel media access control (MAC) and physical layer (PHY) protocols, capable of supporting power line communication networks at speeds comparable to wired local area networks (LANs). In this paper we motivate the use of power line LAN's as a basic infrastructure for building integrated ”smart homes,” wherein information appliances (IA)—ranging from simple control or monitoring devices to multimedia entertainment systems—are seamlessly interconnected by the very wires which provide them electricity. By simulation and actual measurements using ”reference design” prototype commercial powerline products, we show that the *HomePlug* MAC and PHY layers can guarantee QoS for real-time communications, supporting delay sensitive data streams for ”Smart Home” applications.

Keywords

Power Line Communication, Home Networks, Multimedia, Real-time Traffic, Congestion.

I. Introduction

Many next-generation appliances are being equipped with processors featuring sophisticated communication capabilities.. For instance, on April 7, 2001, IBM and Carrier announced plans to produce an air conditioner with JAVA support that can E-mail manufacturers regarding errors, and will allow users to remotely send commands to the unit to adjust temperatures or shut it down. *“Smart Homes”* will eventually have many types of information appliances (IA’s) communicating among themselves and with the outside world. Soon, many of these IA devices are expected to have multimedia capability. Supporting multimedia communication for these IA devices will be of crucial importance for the intelligent homes of the future.

Providing the right infrastructure for connecting these IA devices will be a major need. For home applications, this infrastructure must be: easy to setup, inexpensive to install and maintain and must perform well. Ordinary people are not network experts, and a typical high performance network is too complicated for casual daily usage. The supporting infrastructure should be as easy to set up and the effort to maintain this infrastructure should be minimal. Many existing networking technologies compete to support this mission. For example, a comprehensive Ethernet network can be constructed by installing UTP-5 special cabling around the house. Alternatively, wireless networks such as *802.11x*, *Bluetooth*, and *HomeRF* can be constructed by installing multiple interconnected wireless access points(WAP) and base stations within the home. However, the IA devices themselves would need wireless capabilities, and the above three infrastructures all require a significant effort and cost to build up the networks externally. Phone line networks such as *HomePNA*[1] may seem attractive, but the convenience of mobility is limited by available phone sockets in a home. An extensive study of other infrastructure options and technologies appropriate for a home network is given in [2].

In this paper, we advocate the direct use of the existing electrical wiring and outlets as the medium for data communication within the home. Using power lines as the network infrastructure has many advantages over other technologies. First, no new wires are needed since the IA devices will communicate over the very wires which provide them electrical power. Second, there are many access points (power sockets) in a home (4 or more per room). Currently, *Power*

TABLE I
TECHNOLOGY COMPARISON

Technology	Media	Data rate	QoS Support	Cost
10 Base T	UTP	10 Mbps	No	$20
100 Base T	UTP	100 Mbps	No	$80
Bluetooth	Wireless	1 Mbps	Yes	$5
HomeRF 2.0	Wireless	10 Mbps	Yes	$110
802.11x	Wireless	11 Mbps	No	$125
HomePNA 2.0	Phone line	10 Mbps	No	$80
HomePlug	Power line	15 Mbps	Yes	$120

Line Communication (PLC) as specified by the *HomePlug* 1.0 standard [3] provides a 14 Mbps raw data rate, which is adequate for daily IA device communication. It also has a built-in QoS protocol, making it attractive for real-time streaming applications and it is planned ot provide 100Mbps PLC services to support high quality digital multimedia. Finally, the cost to build a power line network is low when compared with other technologies. For example, it was observed that the *802.11x* wireless network card has approximately the same street price as the *HomePlug* network card (about $120). It is expected that with mass production requiring no expensive RF components, the cost of the PLC cards will be about 50% less than comparable wireless cards. Moreover, the cost of a required *802.11x* base station is high (more than $250). *100 Base T Ethernet* has the highest performance/cost ratio, but requires new cables and expensive installation. Table I shows costs and other various characteristics of a home network technologies. Installation costs which are high for 10/100 BT are not shown.

From a marketing perspective, the less expensive and easier to use PLC home network is becoming more attractive and the potential market is huge. The Yankee Group estimates that at least 21 million households in the United States are interested in home networking and that 12.4 million would like to implement in-home networks within the next year. According to Parks Associates, 30 million households in the United States will have fast internet connections by 2004, and 17 million of them plan to have home networks.

In the past, power lines were considered unacceptable for signal transmission, since the channel contained a lot of noise, interference, and fading. However, the appeal of using the existing power line as a transmission medium for data exchange was too great to be ignored. The advancement of signal modulation technologies, digital signal processing, and error control coding [5] has minimized the restrictions of channel imperfections, and high speed signal transmission through power lines is now feasible [3].

Using the existing power line infrastructure as the medium for supporting IA communication requires a careful design of the overlaid communication systems in order to provide acceptable communication services. It is desired, for example, that when watching digital TV while downloading data from the web, there will be no delay-jitter in the video quality. Current research shows the maximum raw data rate of first generation PLC is about 14 Mbps [3]. However, the effective data rate is expected to be around 10 Mbps after compensation for impairments and error corrections. On the other hand, research is currently underway to develop PLC chips which operate at 100 Mbps with average throughput of the range of 30-60 Mbps.

In this paper, we investigate the performance of multimedia over power line networks using simulation studies and actual measurements on a *Homeplug* 1.0 compliant PLC network. We are particularly interested in measuring the PLC network raw data rate, TCP performance, and the performance impact when QoS support is involved. We are also interested in analyzing the network performance with different traffic types, including continuous media data streams (i.e., soft real-time traffic).

We first built a network simulator that generates various types of traffic, and then applied the same scenarios to a real-world PLC network and to a simulation model. The performance comparison between the simulation results and real-world performance are given in this paper. A maximum throughput of 8.08 Mbps for UDP was obtained from our simulation, while a 6.21 Mbps TCP throughput was observed in the real-world PLC network experiment. The results show that PLC networks can successfully deliver real-time traffic concurrently with traditional data traffic.

Our contributions in this paper also include modelling human behavior in the use of IA devices, modelling the types of traffic generated by IA devices communicating over the power line, and measuring the performance of real applications over PLC networks. We also give a description of a practical implementation of the PHY and MAC layers for PLC networks as well as associated simulation results.

The next section discusses the background for implementing power line communication networks, typical applications of power line communication networks, and the human behavioral model using these appliances. Section 3 presents the physical limitations of power line channels, and describes a practical signal modulation scheme and MAC protocol as used in the *HomePlug* 1.0 protocol proposed by the *HomePlug Powerline Alliance*. Section 4 compares the simulation results with real world PLC network performance. Finally, Section 5 contains some conclusions and suggestions for future work.

II. Applications over Power Line Communication

A. Power Line Communication Application In A Home

Traditionally, power lines are used for conveying electrical power to devices. Power lines were not designed for delivering high frequency signals, and so the electrical and frequency response requirements of a power line are not as critical as those of data network cabling. The poor quality of a power line is not ideal for signal transmission because the channel contains noise and interference. The medium is made of different conductor types, therefore a variety of characteristic impedances will be encountered. Further, the network terminal impedance will tend to vary with frequency and time as the consumer's load pattern and load types vary. Impedance mismatch causes a multi-path effect resulting in deep notches at certain frequencies. These channel imperfections make signal modulation over a power line difficult [4]. However, the advancement of signal modulation and error control coding techniques now make power line communication possible.

The common power line topology of a North American home is depicted in Figure 1. The figure shows a tree-like power line topology in a house. Typically, there are two power line trunks, one being 110V and the other being 220V. Each power line trunk can be divided into several branches. Power line communication aims to transmit data packets over these branches and trunks. The topology of the power line network and the convenience of its power sockets as potential access points make it a good candidate for smart home IA device networking.

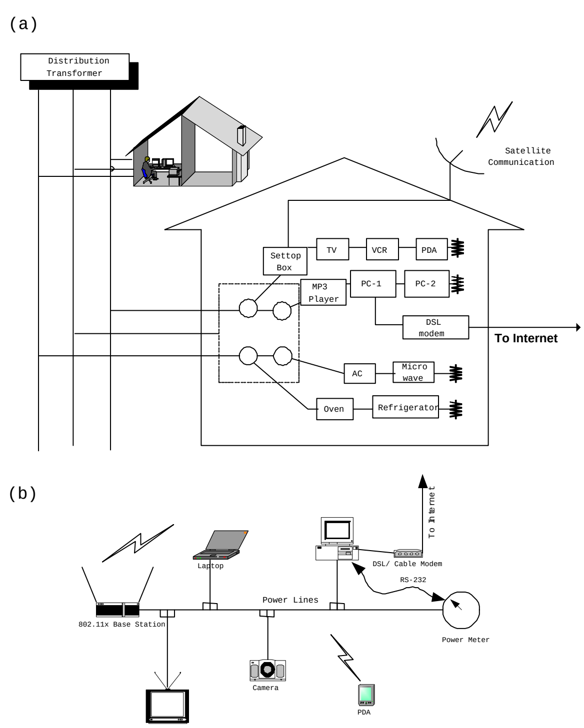

Fig. 1. a).Power Line Topology In A North American Home b). An example of using one of the computers as the PLC, DSL or Cable Modem router

Table II shows the results of a survey from which we inferred usage and traffic patterns generated by typical IAs. The table also suggests some current and future PLC applications. For instance, when merchandize is advertised on a digital TV service, the product information (such as the barcode or webpage) can be downloaded to your computer through a power line. Afterwards, you can send your order information from the computer to the supplier or you can use the downloaded URL to browse the product web page and get more details. We also anticipate the ability to record music or videos through a power line. For example, when a song is broadcast on TV or a music channel, you can download the song directly to an MP3 player through the power line. Another application is the opportunity to record digital video directly into a PC or even a digital VCR.

TABLE II

APPLICATION TRAFFIC AMOUNT IN A HOME

Row No.	From Node	To node	Estimated data size	Frequency	Possible time period
1	Refrigerator	Microwave	160 bytes	2 times a period	7:00-9:00,11:00-1:00, 17:00-19:00,21:00-23:00
2	Microwave	AC	72 bytes	2 times a day	7:00-9:00,11:00-1:00, 17:00-19:00,21:00-23:00
3	TV	Refrigerator	750 bytes	3 times a day	11:00-1:00,17:00-23:00
4	TV	VCR	11KBytes	3 times a day	11:00-1:00,17:00-23:00
5	TV	Computer	360 bytes	3 times a day	11:00-1:00,17:00-23:00
6	TV or Settop box	PDA or MP3 player	15 Mega bytes	3 times a day	11:00-1:00,17:00-23:00
7	Computer	PDA or MP3 player	50 Mega bytes	1 time a day	11:00-1:00,17:00-23:00
8	Computer	Computer	60 MB to 180 MB	1 time a day	6:00-24:00
9	Settop box	Computer	320 MB to 640 MB	1 time a day	11:00-1:00,17:00-23:00
10	Computer	Internet	44 MB to 131 MB	1 time a day	11:00-1:00,17:00-23:00
11	VCR	Computer	320 MB to 640 MB	1 time a day	6:00-24:00
12	Front door camera	Computer	110 MB to 1100 MB	3 times a day	6:00-24:00

Other applications of IA's can be easily accomplished using a PLC network. For example, a refrigerator can order food through the power line network according to its inventory, or it can send cooking instructions to the microwave. A smart oven can send predicted environmental temperature information to the air conditioner through a power line, allowing the air conditioner to pre-adjust the temperature and keep rooms comfortable.

The applications over PLC are not only for novel IA devices. PLC as a home network facilitates data exchange between traditional data processing devices such as PCs and computer peripherals. IA devices that talk with PCs are also possible. For example, sending multimedia data from TVs or VCRs to PCs can be easily done by PLC network, but is difficult with other infrastructure technologies. Home security can also be implemented by PLC so that a digital camera installed on the front door can send video to the TV.

Table II also gives an estimate of the daily traffic volume generated by typical IA applications. These values are based on likely information size. For example, the instruction size that the refrigerator sends to the microwave in row 1 is estimated by the number of steps required to cook the food (1 byte), the cooking time for each step (4 bytes for each step), the power level for each step (2 bytes), and the packet header size. Added together, the entire instruction size is 160 bytes. Row 7 exemplifies storing digital music from a computer to an MP3 player. The 50 Mbyte traffic volume is calculated from the number of songs in an album, the length of a song (5 minutes), the encoded data rate (128kbps), and the packet header size. The frequency and the time period during which each event occurs are also shown. By using this data and typical household dynamics for concurrent events, we can generated a traffic flow for the power line network for a typical day.

B. Internet Bridging

Currently, in-home PLC networks have to rely on other technologies to send data to the Internet and communicate with mobile devices. Most of the homes in the United States will eventually be equipped with broadband connections like DSL or cable modem services. To share the broadband Internet connection with PLC capable devices, we can add a PLC Internet router to the PLC network. One possible setup is depicted in Figure 1(b).

In this figure, a desktop computer acts like a data center. Devices that need to communicate with other devices on the Internet will send data to the desktop PC via the power line. The desktop PC decides whether to send it to the Internet. In the future, an IA routing device may be unnecessary. Researchers are developing a solution to make PLC home networks talk directly with other homes, power plants and the Internet using the external distribution power line. Such a network infrastructure for the Internet access would be especially attractive to developing countries, since no additional expenditure is needed for data network infrastructures.

To support data exchange with mobile devices, PLC networks will also need to cooperate with wireless networks. The easiest way to achieve this is to make the 802.11x base station PLC compatible. The base station is treated as an ordinary IA device with a PLC chip built-in (see Figure 1(b)). Mobile devices with wireless capability can then talk to devices attached to the power line. This is especially indeal when communication is desirable but large coverage area require multiple interconnected wireless access points - the interconnection is then provided with "no new wires" using the existing power line infrastructure which would be needed to power the WAPs in any event.

The above PLC applications require a properly designed protocol. In addition, to make the PLC network real-time traffic friendly, special care is needed to support delay sensitive traffic. In the following sections, we discuss the physical limitations of power line channels and then describe a robust power line protocol.

III. PLC DESIGN ISSUES

A. Physical limitations

A power line is used for transmitting 50 or 60 Hz signals but was not designed to convey high frequency signals such as the 20MHz communication signal used in the *Homeplug* 1.0 protocol. A power line channel is somewhat like a wireless channel - both of them suffer from noise, fading, multi-path and interference. Power line noise is produced by the operation of electrical devices. Fading, multi-path and interference are caused by the imperfection of power line channels.

Typical attenuation characteristics in power line channels are given in [6]. The author reports that even when all devices are unplugged, the noise still persists and this drastic variation of attenuation is hostile to power line communication. Furthermore, the Federal Communications Commission (FCC) also limits the available bandwidth for communication purposes. In compliance, the usable bandwidth in the *HomePlug* standard is 25MHz. An extensive study of the power line channel characteristics and design issues is given in [7].

To conquer these problems, a robust signal modulation and data coding is needed.

B. Signal Modulation

To modulate digital signals on to the power lines, we can use many of the same techniques that are widely implemented in wireless communication. Basic modulation techniques such as Phase Shift Keying (PSK), Frequency Shift Keying (FSK), Minimum Shift Keying (MSK), and Gaussian Minimum Shift Keying (GMSK) can be used for low data rate communication. Other more advanced techniques such as M-ary Phase Shift Keying (MPSK), M-ary Quadrature Amplitude Modulation (MQAM), M-ary Frequency Shift Keying (MFSK) and Orthogonal Frequency Division Modulation(OFDM) can be used when higher data rates are desired. A thorough study of signal modulation over power lines is given in [8].

OFDM was adapted by *HomePlug Powerline Alliance* because of its robustness to noise and the fact that it is a parallel data transmission method using a number of parallel frequency division multiplexed subbands. The main problem in using OFDM on wireless networks is frequency offset, caused by the Doppler effect when the user is moving. The Doppler effect will cause performance degradation, but in a power line network there are no moving devices, and thus no Doppler effect. The other problem is timing offset, which can be mitigated by offset estimation and compensation.

Spread spectrum signal modulation is different. Since the useful bandwidth in the power line channel is under 25Mhz, the effect of spread spectrum modulation is considered limited. Using a single carrier modulation on the power line is possible but equalizers could be needed to reduce the delay spread effect, and the associated cost is high.

In order to cope with the wide variation in channel conditions, the physical layer protocol(PHY) for PLC must be adaptive intelligently using more robust modulation and coding schemes, with lower data rates as needed. In addition, critical protocol management information requires high fidelity forward error correction(FEC) coding ro ensure that the protocol functions correctly in the worst case situations.

C. MAC Layer Protocols

In PLC home networks, the power line media can be accessed by multiple devices simultaneously. To decide which device gets the floor to send its data, a medium access control(MAC) protocol is needed. There are many existing protocols that can be implemented on the power line network. CSMA/CD, CSMA/CA, TDMA and hybrid protocols such as TDMA+CSMA are all potential candidates.

The most popular wired MAC protocol, CSMA/CD, could be also applied on a power line network. However, the large variation in noise on the power line makes collision detection very difficult. This characteristic is again very similar to a wireless network, so some have applied the CSMA/CA protocol as suggested in *IEEE802.11* to the power line network. However, the hidden node problem arises when the signal travels through different power lines with highly variable attenuation. To conquer this problem, a RTS/CTS scheme has to be implemented. Though the RTS/CTS scheme solves the hidden node problem, it degrades the network performance.

The benefits of using TDMA is that it provides an upper bound of access delay thus QoS is guaranteed. However, the difficulties in generating a synchronized clock signal in power line networks between devices remains a problem. Other hybrid protocols like TDMA+CSMA provide QoS capabilities in nature, but the network efficiency and beacon generation between TDMA slots and CSMA/CA slots remains unsolved. A detailed discussion of the hybrid TDMA+CSMA/CA protocol is provided in [10]. *Homeplug* 1.0 protocol also provides some level of QoS support in the uses of multiple priority levels that can be used in conjunction with VLAN tagging.

The issue of privacy of power line networks is important to their practicality. Like wireless channels, Power line network channels should be treated as open and as with all open channels, nothing prevents a device from receiving signals. To provide a secure network environment, the *HomePlug Powerline Alliance* defined a 56-bit DES encryption mechanism. Once a signal is encrypted, a device with a different encryption key cannot interpret it and privacy is achieved.

This privacy protection seems adequate but stronger encryption may be needed when power line networks are adopted for office environments or apartment building and hotels. We believe that stronger privacy protection should be implemented in the physical layer, so that hackers can not easily break the code.

IV. Performance Results and Analysis

In this section we report the measurements observed using an event-based C program to simulate a *Homeplug* 1.0 power line network. All scenarios assume QPSK and a 3/4 coding rate on various links and a maximum TCP segment size of 1460 bytes. In this simulation, we use UDP, TCP, and VOIP traffic. UDP traffic is generated with an exponential inter-arrival time with a 100 microsecond average. The UDP packet size is assumed to be a constant 1460 bytes with priority 0. TCP traffic is also generated with exponential inter-arrival time with 100 microsecond average and we assume that TCP traffic sources always have data to send. TCP traffic is treated as priority 0 packets. Every time a node has a chance to send, it is allowed to send the maximum segment size of 1460 bytes without headers. VOIP is isochronous traffic with a 20 msec interval. The packet size of VOIP is 160 bytes and is assigned the highest priority(3).

A. Simulation Results

In Table III, we provide the of simulation results of a power line network. The UDP traffic simulation scenario 1 shows the best throughput in our simulations since there is no contention at all. Table III also shows channel contention with 2 and 3 UDP nodes causes a modest reduction in channel throughput.

In the TCP traffic simulation, though scenario 1 has only one traffic source, the bandwidth must be shared with data and response frames(e.g., ACK packets) thus it provides lower performance than the UDP traffic simulation. The MAC throughput represents the total number of transmitted bytes divided by the simulation time regardless of successful delivery. The TCP throughput includes only the successfully delivered data and ACKs.

The third metric we provide in Table III is the PLC simulation results of one VOIP and multiple UDP connections. The high priority VOIP always wins the contention and the UDP nodes can send packets only when there is no VOIP traffic. In this simulation, the queuing delay refers to the time a packet waits in a queue before it enters the transmit

TABLE III

A POWER LINE NETWORK SIMULATION RESULTS

Throughput of multiple UDP traffic			
	Scenario 1(1 UDP)	Scenario 2(2 UDP)	Scenario 3(3 UDP)
MAC Throughput	8.08 Mbps	7.46 Mbps	7.46 Mbps
Throughput of multiple TCP traffic			
	Scenario 1(1 TCP)	Scenario 2(2 TCP)	Scenario 3(3 TCP)
MAC Throughput	6.16 Mbps	6.15 Mbps	6.12 Mbps
TCP Throughput	5.92 Mbps	5.91 Mbps	5.88 Mbps
Throughput of one VOIP and multiple UDP traffic			
	Scenario 1(VOIP + 1 UDP)	Scenario 2(VOIP + 2 UDP)	Scenario 3(VOIP + 3 UDP)
MAC Throughput	7.89 Mbps	7.33 Mbps	7.29 Mbps
Queueing Delay	0.25 msec	0.25 msec	0.25 msec
Net Delay	2.75 msec	3.00 msec	3.00 msec
Throughput of one VOIP and multiple TCP traffic			
	Scenario 1(VOIP + 1 TCP)	Scenario 2(VOIP + 2 TCP)	Scenario 3(VOIP + 3 TCP)
MAC Throughput	6.04 Mbps	5.85 Mbps	5.77 Mbps
TCP Throughput	5.72 Mbps	5.54 Mbps	5.45 Mbps
Queueing Delay	0.25 msec	0.25 msec	0.25 msec
Net Delay	3.25 msec	3.25 msec	3.25 msec

buffers. The net delay is the total time for which a packet propagates in the networks. Only low priority packets are considered for this delay because the high priority packets will be delivered as soon as they appear in the queue.

The Table III also shows the simulation results of one VOIP and multiple TCP connections. The throughput of VOIP is only 80 kbps, and hence the total throughput is dominated by the TCP component.

B. Real world PLC network performance

In addition to simulating the performance of the *HomePlug Powerline Alliance* protocol, we were also able to construct a real PLC network using “reference designs” of actual commercial *HomePlug* devices. Since there are currently no real IA devices with PLC capability, we used traditional network applications (i.e., ftp and streaming multimedia content) as the basis for measuring PLC network performance.

In this experiment, there were 4 desktop computers. A 450 MHz Pentium II desktop computer (PC-2 as a file server) is equipped with 128 MBRAM, a 3-COM fast Ethernet card, and a PLC PCI card. Two 700 MHz Pentium III desktop computers (PC-3 and PC-4) are both equipped with 256 MBRAM , and PLC PCI cards. A 266 MHz Pentium MMX desktop computer(PC-1) is equipped with 64 MB RAM, and a 3-COM fast Ethernet card.

The PC-1 computer is connected to an Ethernet-to-power line bridge, which converts packets generated from the Ethernet card into PLC compatible packets, and vice versa. All computers are connected to power lines.

In this experiment, we seek to determine the performance of the PLC network in handling streaming video and large file transfers.

B.1 Performance for Delivering Streaming Video

We first examined the ability of the PLC network to deliver real-time traffic. Four video files are involved in this experiment. The first file is encoded in Real media format with a bit rate of 550 kbps; the second is encoded with bit rate of 1396 kbps, the third is encoded at 2 Mbps, and the fourth is an MPEG2 video file with variable bit rate, and the average bit rate is 8 Mbps. In the first experiment, three client computers simultaneously issued requests for low bit rate (550kbps) video service to the file server. In the second experiment, the same procedure was executed, but a medium bit rate (1394 Kbps) video service was requested. In the third experiment, the 3 clients requested a high bit rate (2 Mbps) video service. Finally, the MPEG2 video service request was issued by the PC-3. The experimental results are shown in Table IV.

The PLC network successfully delivered both low and medium bit rate streaming videos. We did not observe any packet drops during the experiments. The results met our expectations, since the peak data rate was only 4185 kbps. We did another experiment to further investigate the performance of PLC network in delivering streaming video. A 2 Mbps MPEG-1 file is used in this experiment. As the video begins, a significant video freeze-then-go (halting) phe-

TABLE IV
REAL WORLD PLC NETWORK PERFORMANCE

Performance of delay sensitive traffic				
	Number of Connections	Aggregated bit rate	Packet drop	delay-jitter
Low Bit Rate	1	550kbps	No	No
	2	1100kbps	No	No
	3	1650kbps	No	No
Medium Bit Rate	1	1395kbps	No	No
	2	2790kbps	No	No
	3	4185kbps	No	No
High Bit Rate	1	2000kbps	No	No
	2	4000kbps	No	No
	3	6000kbps	N/A	Moderate
	Number of Connections	Average bit rate	Environment	
Variable Bit Rate	1	8Mbps	PLC network	
	1	8Mbps	Fast Ethernet	

Performance of elastic data traffic		
	Number of Connections	Average bit rate
Elastic data traffic	1	6.21Mbps rate
	2	6.15Mbps rate
	3	6.27Mbps rate

Performance of combined delay sensitive traffic and elastic data traffic		
	Connections	Aggregated bit rate
Hybrid data traffic	One ftp connection and One video service	6.26 Mbps rate
	Two ftp connection and One video service	5.92 Mbps rate

nomenon was observed, causing staccato playback. After several seconds(3-5 seconds) the freeze-then-go phenomenon disappeared.

In the case of MPEG2 video file, the average data rate is 8Mbps. During the experiment, a significant “video staccato” phenomenon was observed. To exclude the possibility that the observed phenomenon was caused by the client computer’s hardware capability, the experiment was repeated with same configuration, while connected to a fast Ethernet. During that experiment, no such phenomenon (halting playback) was observed.

B.2 Performance of Elastic Data Traffic

The occurrence of the momentary video freezing phenomenon during playback of variable bit rate streaming is likely because the aggregated data rate was close to or exceeded the PLC network capacity. To understand the real throughput of a PLC network, we conducted another experiment A 215,502,106 byte file was placed on the server running an FTP daemon (The file size was chosen to minimize hardware uncertainty and human error.) Client computers made FTP requests for the file. We tested different numbers of FTP connections, up to 3, using individual client machines in our PLC network. The experimental results are also given in Table IV.

The aggregated traffic in the table is calculated by adding all observed data rates of all connections. The experimental results show that the real PLC network performance is about 6 Mbps. When there is only one FTP connection, the observed throughput is 6.21 Mbps. By our analysis, one TCP connection will not fully utilize the PLC network, because the server has to stop if no ACK packets are received from the client.

Aggregated traffic volume decreased as the number of connections increased from 1 to 2. This phenomenon is because of the ACK packets and the packet overhead increase as the number of connections increased. Although the network utilization improves, the improvement cannot compensate for the loss due to these overheads.

When we increased the number of connections from 2 to 3, the PLC network had the highest throughput of 6.27 Mbps. This is because the network utilization increased as the number of connections increased which compensated for the packet overhead and ACK overhead.

These experimental results explain the phenomenon of momentary DVD video freezing playback. The requested bandwidth for DVD streaming exceeded the maximum bandwidth the present PLC network can provide.

B.3 Performance of combined delay sensitive traffic and elastic data traffic

Although we could not explore the QoS service and packet priority provided by the real PLC network, we were eager to learn the effect of mixed traffic on the PLC network. This experiment was conducted as follows: The file server provided two services: one for streaming video with bit rate 550 kbps, and the other one for file transfer with a file size of 215,502,106 bytes. PC-1 requested streaming video while PC-2 and PC-3 requested the file transfer. Each experiment lasted 285 seconds (i.e., the length of the video file), after which both video player and FTP client are forced to stop. Table IV shows our experimental results.

When the number of FTP connections increased, the observed data rate decreased as was the case in the previous experiment. However the overall average data rate was comparable to the case of multiple FTP traffic.

V. Conclusion

The emergence of Information Appliances (IA) for the smart homes of the future will undoubtedly make our lives much more comfortable than ever. However, the infrastructure that supports multimedia traffic and conventional elastic data traffic for communication among IA devices is a critical component of a smart home.

We advocate power line as the infrastructure for smart homes based on the convenience of the power sockets and the layout of the power line network existing in every home. At present, 6 Mbps of bandwidth was measured through real-world PLC network experiments. Our studies showed that the PLC network can provide 3 low bit rate or 3 medium bit rate multimedia streams concurrently with no packet drops and jitters. It also successfully delivered one low bit rate multimedia data stream and 2 large ftp file transfer concurrently with no packet drops and jitters.

In this paper, we discussed only the PLC networks for communication *within* the smart home, but the ultimate goal of PLC network could be the ability to connect to the Internet without dialing up to an ISP server, entirely using electrical wiring only. This can be illustrated as in Figure 2.

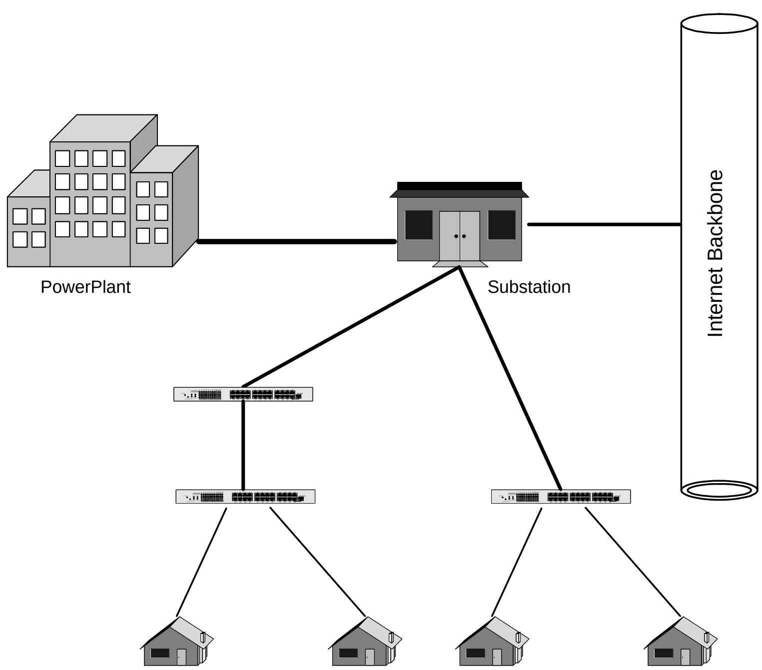

Fig. 2. Connecting PLC Networks to The Internet

Private home networks are connected to substations, in which a PMTS (Powerline Modem Terminal Service) connects PLC networks within homes to the Internet backbone. The PLC network gateway for a private home network could be installed in the fuse box of that home and then it could be connected to one or more repeaters. Repeaters are for increasing signal strength when the signals level fall below some value.

We expect to see higher data rates in power line networks in the future as signal modulation technologies improve; however, issues like network security and the network characteristics with a large number of nodes need further development. Further research on these issues is of critical importance when power line networks are applied to offices and large multi-user buildings.

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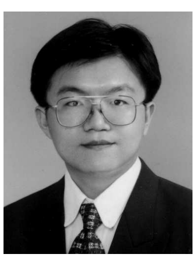
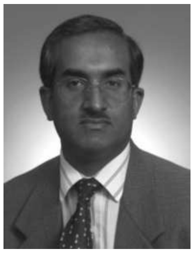
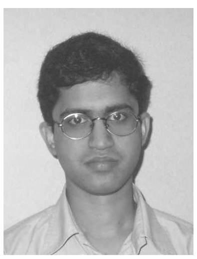


Yu-Ju Lin was born in Taiwan. He received the Bachelor of Engineering degree from National Central University, Taiwan in 1990, and the MS degree in computer and information engineering from Chung-Yuan Christian University, Taiwan in 1995. He is currently a Ph.D. student in the Department of Electrical and Computer Engineering, University of Florida. His current research interests include multimedia communication and computing, power line communication and high-speed networks.



Dr. Haniph A. Latchman was the 1983 Jamaica Rhodes Scholar and received his Ph.D. from Oxford University in 1986 and his Bachelor of Science degree (First Class Honors) from the University of The West Indies-Trinidad and Tobago, in 1981. Dr. Latchman teaches graduate and undergraduate courses and conducts research in the areas of Control Systems, Communications and Computer Networks and he has received numerous teaching and research awards, including the University of Florida Teacher of the Year Award and the IEEE 2000 Undergraduate Teaching Award with a citation "for innovative and inspirational teaching and advancing the use of information technology in education." Dr. Latchman is a Senior Member of the IEEE and has published over 80 technical articles in the areas of his research. He is the author of the books Computer Communication Networks and the Internet published by McGraw Hill and Linear Control Systems - A First Course published by John Wiley. Dr. Latchman is also an Associate Editor for the IEEE Transactions on Education.

Minkyu Lee received the MS degree in Electrical and Computer Engineering from University of Florida in 1999. He is currently working toward the Ph.D degree in electrical and Computer Engineering at University of Florida. His research interests are in the area of power line home network, to support QoS and to design next generation PLC protocols.



Srinivas Katar was born in India. He received the Bachelor of Technology degree in Electrical Engineer in 1998 from Indian Institute of Technology, Kanpur,India. From 1998 to 2000, he studied at the Department of Electrical and Computer Engineering, University of Florida, where he received the Master of Science degree. In May 2000, he joined the Research and Development team at Intellon Corporation, Ocala, FL. His current research interests include networking protocols, multicarrier communications, and error control coding.