A Comparative Performance Study of Wireless and Power Line Networks

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Abstract

Local Area Networks based on the IEEE 802.11a/b wireless networking standards and emerging Power Line Communication (PLC) standards are attractive for establishing networks with "No New Wires" for in-home and business applications. This paper presents a theoretical performance comparison of the 802.11 a/b and the HomePlug 1.0 PLC protocols. The paper also presents comprehensive comparative field test results addressing such issues as coverage, channel stability and reliability as well as the associated implications on the capability of these technologies to provide QoS support for multimedia traffic in typical residential settings.

Keywords

Network measurements, Power Line Communication, Wireless Network, Home Networking Design, Multimedia Applications, 802.11b, 802.11a, 802.11g, HomePlug 1.0, Quality of Service (QoS)

I. Introduction

Candidate networking technologies for providing convenient and widespread residential and SOHO networking services may be categorized as *Wireless Networks*, *Wired Networks* and *No New Wires Networks*. An extensive study of various infrastructure options and technologies appropriate for home networks is given in [1]. Below, we give a short discussion of networks in the above three categories.

Wireless Networks such as 802.11x, BlueTooth, and HomeRF can be constructed by installing multiple interconnected wireless access points (WAP) and base stations within target areas. The best benefit of using wireless networks is the freedom to move around while maintaining network connectivity. BlueTooth technology is targeted at personal communications and the coverage is expected to be limited. On the other hand, though HomeRF has been on the market for a few years, it is not yet widely accepted. Thus the most interesting and widely accepted wireless networking technologies are the 802.11x family. 802.11b operates in the 2.4 GHz band and provides a maximum data rate of 11 Mbps; 802.11a supports speeds of up to 54 Mbps and operates in the 5 GHz band. Standards for the newer IEEE 802.11g, which should provide data rates up to 54 Mbps in the 2.4 GHz band, have not been finalized, and equipment was not available for testing.

For *Wired Networks*, a comprehensive Ethernet network can be constructed by installing special UTP-5 cabling. While the stability and the security of wired networks are guaranteed, installing new wires in existing home or other buildings may be costly, negating the low cost of the network interface cards.

For the *No New Wires Networks* category, there are phone line networks, cable networks, and power line networks. Using the existing phone line as an infrastructure, as in HomePNA[2], may seem attractive, but it is limited by available phone sockets in a home. Home Cable Network Alliance (HomeCNA)[3], established in June 2001, proposes a home network infrastructure using existing coaxial TV cable. There is as yet no standard for HomeCNA and it also suffers from the major drawback of limited convenient connection points.

Power Line Communication (PLC) networks such as HomePlug[4] were introduced to the U.S. consumer market in May 2002. European PLC networks have been deployed in recent years. With multiple outlets in almost every room, residential power lines are already the most pervasive network in the home or small office. The HomePlug 1.0 PLC standard supports PHY data rates of 14 Mbps and is thus comparable to the 802.11b declared data rate.

A major objective of this paper is to conduct a real-world performance study of the capabilities of wireless (IEEE 802.11b and 802.11a) networks and PLC networks based on the HomePlug 1.0 standard. Our interest is to determine the relative performance of these technologies.

This paper presents a comparative analysis of the TCP performance of power line networks and wireless networks using actual measurements on HomePlug 1.0 compliant PLC networks and 802.11a/b compliant wireless networks. The tests were conducted in 20 houses ranging in area from 1500 to 5000 sq. ft. with an average area of 3000 sq. ft. The paper presents qualitative theoretical and measured throughput performance for 802.11a/b and HomePlug 1.0 PLC. Other issues like the relationship between QoS and channel stability as well as overall coverage are also discussed.

The next section briefly describes the HomePlug 1.0 protocol. Section III presents a theoretical performance analysis of IEEE 802.11a/b and HomePlug 1.0. Section IV describes the experimental setup while Section V gives our field test results. A summary is given in Section VI.

II. HomePlug 1.0 Protocol

The parameters and details of 802.11x protocols are well documented in the literature and Internet publications[5]. Here, we briefly describe the HomePlug 1.0 standard.

A. PLC Environment

Power lines were originally devised for distributing electrical power using the frequency range of about 50-60 Hz. The use of this medium for high speed communications presents some technically challenging problems. Electrical noise from appliances and the uncontrolled nature of the wiring result in severe signal distortions. The PLC channel is made up 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 multi-path effects resulting in deep notches at certain configuration dependent frequencies. These channel imperfections make signal transmission over a power line very difficult[6].

Reliable data communication over this hostile medium requires powerful Forward Error Correction (FEC) coding, interleaving, error detection and Automatic Repeat Request (ARQ) techniques, along with appropriate modulation schemes as well as a robust Medium Access Control (MAC) protocol. The lack of affordable processing techniques needed to overcome the harsh power line environment resulted in limited success of power line communications in the past. However, both the advances in the ASIC density and speeds, and the advancement of signal modulation, processing and error control coding techniques now make power line communication possible.

B. HomePlug 1.0 PHY

To overcome the hostile PLC environment, Orthogonal Frequency Division Modulation (OFDM) with a Cyclic Prefix (CP) was adopted by the HomePlug 1.0 PLC standard. Using OFDM has many benefits. For example, it exhibits excellent mitigation of the effects of time-dispersion, provides excellent Inter-Channel Interference (ICI) performance, and is good at minimizing the effect of in-band narrowband interference. OFDM splits available bandwidth into many small frequency bands called sub-carriers, then may mask out unusable subcarriers and apply the best modulation and coding methods to the usable subcarriers. This approach is used by HomePlug 1.0. A more advanced technique called bit-loading allows use of different modulation and coding schemes for each sub-carrier. In either case, OFDM can adapt bandwidth/data rates according to channel conditions.

Unlike 802.11, the bandwidth in HomePlug 1.0 can vary from 1 Mbps to 14 Mbps practically continuously according to the channel conditions[1]. Active HomePlug 1.0 nodes perform channel estimation at least once every 5 seconds. This feature allows the PLC network to maximize its data rate adaptively.

A preamble and frame control form delimiters used for synchronization and for control. The frame control of start of frame, end of frame, and response delimiters all include delimiter type[2], and contention control information. In the start of frame delimiter, the frame control field includes the tone map information needed by the receiver to decode the rest of the frame, and a length field. The end of frame delimiter contains priority information used for contention control. Response delimiters contain information that allows a sender to verify that the response was indeed sent in response to the frame it just transmitted. An end of frame gap (EFG) of 1.5 μs is inserted between the frame's frame check sequence (FCS) and the end delimiter to allow for processing.

C. *HomePlug 1.0 MAC*

The HomePlug 1.0 Medium Access (MAC) protocol is a modified CSMA/CA (Carrier Sense Multiple Access / Collision Avoidance) protocol with priority signaling. HomePlug 1.0 devices operate in an ad hoc mode in the sense that devices communicate with each other freely, without any centralized coordination.

The frame structure and protocol of HomePlug 1.0 is depicted in Figure 1.

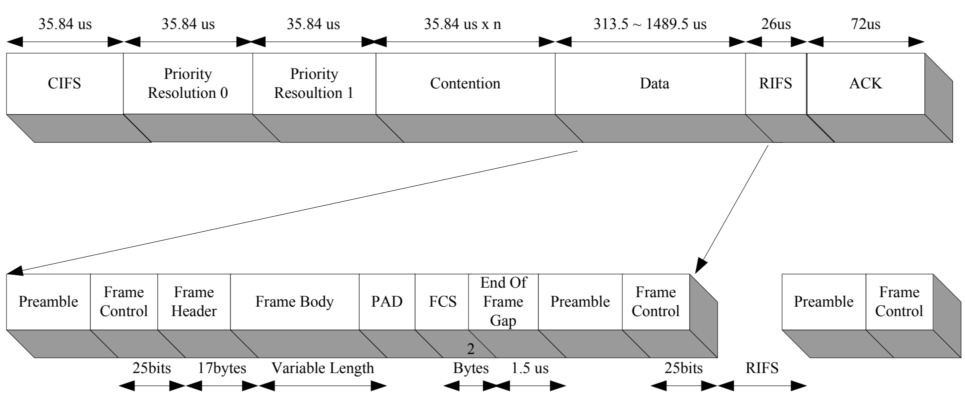


Fig. 1. HomePlug 1.0 frame structure and protocol

[1]There are 139 distinct data rates in that range according to number of usable carriers, modulation methods, and coding rate.
[2]Response expected is indicated in the delimiter type, and Response delimiter does not have a response expected/not expected indication.

The HomePlug 1.0 standard uses different terms and stages for inter-frame spacing and for the contention windows than 802.11b. The RIFS shown in the figure is "Response Inter-Frame Spacing." Unlike 802.11, there is no SIFS (Short Inter-Frame Spacing) between continued frames. Rather, a frame control bit is used to indicate the desire of a station to continue to send data, allowing preemption only by higher priority traffic. The spacing between the last frame and the incoming frame is CIFS (Contention Window Inter-Frame Spacing).

HomePlug 1.0 provides four priority classes - CA3, CA2, CA1 and CA0 from highest to lowest. Priority resolution is done by asserting signal of the priority level in the PR0 and PR1 slots. For example, to send a CA2 packet, the PLC device should assert a 1 in PR0, causing any node with CA1 traffic to defer, and not assert 1 in PR1 as it would do otherwise. Nodes with CA3 data assert a 1 in both priority slots, and CA0 in neither. This effectively resolves contention between different priority classes. Contention within the same priority class is resolved during the contention period.

The contention period is a contention period. The contention period is a form of CSMA/CA with a priority dependent backoff window size schedule. For the lower two priority classes, it is 8-16-32-64 slots, while it is 8-16-16-32 slots for the two higher priority classes. On collision, the range of contention slots over which a transmission is started is increased according to the schedule. Aside from starting with a smaller range (8 slots compared to 32 slots), a major difference from the IEEE 802.11 standard is that when a HomePlug 1.0 node defers (detects another node's transmission in an earlier slot), it uses this information to back off, but less aggressively than in the case of a collision. This technique serves to reduce costly collisions further. For protocol details, please see the HomePlug 1.0 Specification [4].

III. Theoretical Performance of 802.11a/b and HomePlug 1.0

To compare the protocol performance of 802.11a/b and HomePlug 1.0, we first analyze the theoretical performance differences between them. In next section the protocol analysis to calculate the theoretical performance of 802.11a/b and HomePlug 1.0 is presented. The analysis assumes that a single station is continuously transmitting frames with 1500 bytes of payload over the medium.

A. 802.11a/b Theoretical Network Performance

In the absence of competition, an 802.11b node picks a contention slot between 0 and 31, and starts transmission then. The average contention period delay for a packet without competition is 31/2 = 15.5

slots or 310 μ sec. The transmitting node will start to send data and wait for the receiver's acknowledgment.

Each frame is made up of a PLCP header, a MAC header, a DATA field and a CRC field. If it is an ACK frame then the DATA field is not present.

In practice, the maximum data payload sent via the 802.11a/b is limited to the Ethernet maximum of 1500 bytes. Table I summarizes the MAC throughput and efficiency for IEEE 802.11x protocols at various data rates. Packet fragmentation and MAC level packet concatenation are not considered.

TABLE I
802.11A/B MAC THROUGHPUT WITH PAYLOAD 1500BYTES

Technology	PHY Data Rate	MAC Throughput
802.11b	1 Mbps	0.91 Mbps
	2 Mbps	1.73Mbps
	5.5 Mbps	3.99Mbps
	11 Mbps	6.38Mbps
HomePlug 1.0	1 Mbps	0.70Mbps
	2 Mbps	1.74 Mbps
	5.5 Mbps	3.77 Mbps
	11 Mbps	8.08 Mbps
	14.1 Mbps	8.08 Mbps
802.11a	6 Mbps	5.38Mbps
	9 Mbps	7.78Mbps
	12 Mbps	10.02Mbps
	18 Mbps	14.12Mbps
	24 Mbps	17.61Mbps
	36 Mbps	23.74Mbps
	48 Mbps	28.47Mbps
	54 Mbps	30.80Mbps

From Table I, the maximum throughput is 6.38 Mbps for 802.11b and 30.8 Mbps 802.11a, representing efficiencies of 58% and 57% respectively. At 1Mbps the MAC efficiency of 802.11b is as high as 91% assuming there is no packet fragmentation.

B. Performance analysis of HomePlug 1.0

From Figure 1, the data transmission time ranges from 313.5 to 1489.5 μs, however to transmit a 1500 byte payload at the maximum data rate, 120 symbols are required, taking 1153.5 μs. Excluding physical level control overhead results in 1008 μs for actual data transmission. The maximum data payload size is limited to the smaller of 1500 bytes and $1344R - OH$ bits, where R is the physical data rate, and OH is the number of overhead bits. Each Ethernet frame incurs an overhead of at least 120 bits for encryption and integrity checking for the corresponding service block. Segment bursting allows a station to send all the segements associated with a service block consecutively, avoiding contention unless it is preempted by a station with higher priority traffic. A service block is broken into physical layer segments, each of which has 19 additional bytes of overhead for addressing and segement control. Additionally, each segment must be a multiple of 20 symbols long, up to 160 symbols maximum, which further complicates throughput analysis.

The initial contention window size is 8 slots, so the average contention delay without competition is 3.5 slots. To successfully deliver a data packet of 120 symbols takes

$35.84\ \mu s + 35.84\ \mu s + 35.84\ \mu s + 35.84\ \mu s \times 3.5 + 1153.5\ \mu s + 22 \mu s + 26 \mu s = 1484.86 \mu s$

The maximum physical layer data rate is 14.18 Mbps, thus the maximum throughput is

1500×8 bits/$1484.86 \mu s$ = 8.08 Mbps.

The efficiency of HomePlug 1.0 at the maximum data rate is 57%. The 70% efficiency of HomePlug 1.0 at PHY rate of 1Mbps is due to the limits of the data transmission time to a maximum of 1484.5μsec in order to provide better latency and jitter QoS parameters for higher priority traffic.

Although we can get up to 8 Mbps maximum MAC throughput in theory, the maximum measured TCP throughput in our field testing so far is 6.3 Mbps. matching earlier HomePlug 1.0 simulation results[9].

IV. Experimental Setup

To understand the real world performance of IEEE 802.11a/b and HomePlug 1.0, we conducted field tests in 20 houses located in the Gainesville, Ocala, Orlando, and Belleview areas of Florida. The choice of the houses used in the tests were in the mid-to-large size (1500 sq. ft. to 5000 sq. ft.), since larger houses provide a better range on the performance parameters of interest.

The equipment used in this test included the following.

(i) *AP* Server: A Sony notebook with a 700 MHz Pentium III processor and 128k RAM running Windows2000

(ii) *Mobile* Station: An HP notebook with a 500 MHz Pentium III processor and 128k RAM running Windows2000

(iii) Linksys HomePlug 1.0-based Powerline-to-Ethernet bridges

(iv) Netgear[7] IEEE 802.11b Access Point and PCMCIA Card

(v) D-Link DWL-5000AP IEEE 802.11a Access Point and D-Link DWL-A650 PCMCIA card.

For PLC testing the two laptops were connected through the power line via Powerline-to-Ethernet bridges. For wireless testing, a Modified Infrastructure Mode (MIM) was used. The *AP* Server was connected to an access point using an Ethernet crossover cable to the built-in Ethernet socket. A PCMCIA slot in the mobile station was used to connect the wireless card. Note that typical wireless networks use an Infrastructure Mode (IM). In this mode, all wireless nodes communicate with each other through the access point, and must share the bandwidth over two hops. MIM can be expected for connection from a node to an access point. Since these tests had the *AP* server connected to the access point via Ethernet, there with no other contention possible, the test results should represent the best case scenarios with respect to this aspect.

A. *Experimental Method*

The TCP throughput and distances were measured for various locations of *AP* and *Mobile* stations inside the house. The AP Server was located close to a phone outlet or a cable outlet, the most probable locations for the home network to be connected to the broadband access network. The Mobile Station was located at various places where it would be likely to find other networked devices in the home. The AP Server antenna and Mobile Station antenna were placed randomly to minimize the effect of directional antenna gain. We argue that this is the typical antenna placement since ordinary users probably don't know how to set antenna directions to maximize throughput. Besides, not all locations are susceptible to antenna direction adjustment due to the surrounding environment.

WSTTCP, a popular TTCP implementation ported to Windows sockets, was used. The TCP buffer size was chosen to be 11680 bytes (1460×8). The number of TCP buffers transmitted was chosen such that each test ran for approximately 60 seconds. A single run of WSTTCP involved starting the WSTTCP in receive mode at the receiver on a selected port. WSTTCP was then started at the transmitter with a specific TCP buffer size, number of TCP buffers to be transferred, the receiver IP address and the receiver port number. At the end of transmission, WSTTCP (at both the transmitter and receiver) provided the throughput observed on the link. For several of these tests, real time packet capture was also obtained to observe TCP stability. All the procedures were automated and required minimal human operation.

V. RESULTS

The amount of data collected is too large to be presented in detail in this paper, so only a summary of the most interesting findings are presented[3]. The location, size and age of each of the houses where

[3]The complete data set from our field tests is available on request.

testing was conducted is shown in Table II.

TABLE II
LIST OF THE HOUSES TESTED AND CONNECTIVITY

Location	**House Size (Square Feet)**	**House Age (Years)**	**802.11a Connectivity**	**802.11b Connectivity**	**HomePlug 1.0 Connectivity**
Gainesville	1460	4.5	90%	100%	100%
Gainesville	2000	5	90%	100%	100%
Gainesville	2030	3	75%	100%	100%
Gainesville	2100	7.5	100%	100%	100%
Ocala	2300	33	42.9%	78.6%	100%
Gainesville	2700	4.5	61.9%	100%	100%
Gainesville	2700 (two floor)	1	57%	100%	100%
Gainesville	2700	10	20%	100%	100%
Gainesville	3000	1	91%	100%	100%
Gainesville	3000 (two floor)	9	71.4%	100%	100%
Ocala	3000	9	54.2%	100%	100%
Gainesville	3150	13	55.56%	95.8%	100%
Ocala	3500	6	69%	100%	97.6%
Ocala	3600	10	41.7%	100%	100%
Orlando	3600	4	50%	100%	100%
Belleview	3600	4	42%	92%	100%
Gainesville	3900	5	56%	100%	100%
Gainesville	4000	4	9%	84%	81%
Orlando	4200	67	18.75%	50%	100%
Ocala	5000 (two floor)	15	17%	50%	100%

A. IEEE 802.11a Indoor Performance

The performance and coverage results of IEEE 802.11a are depicted in Figure 2.

Figure 2(a) shows the connectivity (i.e., percentage of good links) as a function of house area. As expected, the connectivity decreased as the house area increased. Results show that connectivity is poor even in moderate size (2500 sq. ft.) houses. For larger houses ($>$4000 sq. ft.) the connectivity decreased to 20 %.

Figure 2(b) shows a scatter plot of throughput as a function of distance. It is interesting to note that IEEE 802.11a connectivity is almost zero when the distance is larger than 50 ft.

Figure 2(c) shows the percentage of links that exceed the throughput values indicated on the X-axis. Note that the maximum IEEE 802.11a throughput obtained from the product being tested was larger than those expected from theory. This could be because of manufacturer-specific proprietary enhancements like the use of higher level modulations.

In summary, the statistics show that

(i) IEEE 802.11a failed on at least one link in 19 of the 20 houses tested,

(ii) 802.11a failed to connect in 45% of the links that were tested,

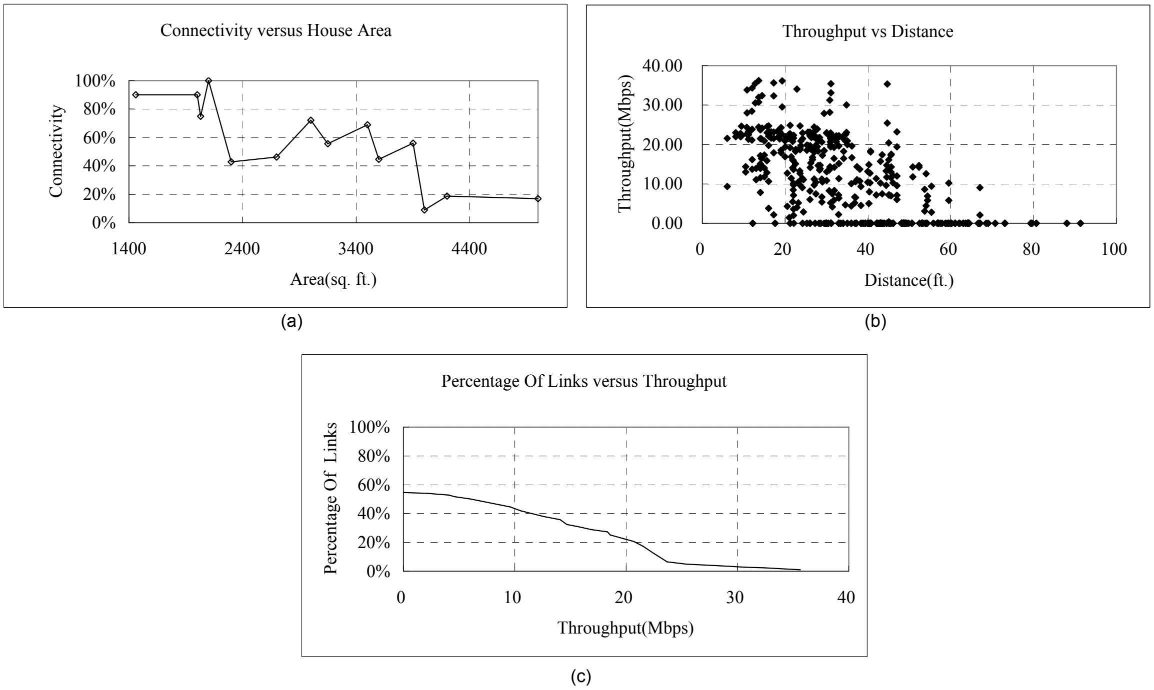


Fig. 2. IEEE 802.11a indoor performance

(iii) 802.11a showed close to zero connectivity at distances larger than 50 feet.

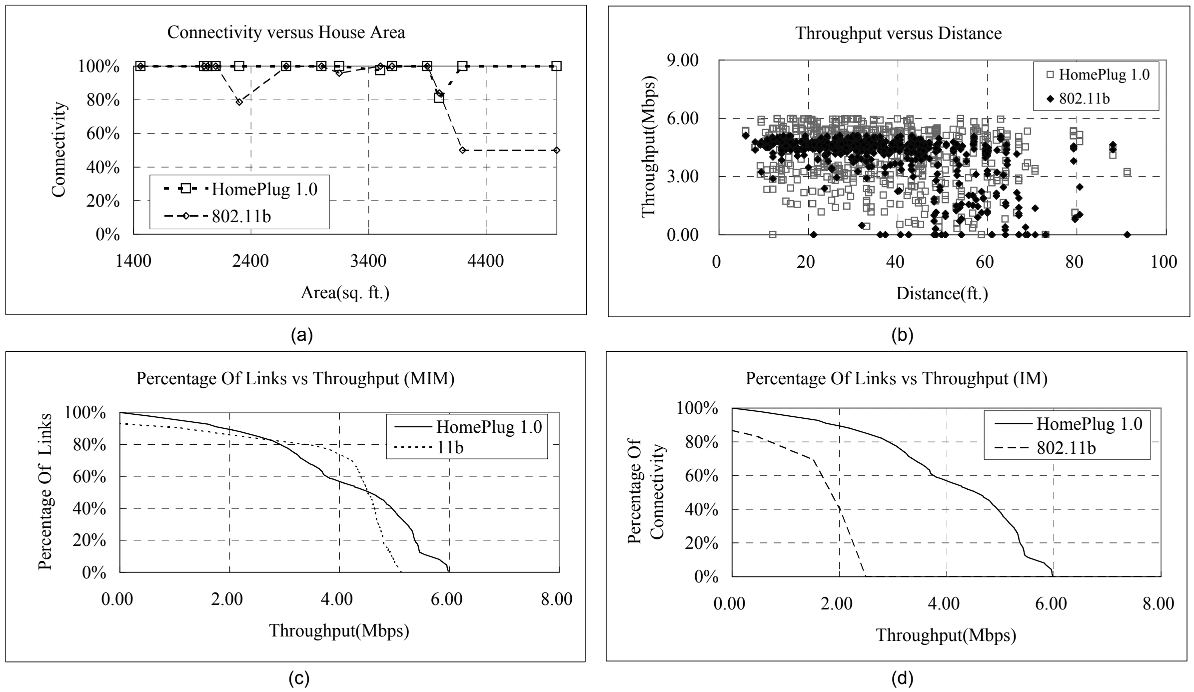
For shorter distances, 802.11a provided excellent throughput in most cases.

A.1 IEEE 802.11b and HomePlug 1.0

To facilitate comparison, the performance and coverage results of IEEE 802.11b and HomePlug 1.0 are shown together in Figure 3. Figure 3 (a) shows the connectivity as a function of house area. Both technologies show high connectivity for houses of size less than 4000 sq. ft. For houses larger than 4000 sq. ft., the connectivity for IEEE 802.11b dropped dramatically to 50% in both of the houses tested, while HomePlug 1.0 continued to show high connectivity.

Figure 3(b) shows a scatter plot of throughput as a function of distance. IEEE 802.11b typically provides close to maximum throughput at distances of less than 50 ft.; for distance larger than 50 ft., the performance exhibited large variations. On the other hand, the HomePlug 1.0 system performance is not correlated with the line of sight distances measured in this experiment. This is because HomePlug 1.0 signals have to pass through the convoluted power line cable runs to reach the mobile station.

Figure 3(c) shows the percentage of links that exceed the throughput value depicted on the X-axis. Our



*Note that because of tone and adaptation, HomePlug 1.0 allocation shows a continuous rate adaptation unlike 802.11b.

Fig. 3. IEEE 802.11b and HomePlug 1.0 indoor performance

experiments showed that the overall coverage of 802.11b was 92%. The maximum throughput observed in field testing was 5.13 Mbps. Figure 3(c) shows that around 70% of the connections operated at more than 4 Mbps and 10% above 5 Mbps. For HomePlug 1.0, the overall coverage is 98%. The maximum throughput observed in testing was 5.98 Mbps. For HomePlug 1.0, 58% of the connections operated above 4 Mbps and 38% had throughput above 5 Mbps.

The interesting crossover phenomena displayed in the graph reflect three aspects of the systems. First, the paucity of data rates supported by 802.11b hurts its performance when channel conditions are sub-optimal. Second, HomePlug 1.0’s ability to adapt to the channel conditions with a nearly continuous selection of data rates allows it to perform better under mediocre channel conditions. Finally, the higher maximum data rate of HomePlug 1.0 allows it to outperform 802.11b when channel conditions are favorable.

It should also be noted that in this experiment, throughput was measured between the access point to the Mobile Station in a modified Infrastructure mode. However, this may not always be the way IEEE 802.11b stations communicate with each other. IEEE 802.11b networks can be configured in either ad hoc mode or Infrastructure mode (IM). In the ad hoc mode, wireless stations communicate with each other directly. However, typical home networks use an IM in which each wireless station communicates with the access point, which in turn forwards the data to the designated receiver. Some of the reasons for using IM include ease of setup, better coverage, and security. Further, most wireless equipment is configured in IM out of the box, and must be reconfigured to ad hoc mode by the customer. Thus, in a typical IEEE 802.11b home network, all station-to-station transmissions, other than those designated to the access point itself (i.e., the access point is the final destination of the transmission) or those that originate from the access point, will be retransmitted by the access point. This reduces the effective throughput experienced between such stations.

We use a simple method to extrapolate the Infrastructure Mode (IM) throughput from the MIM link throughput data which was collected in the field tests. A random sample was chosen from the set of collected data and used as the throughput (R_1) from a TCP Source to the Access point. Another random sample was chosen from the sample and was used as the throughput (R_2) from access point to the TCP destination. The aggregate IM throughput then can be obtained by assuming a fixed packet size of x bits is transmitting through two links with speeds R_1 and R_2. The total time to transmit this packet will require $\frac{x}{R_1} + \frac{x}{R_2}$ second. Thus throughput can be calculated by $\frac{R_1 \times R_2}{R_1 + R_2}$. Multiple iterations were used to obtain the distribution of the IM throughput. Although this method is not fully accurate, it is reasonable to expect the actual performance in IM to be close to the values obtained.

Figure 3(d) shows the percentage of links that exceed the calculated IM throughput value depicted on the X-axis. These results show that HomePlug 1.0 stations provide superior coverage and throughput compared to IEEE 802.11b stations in IM.

From the statistics, we make the following key observations

1. HomePlug 1.0 had a larger maximum throughput that 802.11b(about 1 Mbps larger).
2. On 60% of the links HomePlug 1.0 performed better than 802.11b links in MIM,
3. On an average basis, HomePlug 1.0 gave approximately 0.2 Mbps higher TCP throughput than 802.11b in MIM,
4. In 6 of the 20 houses tested, IEEE 802.11b failed on at least one link,
5. In 2 of the 20 houses tested, HomePlug 1.0 failed on at least one link,
6. On an average basis, HomePlug 1.0 gave approximately 2.3 Mbps higher TCP throughput than 802.11b would be expected to give in IM.

In summary, HomePlug 1.0 was found to provide better coverage and slightly better average TCP throughput than IEEE 802.11b in modified infrastructure mode, which would be typical for Internet access. In infrastructure mode, HomePlug 1.0 was estimated to have throughput about 2.3 Mbps greater than 802.11b. For shorter line-of-sight distances, 802.11x performed better than HomePlug 1.0, but for longer distances, the nearly continuous adaptation capability of HomePlug 1.0 allowed it to make better use of mediocre channels.

B. TCP Link Stability

QoS algorithms usually deal with admission control and resource allocation. Admission control is concerned with the acceptance of new connections, while resource allocation deals with packet-level throughput, delay, and fairness. In either case, predictability is desirable.

Previous studies [8] showed that high channel error rate will reduce the effective bandwidth available for applications, thus negatively affecting application performance. This problem is even more severe for multimedia applications, which typically have bandwidth, delay, and jitter requirements for effective operations; it is important for them that the link remains stationary. However, the 802.11a/b displayed link instability when the PHY data rate was low. This section studies TCP link stability from the realtime capture of 802.11a, 802.11b, and HomePlug 1.0 packets.

During testing, when connection speeds were less than 3 Mbps, the wireless network became unstable. This might have been due to problems in rate adaptation. The 802.11b standard indicates around a 4 dB difference in signal strength between 11 Mbps and 2 Mbps mode. Since the signal strength changes continuously with time (for example, due to movement of people), PHY rate adaptation may cause packet drops that make the wireless network unstable when using TCP. During our tests, few links were found with throughputs in the 1 to 3 Mbps range. To find out the cause of this phenomenon, we used real time packet capture to monitor the TCP link stability. TCP throughput was measured at 100 msec intervals.

Figure 4(a) and 4(b) shows real time captures of typical high speed and low speed links of 802.11a. High speed links have a mean data rate of 20 Mbps, while it is 5 Mbps for low speed links. Note that the link performance from Mobile station to AP server and from AP server to Mobile station (separated by a 3 second delay) are both shown in the figures.

For high speed links, Figure 4(a) shows irregular throughput dropouts during transmission. For AP to mobile link, the throughput differences from one sample to the next can be as high as 22 Mbps. This kind of behavior is exhibited by TCP when packets are dropped. These instabilities would make it very difficult to guarantee QoS. Similar instability was observed for the link from Mobile to AP. A maximum throughput difference of 23 Mbps was observed in this case.

When the data rate of the link was low (Figure 4(b)), the throughput also displayed large variations. A maximum throughput difference of 13 Mbps was observed. For Mobile to AP, a maximum throughput difference of 10 Mbps was observed.

Figure 4(c) and (d) shows the real time capture for a typical high speed and low speed links using IEEE 802.11b. High speed links for 802.11b are links with a data rate over 4 Mbps; low speed links for 802.11b are links with data rate lower than 2 Mbps. The same criteria were applied to the HomePlug 1.0 networks.

Figure 4(c) shows that the 802.11b links were typically more stable than the 802.11a links. However, there were two dropouts - one in the link of AP to Mobile, and the other one is in the link of Mobile to AP as indicated by circles in the figure. This type of dropout often appeared in other captures. In this figure, the maximum throughput differences observed was about 6 Mbps.

Figure 4(d) shows the real time capture for a typical low speed of 802.11b link. For AP to mobile link, the throughput differences can be as high as 3 Mbps. For Mobile to AP link, A maximum throughput difference of 3 Mbps was observed in this case.

Note that the throughput variation is critical at low data rates. User experience will be poor for links with such throughput variations. For example, under these marginal conditions, a file transfer might halt due to excessive packet drops. Applications can crash or show strange behaviors - an extremely unpleasant situation for the user. These links can be considered equivalent to no-connects, in the sense that users will not use these wireless links.

The HomePlug 1.0 TCP link stability is depicted in Figure 4(e) and (f). The figure shows that HomePlug 1.0 provides a fairly stable TCP link on high speed connections. There are no dramatic dropouts during the test. The maximum variation we observed in the figure was 3.6 Mbps for high speed links.

The figure also shows an interesting stair-wise rate adaptation on the transmission from Mobile to AP on the low speed link. This effect is a manifestation of the channel estimation mechanism. Noise over power lines tends to vary with the line cycle. In HomePlug 1.0 stations, the channel estimation is done asynchronously using a small channel estimation packet. Thus the estimated data rate varies depending on when the packet arrives with respect to the line cycle. Thus different channel estimations (typically done every 5 seconds) will result in a different throughput, and hence this stepped behavior. However, the TCP links can be assumed to be stable between channel estimation cycles.

During our testing, we observed that IEEE 802.11b links that operated below 1 Mbps are highly unstable and are frequently marked by disconnects.

VI. Discussion and Conclusions

The main goal of this paper was to conduct a practical and theoretical comparison of the IEEE 802.11x and HomePlug 1.0 protocols and their capabilities in providing networking functionalities. This was done through theoretical analysis and by a thorough field test conducted in 20 houses to obtain the performance of IEEE 802.11b/a and HomePlug 1.0 products.

From the theoretical results shown in Table I, it can be derived that HomePlug 1.0 and 802.11x have similar maximum efficiency. The significantly higher maximum PHY data rate of 802.11a would indicate that it should perform better than the other two standards, but in field tests its coverage was not as good. In the field tests, the 802.11x products were configured as they came out of the box, and in some cases the wireless links may have used the RTS/CTS (Request To Send/Clear To Send) mechanism needed by 802.11x to handle hidden nodes. Use of RTS/CTS can have significant effects on the performance of the 802.11x protocols. RTS/CTS overhead degrades throughput and is most significant at high data rates, theoretically costing up to 10% in throughput performance. However, use of RTS/CTS can improve performance when there are collisions, as one can expect even on a single link when there are asynchronous, bidirectional exchanges (as TCP does by acknowledging received segments). 802.11x infrastructure mode (IM) also degrades performance, as opposed to modified IM (MIM) or ad hoc mode. In field tests, ad hoc mode was found to be nearly unusable over any but short distances. Fortunately, MIM would be typical for connection to an internet access point, which one might expect to bear the greatest amount of traffic. The wireless protocols have an advantage that these tests cannot show, which is their use of multiple channels. With three channels available, one could expect the wireless protocols to perform better under congested conditions, whereas the PLC protocols use all of the available bandwidth for a single channel.

Coverage is much harder to predict theoretically, but field tests showed that HomePlug 1.0 had the best coverage, followed by 802.11b, with both trailed significantly by 802.11a. The latter only functioned over line-of-sight distances under 50 ft., and had complete coverage in only one of the 20 houses tested. IEEE

802.11b had severe coverage problems in houses over 4000 sq. ft., and had non-connects or marginal links in more than half of the houses tested. HomePlug 1.0 provided 100% coverage in all but two of the houses tested. This showed convincingly that the absence of an RTS/CTS mechanism in HomePlug 1.0 is not likely to be a problem for single home deployments. Whether or not it is an issue for multiple residences serviced by the same transformer remains to be seen.

Throughput showed more interesting behavior. The throughput of IEEE 802.11a was nearly always very high on links less than 50 ft. line of sight, but dropped to zero for links longer than this. 802.11b and HomePlug 1.0 showed crossovers in the percentage of links with data rates meeting some target rate. With its better coverage due to a more robust PHY and MAC, HomePlug 1.0 did better at meeting minimal data rates, but was surpassed by 802.11b at rates around 4 Mbps. For data rates of 5 Mbps and higher, HomePlug 1.0 retook the lead due to its slightly higher maximum data rate. HomePlug 1.0 also showed a much more gradual curve, due to its greater range of PHY data rate selections for adapting to the channel.

The continuum of link speeds also allowed HomePlug 1.0 to exhibit greater link stability (as measured by short term variability in TCP throughput). Effects of channel estimation at 5 second intervals and variability of the channel due to the 60 Hz line cycle were evident in these tests. IEEE 802.11b showed greater variability in both low- and high-speed links, most likely due to its sparser choices in adaptation to channel conditions. 802.11a had tremendous and frequent speed fluctuations, which brings into question its ability to offer QoS guarantees for multimedia applications.

Both PLC and wireless technology have scope for improvements over the exist standards as evaluated in this paper. For PLC networks, larger bandwidth, the use of higher order modulation, more powerful forward error correction technique, and improved channel estimation can substantially improve performance. Wireless technologies can also invoke similar enhancements along with larger transmit power and antenna diversity to achieve significant improvement. However, increasing crowding in the 2.4 GHz ISM bands used by 802.11b/g are likely to degrade their performance in locations where they must co-exist with competing transmitters (including BlueTooth, HomeRF, 2.4 GHz phones, microwave ovens, etc.).

Despite its problems, there are still situations for which wireless technologies are needed. Mobile users with handheld devices and nomadic users without access to power outlets will require wireless connectivity. For nomadic users who are able to plug into the home power distribution system, however, PLC offers a robust, stable, and speedy alternative. PLC solutions will be even more desirable for providing QoS support for multimedia applications with the future and emerging PLC technologies offering data rates in excess of 50 Mbps.

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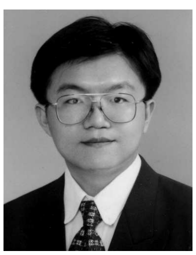

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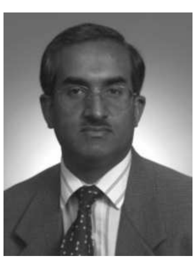

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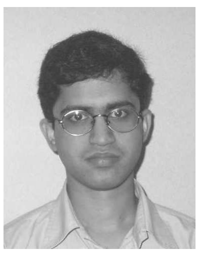

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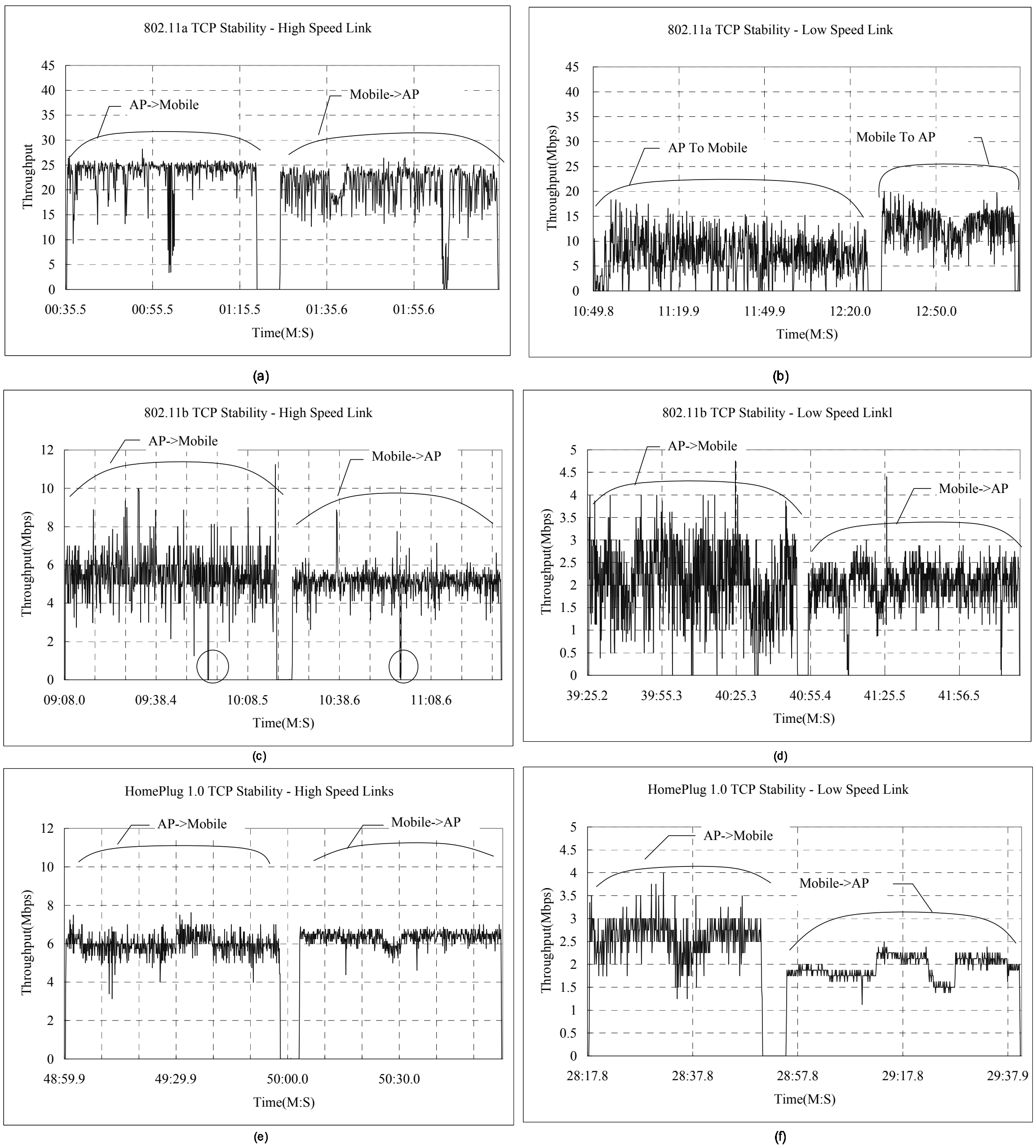

Fig. 4. IEEE 802.11a/b and HomePlug 1.0 Realtime Capture