Exploring Powerline Networking for the Smart Building

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ABSTRACT

The SmartGrid is ushering in an era of new IP endpoints that already reside on the power grid today, but lack network connectivity. Many of these endpoints – refrigerators, air conditioners, and power strips – will be networked wirelessly. However, since they already exist on the power grid, a natural question is whether they might be networked over the same wires that supply their power. Such an approach would allow SmartGrid sensors to vacate increasingly congested spectrum and allow information to flow along the same path as power, perhaps simplifying deployment in the short term and deep demand response in the long term. In this paper we explore the current state of Powerline Communications (PLC) and explore the efficacy of PLC as a sensor network backbone in a modern building. We evaluate several different PLC modems in both end-to-end and multi-hop configurations. We further analyze building blueprints to identify and correlate several PLC "disruptors" – building facets that inhibit PLC. Our preliminary results show that PLC is a promising technology for networking sensors in the Smart Building. However, a number of anomalies suggest a more in-depth study is warranted.

Categories and Subject Descriptors

B.4.1 [**Hardware**]: Input/Output and Data Communications—*Data Communications Devices*; C.2.5 [**Computer Systems Organization**]: Computer-Communication Networks—*Local and Wide-Area Networks*

General Terms

Experimentation, Measurement, Performance, Reliability, Standardization

Keywords

Powerline Communications, PLC, IPv6, 6LoWPAN, Sensor Networks

1. INTRODUCTION

A growing number of *wireless* sensors are being used to instrument *wired* loads in support of SmartGrid efforts. The goal, in many cases, is to increase visibility and control over building loads to make them more responsive to the supply and demand of grid power. Today, most of these sensors connect wirelessly, and some employ IP-based communications, to support data collection and device control [4, 6, 13]. A natural question that arises, since these devices are already attached to the electrical wiring within a building, is whether the power wires might also be used for network connectivity. Much like the Power-over-Ethernet (PoE) technology has simplified powering a range of networked devices (e.g. IP phones, wireless APs, and sensor gateways), IP-over-Power ("IPoP") could simplify the deployment of smart and responsive plug loads.

Powerline Communications (PLC) is a decades-old technology that is experiencing a new renaissance. While it is an appealing technology to facilitate and simplify networking, PLC has not yet seen widespread adoption. One reason for the slow growth of PLC is a general malaise that the technology simply will not work and will not scale, as described to us by utility industry insiders. PLC has seen some growth in residential networking [12], but to the best of our knowledge, has seen relatively little commercial- and industrial-scale deployment. Previous work has performed an in-depth analysis of PLC technology in theory, laboratory, and home settings [5], as well as in extremely harsh environments [7], however we are unaware of any investigations exploring the operation and dynamics of large PLC network, nor any PLC network in a medium to large scale building.

In this paper, we begin to explore the challenges of using existing building wiring to network intelligent plug loads. We ground our study in a modern computer science and engineering building. This work seeks to identify the powerline networking characteristics of such buildings, and in so doing, determine the feasibility of networking with PLC. We also seek to identify potential PLC "disruptors" – building facets that would inhibit PLC – and find unintended (over-the-air) coupling between adjacent power subtrees, physical attenuators, and wiring anomalies. Our preliminary results suggest that a building-wide PLC network is plausible, leaving to follow on work the details of its design, construction, and evaluation.

The rest of this paper is organized as follows. Section 2 provides an overview of PLC Technology, including a brief survey of technologies, standards, and implementations. Section 3 describes our testbed – a university building – and details the electrical "subnets" of the building's fourth floor. Section 4 describes our experiments, including assessment noise floor, connectivity, broadcast performance, and electrical interference. Section 5 summarize our findings and identifies future work.

Technology	PHY Bitrate (Ideal)	Modulation	MAC Datarate (Empirical)	Standard / Proprietary	Application Space
X10	20 bps	ASK	N/A	Standard	Basic Home Control
Insteon	2,880 bps	BPSK	N/A	Proprietary	Basic Home Control
Ariane	30 kbps	FSK	N/A	Proprietary	Building Control
HomePlug 1.0	14 Mbps	OFDM	1-5 Mbps	Standard	IPoP
HomePlug AV	200 Mbps	OFDM	45-80 Mbps	Standard	IPoP

Table 1: A summary of PLC technologies comparing listed (marketed) PHY speeds and the (more practical) measured MAC speeds.

2. PLC BACKGROUND

Several different major PLC technologies have emerged over the years including X10, Insteon, Ariane, HomePlug 1.0, and Home-Plug AV, as shown in Table 1.

X10 was the first PLC technology and is widely deployed in home automation and hobbyist setups where basic connectivity is all that is required and bandwidth is not of much value. X10 sends bits on the zero-crossings of the 60 Hz AC wave. This vastly simplifies X10 controllers, as there is no need for any form of synchronization beyond the 60 Hz AC line. While useful in its domain, X10's limited throughput make it unsuitable as a network backbone, even for low-rate sensor systems at modest scale.

Insteon is both a company and a PLC protocol specification. It aimed to be an iterative improvement over X10 as all Insteon devices are backwards-compatible with X10, despite being a completely different protocol (Insteon devices have two modems to facilitate this function, which should be considered primarily as further evidence for the low cost of X10 hardware). Insteon utilizes Binary Phase-Shift Keying (BPSK) on a 131.65 kHz carrier wave which allows for a sustained data rate of nearly 3 kbps [3]. Operating at a relatively low carrier frequency, Insteon is sometimes vulnerable to interference from electrical devices introducing noise into the system. In addition, Insteon's bandwidth still remains too limited to be feasible as a network backbone, especially as the number of endpoints grows to dozens or hundreds.

Ariane Controls introduced another proprietary PLC protocol. It utilizes narrowband Frequency Shift Keying (FSK) with a run-time configurable carrier (50-500kHz). This allows for PHY speeds of up to 30 kbps. This milestone is particularly noteworthy as it is on par with first generation 802.15.4 networks in the 868/915 MHz bands (20/40 kbps PHY respectively). In addition, Ariane provides easily available hardware for immediate development to both small-scale and large-scale distributors.

HomePlug 1.0 is the first PLC technology geared towards networking over power lines. The underlying technology is Orthogonal Frequency Division Multiplexing (OFDM) on any of 84 channels (76 in the US) ranging between 4.49 and 20.7 MHz. HomePlug 1.0 has a theoretical upper bound of 14 Mbps throughput, however such speeds are rarely achieved outside of ideal conditions. One measured home found 5 Mbps between 80% of endpoints and at least 1 Mbps between 98% of endpoints [5]. Our experiments confirm these findings, and furthermore show that in a modern office building with new wiring, it is possible to achieve nearly 5 Mbps.

HomePlug AV is the newest PLC standard, introduced in August 2005. It offers a throughput of about 80 Mbps at the MAC layer (it is worth noting that the physical layer achieves 200 Mbps, and is often the marketed number, however not the practically observed figure). HomePlug AV also utilizes OFDM, although it uses adaptive modulation and a slightly wider frequency range (1.8 to 30 MHz) to reach 1155 OFDM sub-carriers, far exceeding HomePlug 1.0's 84 [10]. Our experiments found much greater variation in achieved throughput with HomePlug AV, in some cases ranging from 45 Mbps to 80 Mbps on the same physical connection.
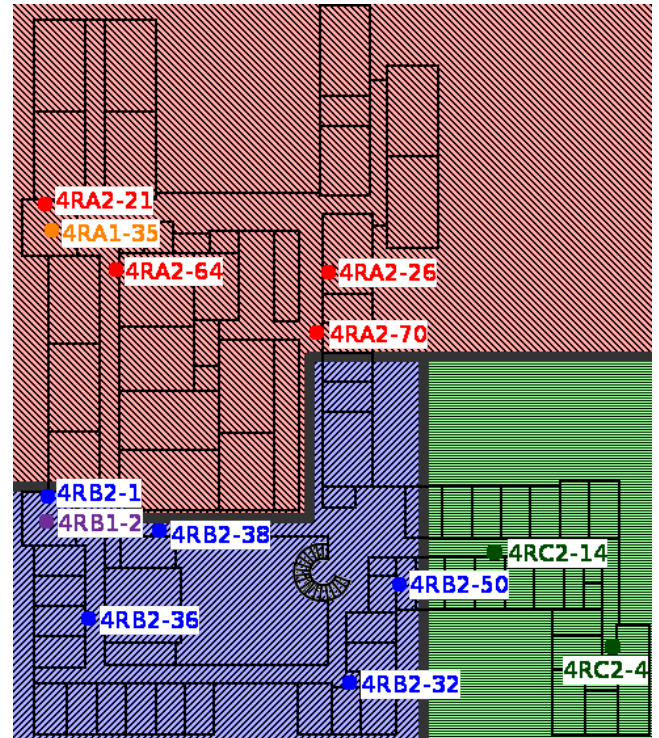

Figure 1: An annotated schematic of the 4th floor of the CSE building. The 4th floor (4R) is subdivided into 3 electrically distinct sections (4RA, 4RB, 4RC), which are further subdivided into two primary circuits (e.g. 4RA1, 4RA2). Nodes (outlet boxes) are each uniquely numbered (e.g. 4RA2-21).

A new spec, HomePlug AV2 is currently under active development and is expected to be complete later this year (mid 2011) [10]. HomePlug AV2 will offer speeds up to 1 Gbps at the physical layer (600 Mbps at the MAC layer).

3. EXPERIMENTAL SETUP

We ran our experiments in the Computer Science and Engineering (CSE) Building at the University of Michigan. CSE is one of the newest buildings on campus, constructed between 2003 and 2005. It has four usable floors that house a mix of offices, labs, conference rooms, classrooms, machine rooms, and large open areas. The upper three floors are architecturally similar. Figure 1 shows the 4th Floor of the CSE building, annotated with our test points and the floor's electrical divisions (or subnets). The floor is divided into three electrically distinct divisions.

We digress briefly now to explain the power distribution of the CSE building. From our understanding, CSE's power distribution scheme is typical of many modern buildings, and thus is an appropriate model.
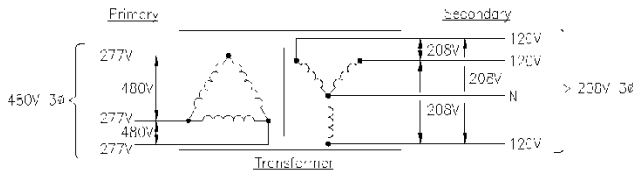
(a) A typical 480 V / 208 Y conversion (here V and Y indicate Delta and Wye transformers respectively). Notice that on the output between any phase and neutral is 120V
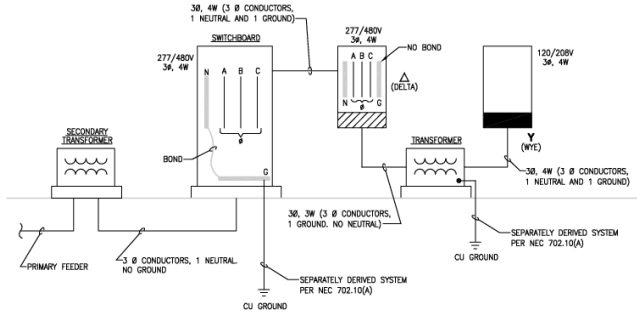
(b) A simplified diagram of a typical installation. Considering section 4A of the CSE building as an example, DP-2DA would be the "Secondary Transformer" in this diagram; TX-4RA1 and TX-4RA2 would be two "Transformer"s.

Figure 2: Diagrams taken from http://www.electrical-design-tutor.com/threephasetransformers.html

The electric company (and a backup generator) provide a 3-phase 480V main supply to the building. This input is fed into several different transformers depending which logical and physical section of the building is being fed. Since lighting and HVAC are generally high-amperage systems, there are great effeciency gains to running them directly at a higher voltage. In the CSE building this means they are run off of two of the three phases of a 480V input line ($120°$ of 480V is 277V). As a result, lighting and HVAC are "electrically isolated" from the "outlet power." This is useful for PLC modems as it provides more isolation from the high-frequency feedback sometimes introduced by fluorescent light fixtures or the electrical noise generated by HVAC equipment. "Outlet power" is fed by a 480 V / 208 Y / 120 V 3-phase transformer, that is, a 480 V to 208 V Delta-Wye 3-phase transformer, with 120 V between each output phase and neutral. Figure 2 shows the details of typical wiring configuration that follows this approach.

Each floor of the CSE building is supplied by six such transformers: TX-4RA1, TX-4RA2, TX-4RB1, TX-4RB2, TX-4RC1, and TX-4RC2; TX-4RA1 and TX-4RA2 are supplied by the common DP-2DA, TX-4RB1 and TX-4RB2 from DP-2DB, and TX-4RC1 and TX-4RC2 from DP-2DC. The previous bears some explanation. Firstly, let us break open the abbreviations and acronyms: "TX" is Transformer and "DP" is Distribution Power (a transformer directly connected to the "power distribution center" – the electric company's lines). Figure 2b shows this graphically. The 4's all indicate the fourth floor of the building, which is the floor that we consider here. The letters 'A', 'B', and 'C' indicate the distribution transformers from which the circuit is drawing. Each distribution transformer powers two step-down transformers (e.g. DP-2DA supplies TX-4RA1 and TX-4RA2). From this initial understanding we hypothesize that the fourth floor is divided into six "electrically isolated" regions, which we shall name 4A1, 4A2, 4B1, 4B2, 4C1, and 4C2.

We introduce some additional nomenclature to ease future discussion. We define 4A, 4B, and 4C to be the three "sections" of the building. We define 4A1 and 4A2 to be two "subsections" within the 4A section. Within each subsection we define a node. A node corresponds to any individual circuit of a subsection, that is to say that in a subsection's breaker box there is one circuit breaker for every node. Typically, nodes represent 2 or 4 outlets on a wall somewhere in the building. When wiring a building, an effort is made to distribute load evenly across the three phase taps of the Wye transformer; thus if a circuit box for 4RA1 had 60 breakers (nodes), one would expect 20 of them to be connected to each phase tap. We name nodes identically to the building blueprints, thus "4RA2-31" would be node number 31 of subsection A2, section A. The largest subsection contained 70 such nodes.

4. EXPERIMENTS AND RESULTS

In this section we explore in some detail the characterisitcs of two PLC modems: A HomePlug 1.0 modem from Netgear (model number XET1001) and a HomePlug AV modem from ZyXEL (model number PLA-401). If data for only one pair of modems is presented, it is assumed to be the HomePlug AV modems.

4.1 Noise Floor

We begin by observing that the power provided in CSE is significantly cleaner than that of a household power network (the more traditional PLC domain). Figure 3 compares the power signature of a student's apartment to that observed in the CSE building. The CSE building's power is much cleaner. This result is promising, as one of PLC's greatest limitations is noise on the power lines. However, as PLC has shown promise in the home - selling over 65 million HopePlug devices to date [11] - we find it a reasonable hypothesis that it will work as well or better in a cleaner environment.

4.2 Connectivity

Our first PLC experiment is one of basic connectivity. The results are summarized in Figure 4. The connectivity aligns well with what we know of the building's power distribution. Nodes on the same electrical subsystem (e.g. 4RA2) are all capable of communicating with one another; nodes on the same section (4RA) but different subsystems (4RA1, 4RA2) are only sometimes capable of weak communication, or in the case of 4RA1-45 and 4RA2-70, no connectivity at all.

We take a moment now to explore the interesting links provided by the nodes 4RB2-1, 4RB2-38, and 4RB1-2 (show in Figure 5). Specifically, we observe that pairwise, 4RB2-1 and 4RB2-38 can communicate, 4RB2-38 and 4RB1-2 can (weakly) communicate, however 4RB2-1 cannot reach 4RB1-2. When a modem is placed at all three of these nodes, 4RB2-1 is still incapable of communicating with 4RB1-2. In fact, only two of the three nodes can ever communicate successfully, depending on initialization order. Whichever link (4RB2-1 <–> 4RB2-38 or 4RB2-1 <–> 4RB1-2) is established first will dominate and the other link's connectivity is lost. This result is extremely interesting as it indicates that *two disjoint PLC networks cannot trivially be joined by the addition of a modem capable of seeing both networks*.

4.3 PLC as a Broadcast Network

We explore further from the previous insight and attempt to briefly characterize PLC as network. PLC nodes form a broadcast network, that is traffic sent from 4RA2-70 to 4RA2-21 will also be seen by 4RA2-26. Broadcast networks, such as WiFi, have scalability problems [14, 16]. Even with a well designed time-division mechanism, only so many nodes can contend and communicate ef-
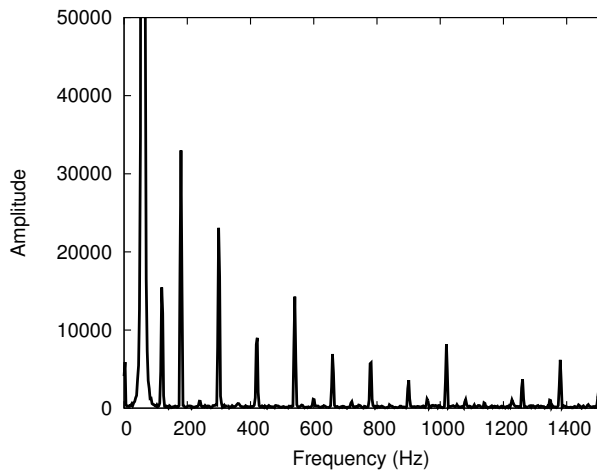
(a) An Apartment Building
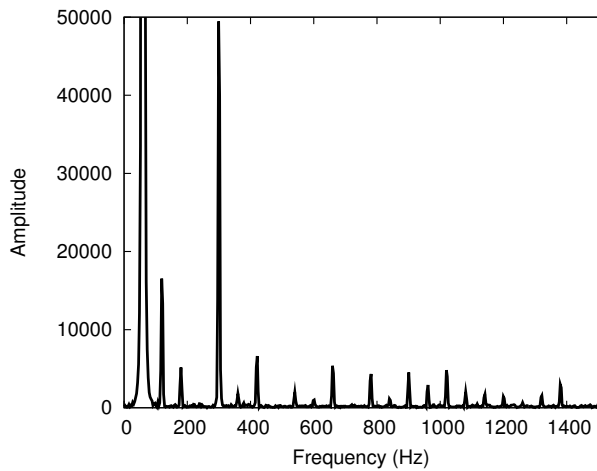
(b) CSE Building

Figure 3: A comparison of the "baseline" noise floor power signatures of an apartment building and CSE. While neither environment has much (any) noise in the 1-30MHz range of HomePlug technologies, we observe a much cleaner line in the CSE building than a home. We infer then that if PLC is shown to work in the home, it should work as well or better in CSE.
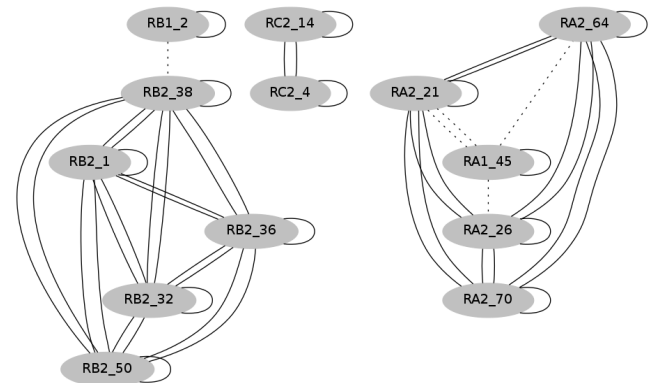

Figure 4: Connectivity of a sampling of nodes. Note that the connectivity indicated by dashed lines is extremely atypical. A node may either connect to all of its solid-line neighbors, or only one of it's dashed-line neighbors; if a node connects to a dashed-line neighbor, it can connect to none of its other neighbors. This bizzare connectivity is shown in more detail in Figure 5.
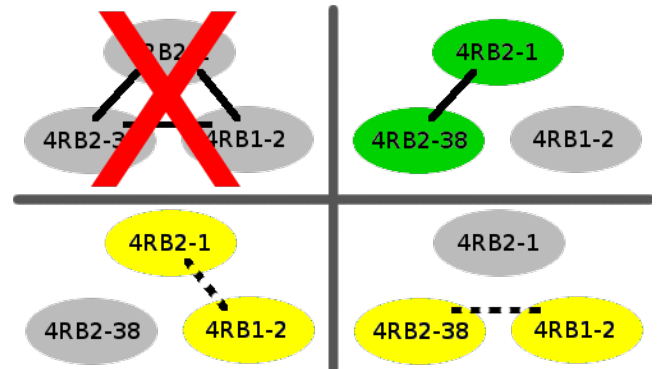
Figure 5: The PLC Connectivity "triangle". In our observation of PLC systems, for a set of nodes to cooperate, all nodes must be able to see one another. If any node established a "weak" link, the two weakly connected nodes would form their own isolated network

ficiently in a single collision domain and still expect successful data transfer to occur. We find, then, the compartmentalization of PLC networks to isolated subsections of the building to be of great benefit rather than issue and we argue that given the current capacity of PLC networking technology this separation of networks is *required* for PLC to be a feasible technology on a building-wide scale.

Continuing with the WiFi analogy, an entire building may be covered by WiFi, but it must be done with several wireless routers, each covering a specific *subsection* of the building; were one wireless router to cover the entire building, the many hundreds of nodes (computers, phones, etc) would not receive sufficient bandwidth to communicate. By the nature of the technology, however, the size of the individual broadcast networks is restricted and individual broadcast networks are connected via Ethernet (or other means). We observe then that PLC is very similar to WiFi: while WiFi is *geographically* isolated, PLC is *electrically* isolated. In PLC, each electrical subsection creates its own, restricted "broadcast" network

with adjacent subsections either bridged or routed. With this comparision in mind, we argue empirically that if WiFi scales, PLC should as well.

Conceptually, the issue of PLC as a broadcast network has been addressed before [15] [2], however to our knowledge it has never actually been tested in practice. Given the plethora of varying PLC models ([9], [8], [1]...), this is distressing. While our initial results would trend towards agreeing that PLC can support many nodes, we are somewhat troubled by the results of Section 4.2, and find the interconnection of isolated PLC networks to still be an open problem. We find then that perhaps mere models of PLC are insufficient, and a true, large-scale deployment is necessary to accurately evaluate the technology.

4.4 PLC and Electrical Interference

One of the most common concerns with PLC is electrical interference, both the interference caused by PLC technology and existing interference disrupting PLC technology. We explored the issue of existing interference in 3, but we cover it more in depth here. We also examine potential interference introduced by the use of PLC.

4.4.1 Interference caused by PLC

Recall that PLC is restricted to a range of 1-30 MHz. PLC modulation is also on the order of hundreds of millivolts, less than 1% of a 120V AC line. The interference caused for other electrical devices by PLC is thus minimal and well within the noise threshold of Figure 3. There is, however, an issue of wireless interference. As PLC is operating at such a high frequency, the power lines themselves can act as antenna elements, radiating PLC signals wirelessly as well as the intended wired. Indeed, we observed this phenomenon on accident, achieving a very weak (~60% packet loss) connection between two disjoint networks physically near each other on one occasion. DSL technology suffers from this same drawback, but most DSL lines are buried underground and extraneous radio waves are absorbed by the Earth. Powerlines, however, are often above ground and causing interference.

In our case, the powerlines run through the building walls, which we have directly observed to be insufficiently dense to block wireless PLC emissions. Fortunately, PLC was designed with this in mind [15]. Recall that PLC is bounded to 1-30 MHz; this extremely limited spectral range is primarily for this purpose. Going lower than ~1 MHz runs into issues of existing interference on the line from other electronic devices; going higher is prohibited not because of physical / technological limitations, rather to limit the emissions from PLC. PLC vastly limits its potential frequency range - and as a consequence its potential line capacity - to prevent generating harmful interference.

4.4.2 Interference affecting PLC

We observed in Figure 3b that the CSE building power is very clean, with little or no noise anywhere near PLC spectra. Assuming that this is similar to other office buildings, we focus instead on interference caused by physical obstacles, specifically we seek to characterize the weak leaks, such as the connection of 4RA1-45 to the rest of the 4RA2 subnetwork.

A preliminary analysis is shown in Figure 6. Here we see a strong difference between an "easy" connection - two nodes on the same powerstrip -, a "medium" connection - two nodes on the same subsection - , and a "hard" connection - two nodes on the same section, but different subsections (there is no connectivity between nodes on different sections). We first observe that both modems intelligently adapt their power profiles to send only as strong a signal as is required to reach the other node. As seen in 6c and

6f, however, there is a maximum power transmission (empirically about 250mV and 350mV for the HomePlug 1.0 and HomePlug AV modems respectively)

To analyze the difference, we first refer you back to Section 3 which disucssed the power distribution in the CSE building. Specifially, we observe that each set of 'well-connected' nodes is in the same subsection, or electrically speaking on the same secondary side of a transformer. Recall that despite being on different phases, each tap of the Wye transformer shares a common neutral, which is likely responsible for the quality signal propogation across an entire subsection.

Next we consider the occasional weak connections between subsections. These connections require the crossing of two transformers, once "up" the Wye->Delta from 4RA1 to 4RA and once "down" the Delta->Wye from 4RA to 4RA2. As transformers are not designed for the transmission of high-frequency components, it is not surprising that the signal is attenuated. Having previously observed what we attributed as wireless communication between nodes, we considered briefly whether this may account for the communication here. We do not believe this is the case, however, as communication succeeded *only* between subsections of the same section. Recall the CSE floorplan (Figure 1), 4RA2 and 4RB2 share a large, long common wall; were wireless accountable for the 4RA1 and 4RA2 connectivity, we would expect it to also be present for some degree of 4RA2 and 4RB2 connectivity, yet none could be found.

5. CONCLUSIONS AND FUTURE WORK

Our results suggest that PLC is a viable technology to network a smart building's wired devices. However, a larger-scale deployment would be needed to validate the preliminary observations at realistic scale and with realistic workloads. We find, surprisingly, that our particular test building – a CSE building – offers much cleaner power (fewer harmonics) than a typical apartment building. A broader corpus of building noise floor data are needed to determine how common this phenomenon is, and whether it could improve the SNR of PLC. We find excellent connectivity within "electrical" divisions or subnets under certain circumstances but we also observe some peculiarities with today's PLC technology, including persistent network partitions, that must be addressed for the approach to be usable.

These results are sufficiently promising to warrant going forward with the exploration of PLC as a viable physical and link layer for wired sensor networks. However, we do not believe that it is a forgone conclusion that PLC will be an ideal physical layer for many devices. Plug load meter design, for example, is already challenging enough having to meter the same wires that provide power. Adding data communications to this interface may complicate an already tricky design space. In the future, we plan to run IPv6/6LoWPAN directly over the PLC "links," scale up our efforts to span multiple floors, and evaluate end-to-end performance of the network over multiple hops with multiple contending traffic flows. Eventually, we envision, that PLC will become just another interface to another physical and link layer, alongside serial and radio.

6. ACKNOWLEDGEMENTS

7. REFERENCES

[1] J. Anatory, M. M. Kissaka, and N. H. Mvungi. Channel model for broadband power-line communication. *Power Delivery, IEEE Transactions on*, 22(1):135 –141, Jan. 2007.

[2] J. Anatory, N. Theethayi, R. Thottappillil, M. Kissaka, and N. Mvungi. Broadband power-line communications: The
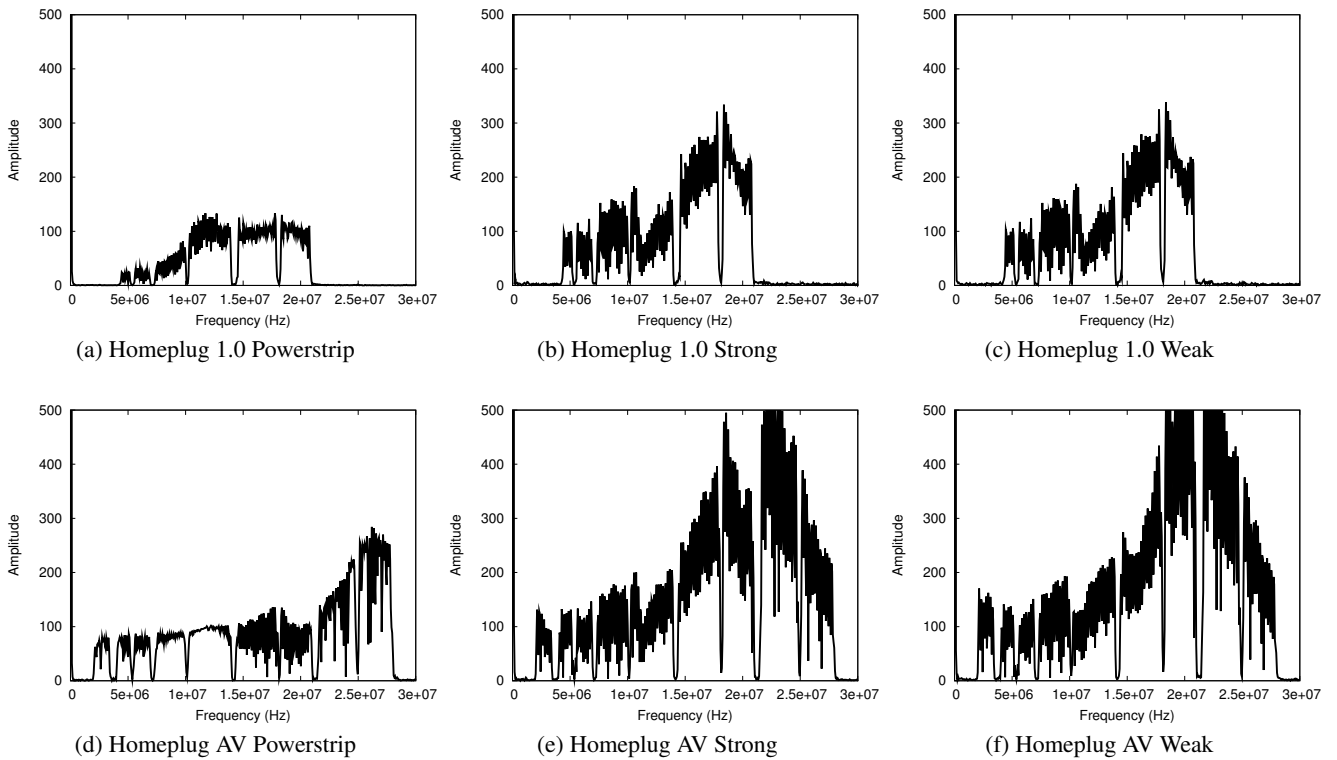
Figure 6: A comparison of the spectra generated by two different PLC modems. All 6 graphs are 1-30MHz on the x-axis and 0-300mV on the y-axis. The first row is a pair of HomePlug 1.0 modems and the second row a pair of HomePlug AV modems. The first column shows the signal when connected trivially via powerstrip, the second column is a connection on the same subsection, and the third column is a connection on the same section but different subsections. Comparing HomePlug 1.0 and HomePlug AV, observe the increased spectrum usage of HomePlug AV, both modems fall perfectly in their specified ranges (4.49-20.7MHz and 1.8-30MHz respectively), providing nice confirmation of the data. As the underlying physical link becomes "weaker", we observe both modems increasing the amplitude of their transmission power, until peak transmit power is reached and link quality ultimately degrades.

channel capacity analysis. *Power Delivery, IEEE Transactions on*, 23(1):164 –170, Jan. 2008.

[3] P. Darbee. Insteon: The details, Aug. 2005.

[4] X. Jiang, S. Dawson-Haggerty, P. Dutta, and D. Culler. Design and implementation of a high-fidelity ac metering network. In *IPSN'09: Proceedings of the 2009 International Conference on Information Processing in Sensor Networks*, pages 253–264, Apr. 2009.

[5] M. K. Lee, R. E. Newman, H. A. Latchman, S. Katar, and L. Yonge. Homeplug 1.0 powerline communication lansâĂŤprotocol description and performance results. *International Journal of Communication Systems*, 16(5):447–473, 2003.

[6] J. Lifton, M. Feldmeier, Y. Ono, C. Lewis, and J. A. Paradiso. A platform for ubiquitous sensor deployment in occupational and domestic environments. 2007.

[7] E. Liu, Y. Gao, G. Samdani, O. Mukhtar, and T. Korhonen. Powerline communication over special systems. In *Power Line Communications and Its Applications, 2005 International Symposium on*, pages 167 – 171, Apr. 2005.

[8] H. Meng, S. Chen, Y. Guan, C. Law, P. So, E. Gunawan, and T. Lie. Modeling of transfer characteristics for the broadband power line communication channel. *Power Delivery, IEEE Transactions on*, 19(3):1057 – 1064, July 2004.

[9] H. Meng, Y. Guan, and S. Chen. Modeling and analysis of noise effects on broadband power-line communications. *Power Delivery, IEEE Transactions on*, 20(2):630 – 637, Apr. 2005.

[10] M. Novak and T. H. Alliance. Homeplug powerline alliance fact sheet, Jan. 2011.

[11] M. Novak and T. H. Alliance. Homeplug powerline alliance hits key milestones in 2010 and demonstrates industry leading technology at ces 2011, Jan. 2011.

[12] N. Pavlidou, A. Han Vinck, J. Yazdani, and B. Honary. Power line communications: state of the art and future trends. *Communications Magazine, IEEE*, 41(4):34 – 40, Apr. 2003.

[13] B. Priyantha, A. Kansal, M. Goraczko, and F. Zhao. Tiny web services: Design and implementation on interoperable and evolvable sensor networks. In *Sensys'08: Proceedings of the 6th ACM Conference on Embedded Networked Sensor Systems*, 2008.

[14] N. Sarkar and K. Sowerby. Wi-fi performance measurements in the crowded office environment: a case study. In *Communication Technology, 2006. ICCT '06. International Conference on*, pages 1 –4, Nov. 2006.

[15] A. Schwager, L. Stadelmeier, and M. Zumkeller. Potential of broadband power line home networking. In *Consumer Communications and Networking Conference, 2005. CCNC.*

2005 Second IEEE, pages 359 – 363, Jan. 2005.

[16] J. Tantra, T. M. Lim, B.-S. Lee, and C. K. Yeo. Effectiveness of explicit stations grouping in crowded wireless lans. *Communications Letters, IEEE*, 11(8):659 –661, Aug. 2007.