Characterizing the End-to-End Performance of Indoor Powerline Networks

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1. INTRODUCTION

In 1998, Dave Clark asked the question: "Are powerline networks ready for prime time?" [2] The paper considered the state of Powerline communication (PLC) technology for connectivity *to* the home, as well as networking *inside* the home.

Today, given the easy availability of technologies such as DSL, Cable, and FIOS, it is difficult to imagine a role for PLC for providing Internet service *to* the home. However, the question about usefulness of PLC for in-home networking is even more relevant today than it was in 1998. Internet usage and popularity has exploded, and good connectivity inside a home is no longer a luxury, but a requirement. And yet, we find ourselves in the situation where many older homes are not wired for Ethernet (re-wiring them is an expensive proposition), and WiFi spectrum is so overcrowded [1], that in high-density urban environments people have trouble setting up a high-performance WiFi network inside their house.

Does PLC offer a viable alternative to WiFi and wired Ethernet for home connectivity? The equipment manufacturers [5] will certainly have you believe so. But independent verification of these claims is hard to come by. In fact, the research on PHY aspects of the protocols involved [7, 3, 8] suggests that these networks are vulnerable to numerous problems such as line noise. What are the implications of these problems to performance seen by higher-layer protocols? There has been very little work in the networking community to answer such questions.

In some ways, the state of research on PLC networks of today resembles that of wireless networks in mid-1990s: there was plenty of literature on PHY-layer aspects (technologies such as OFDM have a long history), the MAC protocol was well-specified, and some equipment was commercially available. Yet the implications of the behavior of PHY and MAC layer protocols on the rest of the networking stack was not well-understood. Since then, we have come a long way, and such issues have now been thoroughly investigated.

This paper represents an early effort to understand the impact of PLC networks on higher layers of networking stack. Our task is made difficult by a number of issues. First, the powerline adapters don't have an open architecture; one has to treat them as black-boxes. Second, the detailed MAC and PHY layer specifications are not publicly available. We rely on a summary white paper [5] for initial understanding of the protocols involved. Third, unlike WiFi networks, these networks can not be "sniffed" at MAC layer without using special equipment (which we do not have). Fourth, equipment from multiple vendors does not always interoperate. Fifth, setting up a "clean" powerline network is not easy.

In the face of these difficulties, we are limited to studying the PLC behavior using end-to-end measurements. Our main findings are that the performance of PLC networks in the home environment is good, but it is far worse than the best-case, rosy scenarios painted by the manufacturers. We explore how simple household devices such as a blender and phone charger significantly impact the performance of these networks. We also explore the MAC protocol behavior and impact of cross-traffic on round-trip times.

Our hope is that this paper will get the wider research community interested in exploring this relatively virgin territory. We certainly plan to continue our studies further. In the future, one can even imagine such networks being deployed in controlled environments such as data centers: these are already well-wired for power distribution, why deploy a second wiring harness for networking, if you don't have to?

2. POWERLINE ARCHITECTURE

We performed experiments with Linksys HomePlug AV (HPAV) powerline PLK200 adaptors, which are advertised to support PHY data rates of 200 Mbps and information rates of up to 150 Mbps. Earlier HomePlug standards support data rates between 14–85 Mbps. We do not take into consideration earlier standards and devices even though they are advertised to co-exist. The HomePlug AV standard [5] is widely adopted by many companies including DLink, Linksys, Aztech, Belkin, Cisco, and Netgear. An HPAV adaptor provides an interface between an IEEE 802.3 Ethernet and the HomePlug-defined MAC and PHY layers.

Note that the HomePlug AV standard is not publicly available and most details in this paper were gleaned from whitepapers published on the HomePlug Alliance website [5]. The IEEE P1901 draft standard for broadband over powerline networks is currently under development.

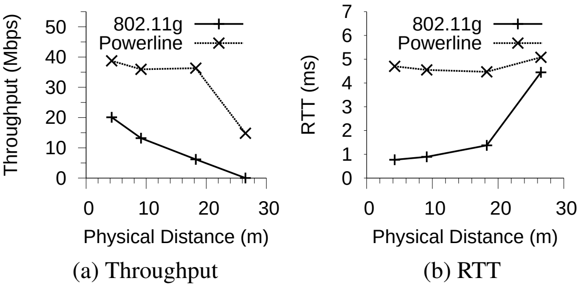
PHY: HPAV devices operate in the 2–28 Mhz range with a 200 Mbps data rate. AC cycle synchronization is used to react to periodic and intermittent appliance-generated line noise. The PHY uses windowed OFDM with 917 independent carriers that can be individually modulated (using BPSK, QPSK, or QAM) based on channel conditions. The PHY also relies on Turbo FEC encoding to provide resiliency to bit errors.

MAC: At the MAC layer, HPAV supports both TDMA and CSMA/CA for data transmissions. TDMA is used when a QoS specification is provided by the higher-level interface, and is intended for audio/video applications. In other cases, CSMA/CA is used to arbitrate access to the medium. CSMA is also used for backwards compatibility with HomePlug 1.0 devices. Each powerline network includes a Central Coordinator (CCo), an adaptor that establishes TDMA slots and manages admission control for connections with QoS requirements. Unfortunately, few details on the MAC protocol are provided in the HPAV whitepapers.

3. EVALUATION SETUP AND METHODOLOGY

We evaluated powerline networks in three different locations: a testbed in an office building, a dormitory, and a house. The office build is a modern structure, built in 1999, housing the Harvard EECS department. The dormitory, which houses over 120 graduate students, is over 110 years old and the electrical wiring has been upgraded in the early 1990s. The house consists of 700 m^2 of living area. It was built in 1992 and there have been no changes to the electrical wiring since.

Our office testbed layout consists of seven powerline adapters connected to embedded PCs running FreeBSD. The nodes are deployed across four adjacent offices in the building. Since this testbed is embedded within a realistic environment, the powerline network is subject to varying AC load and line noise from various electrical appliances, including a large number of computers, desk lamps, several refrigerators, a microwave, and so forth. To isolate these effects, we also performed controlled experiments on an extension cord (EC) consisting of a total of 575 feet of extension cords connected to each other. One end of the EC was plugged into an AC socket in the office building. While the EC is therefore affected somewhat by line noise, it is still beneficial because (i) we can connect powerline adapters on the same segment and (ii) we control the additional line noise on the EC via electrical appliances connected to it. The dormitory and home measurements were conducted with a pair of powerline adaptors connected directly to laptops.



(a) Throughput (b) RTT

Figure 1: *Comparison of powerline performance against a one hop 802.11g link in the home environment*

We treat the powerline adapters as black boxes since (i) the HomePlug AV standard is not published or freely available and (ii) these devices are not programmable. Instead we rely on [5] which lacks technical depth and precise details on the HomePlug AV standard. Therefore, we use end-to-end networking measurements to reason about the performance of such devices. We use the EC to perform controlled experiments that help explain how various factors such as AC line noise or simultaneous transmitters affect performance of the network. Network measurements were performed using a combination of standard tools including `iperf`, `ping`, and `tcpdump`.

4. EVALUATION

The overall goal of our evaluation is to determine if indoor PLC networks have matured to the point of being deployed in homes. This entails studying if powerline networks (i) are impacted by distance, (ii) have high capacity, (iii) low latency, (iv) support multiple transmitters and heterogenous traffic patterns, and (v) can cope with interference from household electrical appliances.

While our focus is on home networks, we will also study PLC performance in an office environment. The contrast between results in the home and office settings is interesting.

Effect of distance: Since the performance of wireless networks is greatly affected by distance, we study how the performance of PLC networks is affected by distance.

We measured TCP throughput (using iperf), and RTT (using ping) between a pair of nodes in a home PC network. We varied the node positions to vary the distance between the nodes. We were constrained to some degree by the location of wall sockets. At each location, we also measured the one-hop wireless throughput (802.11g) between the nodes, by creating an ad-hoc network between the nodes.

Device	Wattage
Phone charger	5
Lamp	150
Blender	350
Microwave Oven	1200

Table 1: *Wattage for various household electrical appliances*

As seen in Figure 1, the TCP throughput fall off for wireless is much more dramatic as the distance increases whereas powerline continues to deliver much better performance. At the furthest distance the throughput achieved on the wireless link was 22Kbps whereas for the same distance a throughput of 14.81Mbps was achieved on the powerline link.

Similarly, the RTT for the wireless link increases with distance while powerline tends to remain stable all along. Thus, powerline is able to deliver good capacity and stable latency to areas of the house that could otherwise not be serviced by a one-hop infrastructure wireless .

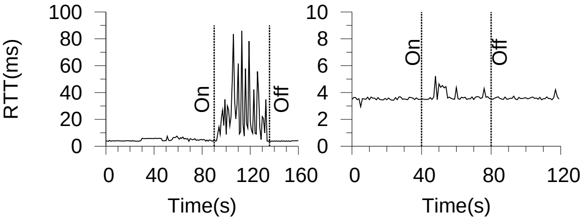
To study the impact of physical distance on throughput, we tried replicating this result on the EC but found distance (in EC length) had no impact on throughput, which remained steady at around 80Mbps. One possible reason is that 575 feet of extension cords are not long enough to show the impact of distance. Another possibility is that TCP the throughput in the house is affected by presence of electrical equipment. We explore this possibility next.

Effect of electrical appliances: The PLC PHY specification [5] hints at the possibility that noise created by electrical equipment will adversely affect PLC performance. To gauge this impact, we carried out the following controlled experiment.

We setup two nodes at either end of the EC. We started a saturating UDP transfer between the two nodes and after a short while, we plugged in and turned on various electrical devices into the EC. After 40 seconds, we unplugged these devices. The results are shown in Figure 2. The wattage of the various devices used is shown in Table 1.

The results show that common households devices significantly impact the effective throughput of PLC networks. It is interesting to note that even though the lamp draws more power than the phone charger, it affects the throughout less. It is probably because the lamp is a pure resistive load, while other devices present inductive and capacitive load as well.

To further examine this issue, we replace the saturating UDP traffic with ping traffic, and re-do the experiments with the blender and the charger. The results are shown in Figure 3. We see that the blender's operation increases the RTT substantially. The phone charger also has an impact, but to a lesser degree. We verified that there was no packet loss. From the summary description provided in [5], it would appear that this behavior is explained by the changing modulation scheme at the PHY layer in response to the AC line noise generated by the blender. For example, at a potentially lower modulation scheme, the time taken to transmit data increases when compared to a better modulation scheme. This is analogous to rate adaptation schemes in wireless networks.



(a) Blender (b) Phone charger

Figure 3: *Impact of electrical appliances on RTT between two nodes*

As further illustration of the the impact of electrical devices on the performance of PLC networks, consider Figures 4 and 5. Figure 4 shows the impact of microwave oven on throughput in a home network. The throughput drops when the microwave oven is on. In Figure 5, we plot the RTT between a pair of nodes in the office testbed over a period of 24 hours. The RTT was measured once every hour using thirty ping packets of 64 bytes each. There was no other traffic on the powerline network. As we see, the RTT shows significant variation throughout the day. We believe that this variation is the result of varying electrical workload.

Simultaneous transmissions: In most home networks, multiple simultaneous network connections are usually active. Thus, it is important to study behavior of PLC under simultaneous transfers. Since the performance of PLC in home environment is affected by the presence of home appliances, we study this using EC.

We performed the following experiment on the EC. We selected a particular node as the sink (node 4). We then picked three other nodes (1 through 3) in various combinations to perform simultaneous TCP transfers to the sink. All four nodes were plugged into the powerline network for the entire duration of the experiment. However,

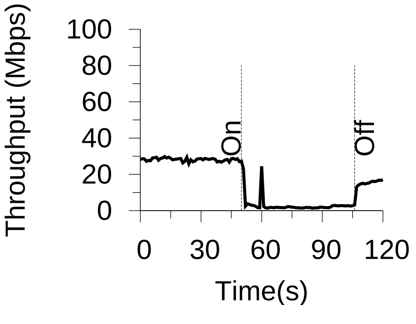
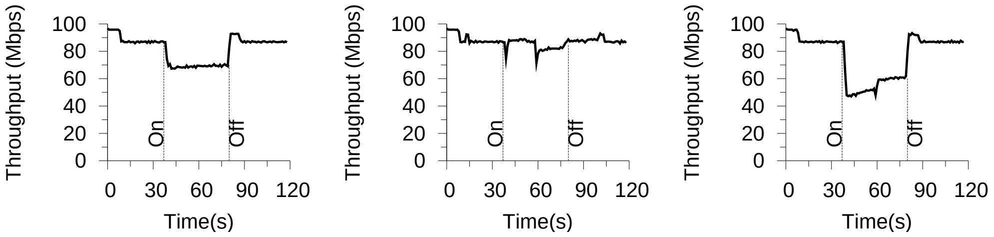


Figure 4: *Impact of a microwave oven on throughput in a home environment*



(a) Phone charger (EC) (b) Lamps (EC) (c) Blender (EC)

Figure 2: *UDP Throughput variation between a pair of nodes on the EC*

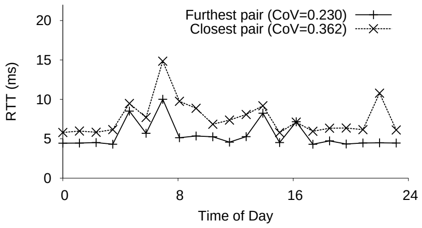


Figure 5: *RTT variation between a two pairs of nodes in the office over a 24 hour time period*

the set of nodes actively transmitting during a particular iteration was determined by each combination. Figure 7 shows the various combinations of nodes and the sum total network capacity for each combination. The x-axis shows the combinations of nodes used in the experiment. We obtain the sum total network capacity by adding up the throughput obtained by each node-sink pair when transmitting simultaneously.

As Figure 7(a) shows, on the EC, for various combinations of transmitters, the throughput is generally divided evenly and the overall network capacity remains the same. We also ran experiments on the EC with multiple sinks and we found the results were similar to the single sink case presented here.

In a realistic setting, a powerline network needs to support a heterogenous mix of traffic patterns. Therefore, it is important to understand the effect different bit-rate traffic has on the throughput and latency in the network. For example, a large file download could potentially severely impact a simultaneous Skype session in progress or a HD video stream could affect a file download. We study the impact cross-traffic of increasing bit-rate has on the RTT in the network. We find as the bit-rate of the cross-traffic increases the median RTT and the spread in RTT values increase.

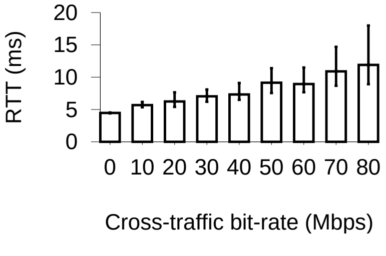
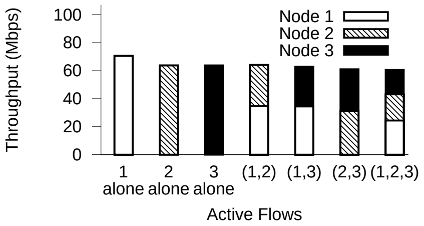


Figure 6: *Impact of cross-traffic (of increasing bit-rate) on RTT with 25th and 75th percentile error bars for powerline and ethernet*

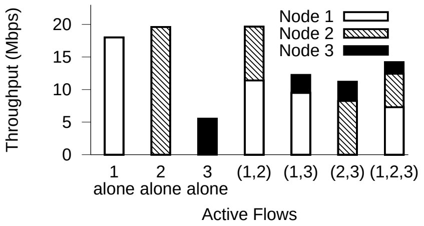
We demonstrate this with the following experiment on the EC. We started a constant bit-rate UDP between two nodes. This is the cross-traffic. Simultaneously, we measured the RTT between two different nodes on the same network. For each successive run of the experiment, we increased the bit-rate for the cross-traffic. We used 100 64 byte ping packets to measure RTT. We present the median with 25th and 75th percentile numbers. As Figure 6 shows, as the bit-rate for the cross-traffic increases, the median values as well as the spread in the RTT measurements also increase.

We repeated this experiment in the office setting, and plot the results in Figure 7(b). In this setting, nodes 1 and 2 achieve higher throughput when running alone (19 and 20 Mbps respectively) than node 3 (5.5 Mbps), possibly because of poor connection around node 3. We also see an interesting property of the PLC MAC. When node 3 is active with any other flow (or a combination of flows), it brings down the capacity of the network. However, the drop in capacity is different from what is observed in the rate anomaly problem of multi-rate CSMA systems, such as Wi-Fi [4]. In rate anomaly, the throughput of all nodes in the system is approximately the same, and therefore the capacity of the system is governed by the poorest performing node in the system. In our experiment, as we see in Figure 7(b), the throughput of all nodes drops proportionally to the contention in the network, and the throughput of the better performing node (nodes 1 and 2) is still much greater than the throughput of the poorly performing one (node 3). For example, when there are two contending nodes, 1 and 3, node 1 gets 9.48 Mbps, and node 3 gets 2.36 Mbps, which is approximately half of their standalone throughput.

The above experiment is inconclusive on the TDMA or CSMA behavior of the PLC MAC. And since the MAC does not have any open documentation, we decided to further explore the behavior of the PLC MAC with another experiment. We set up two PLC devices to constantly unicast 1470 byte packets to a third PLC device



(a) Extension Cord (EC)



(b) Office

Figure 7: *Network capacity being shared when multiple nodes transmit simultaneously to a common sink*

on the EC, and at the receiver we measure the number of consecutive frames that are received from the both the senders. We plot the CDF of the number of consecutive frames from one sender in Figure 8. The CDF for the other sender was similar. For comparison purposes, we also plot results of a similar experiment over Wi-Fi. Since Wi-Fi uses CSMA, each sender has an equal opportunity to send at any time. Hence, the number of packets sent by a node before another node transmits is very close to 1. However, as is clear from the figure, the PLC MAC does not use per-packet CSMA, the MAC used by Wi-Fi. Instead, every time a PLC device gets access to the medium, it sends a chain of packets, which in this case is a multiple of 10. The number of consecutive packets changed for smaller packet sizes. We hypothesize from these results that the PLC network uses a slotted MAC, either TDMA or slotted-CSMA, and is different from the Wi-Fi MAC, although we are still exploring an alternative explanation based on capture effect.

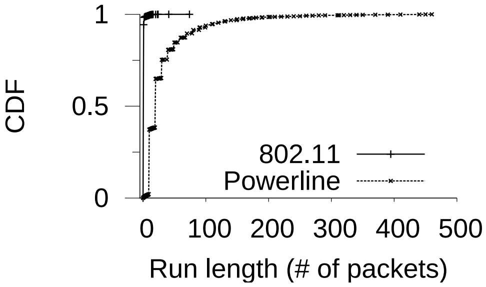


Figure 8: *CDF of run length for two contending nodes in 802.11 wireless vs Powerline*

Channel symmetry: Wired ethernet communication is symmetric and prior studies [6] have shown wireless links tend to be asymmetric. The cause of asymmetrical links in wireless networks are numerous, including interference from devices near the sender or the receiver. While channel asymmetry does not always affect user performance, it can have impact on design of higher-level protocols.

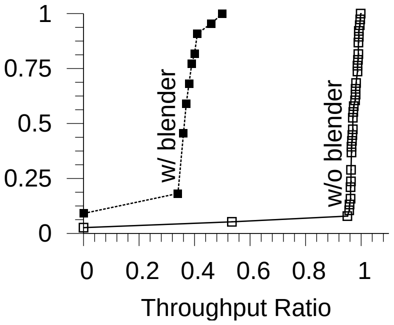


Figure 9: *Channel symmetry measured using the throughput between two nodes on the EC. The x-axis is the ratio between the lower throughput in one direction and the higher throughput in the opposite direction*

To explore channel symmetry in PLC networks, we performed the following experiment. We set up a pair of nodes connected on the EC. We repeatedly measured the TCP throughput between two nodes in both directions. For each pair of measurements, we took the ratio between the higher and lower throughput. This ratio is the x-axis and the y-axis is the CDF of these ratios. Symmetry in an ideal powerline network is represented by a vertical line at x=1.0. As seen in Figure 9, the EC represents a generally symmetric channel. This is not surprising. In each direction we get about 60Mbps of throughput.

We then plug in a blender in the EC, roughly halfway between the two nodes. We repeat the experiment with the blender running. As one would expect from results in Figure 2, we find that throughput in both direction drops. However, surprisingly, we find that throughput in one direction drops to 40Mbps while the throughout in the other direction reduces to 19 Mbps. This results in significant asymmetry, as shown in Figure 9. Thus, we find interference from electrical appliances introduces asymmetry in powerline communication. We are currently investigating this issue further. Interestingly, we have found that in office environment, the TCP throughput show significant asymmetry. We believe that this is because of normal electrical equipment usage in the office environment.

5. DISCUSSION

We now discuss other practical issues in the deployment of PLC networks.

The performance of a PLC device depends on the location of the power outlet. For example, PLC devices do not work across surge protectors, and other voltage inhibiting equipment. Also, PLC devices perform worse in a network with more AC load, which is generated by electrical appliances (refrigerator, blender, etc.). Consequently, power outlets should be carefully chosen to get the best performance from the PLC network.

PLC networks might not be suitable for applications that have extremely low RTT requirement. The reason is that in all our experiments, the minimum measured RTT between any two powerline devices was 3.8 ms. We do not have a definitive explanation for this observation yet.

PLC networks support some basic security primitives. In most cases, the data from an indoor PLC network will not bleed into an outdoor network since power line communication does not work across step up and step down transformers. Even within the network, PLC devices support encryption, and devices need a key to join a network. Multiple PLC networks, each with its own key, can coexist on the same wire.

6. RELATED WORK

Most prior work on PLC networks has focused on PHY-/MAC layer design, and characteristics, and has been done primarily using simulations. To the best of our knowledge, there has been very little work on evaluating these networks from an end-user perspective.

In [7], authors detail the HomePlug 1.0 specification. The evaluation is limited to measuring end-to-end TCP throughput between two pairs of nodes by increasing distance between the two. The authors in [8] perform a few field tests with HomePlug 1.0 which are limited to studying the impact of UDP flows at different bit rates and a FTP transfer on the overall network capacity.

Gutierrez et al. [3] study an outdoor as well as an indoor powerline network that uses the DS2 powerline standard. The authors study the relationship between TCP/UDP throughput and packet sizes on these networks. They also examine how TCP/UDP throughput vary when multiple transmitters as used, as a function of packet size.

This paper primarily differs from prior work in the following aspects: (i) we study HomePlug AV, a relatively new powerline standard, (ii) using end-to-end measurements we show how interference and simultaneous transmitters affect overall network capacity, (iii) our results evaluate the performance of powerline networks in realistic settings.

7. CONCLUSION

The main contribution this paper makes is that it evaluates the end-to-end performance of PLC networking. Out of necessity, we treat PLC devices as black boxes. We study characteristic such as channel symmetry, variation by time of day, impact of distance, impact of electrical appliances and simultaneous transmitters. We find that in a large home environment, PLC can deliver better performance when compared to wireless. However, we also find that (i) the performance is substantially lower than manufacturer's claims (no surprise here), and (ii) common household appliances affect the performance significantly.

Therefore, we conclude that PLC in home environments is useful, but the user experience may vary significantly. In other words, we are cautiously optimistic.

8. REFERENCES

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