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Boosting Powerline Communications for Ubiquitous Connectivity in Enterprises

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Abstract—**Powerline communication (PLC) provides inexpensive, secure and high speed network connectivity, by leveraging the existing power distribution networks inside the buildings. While PLC technology has the potential to improve connectivity and is considered a key enabler for sensing, control, and automation applications in enterprises, it has been mainly deployed for improving connectivity in homes. Deploying PLCs in enterprises is more challenging since the power distribution network is more complex as compared to homes. Moreover, existing PLC technologies such as HomePlug AV have not been designed for and evaluated in enterprise deployments. To this end, we give guidlines for designing PLC networks for providing ubiquitous connectivity in enterprises, based on measurement study of PLC performance in enterprise settings using commodity HomePlug AV PLC devices. Based on our findings, we propose that careful planning of PLC network topology, routing and spectrum sharing can significantly boost performance of enterprise PLC networks.**

I. Introduction

Motivation & Background: Power line communication (PLC) technology has gained popularity as a connectivity solution in homes and various smart grid related applications. PLC devices nowadays can support high-bandwidth applications such as HD video streaming and VoIP, while boasting rates greater than 1 Gbps [1]. However, the deployment of PLCs in large buildings such as enterprises remains largely unexplored. PLC technology has the potential to provide high-speed ubiquitous connectivity and facilitate new IoT and Smart Grid applications in large-building settings (such as enterprises) at low cost, without any need for dedicated network cabling. One reason for the limited industrial-scale PLC deployment is the concern that PLC performance will not scale as more PLC nodes are added in the network [2].

Challenges of Enterprise PLC Networks: The deployment of PLC networks in large buildings such as enterprises is more challenging than home network settings for three reasons. First, for each building in an enterprise, there are typically multiple power distribution lines coming in from main switch boards (MSBs). Each distribution line consists of 3 AC phases, which are further distributed into the building through multiple breaker circuits. Such network components can significantly affect PLC performance. Second, PLC channel dynamics, which can be attributed to a multitude of electrical devices connected to power lines, can be significant and highly location dependent in enterprises. Third, the deployment of PLCs in large buildings requires the deployment of multiple PLC devices to provide ubiquitous coverage, which can lead to high inter-link interferences. Routing and spectrum allocation for improved connectivity in such scenarios remain unexplored.

Measurement Approach: In this work, we perform an extensive and in-depth measurement study of PLC network performance in enterprise settings, using commodity HomePlug AV (HPAV) hardware. We use Meconet HomePlug AV mini-PCI adapters with Intellon INT6300 chipsets, and connect the PLC adapters to ALIX 2D2 boards, which run OpenWrt operating system. We use open source PLC software tool named *open-plc-utils*, which is developed by Qualcomm, to extract PHY and MAC-layer feedback such as *tonemaps* (i.e. per-subcarrier level OFDM modulation information exchanged between PLC nodes during communication), directly from the Meconet HPAV adapters.

Our study departs from recent measurement efforts [2]–[5] in two ways. First, we characterize the impact of the power distribution network components (distribution lines, AC phases, circuit breakers) of large buildings, on PLC performance. Second, our analysis captures the *a) spatial*, *b) temporal*, and *c) spectral* dynamics of PLC networks in enterprise settings. Finally, based on the results from our measurement study, we explore multi-hop routing and spectrum sharing for PLCs. Our results can also be generalized for broadband PLC technologies other than HomePlug AV. Reader can consult our full technical report [6] for detailed discussion on our work[1].

II. Findings

A. Effects of Power Distribution Network Components

We measure the throughput and jitter performance of more than 40 links (PLC transmitter-receiver pairs) to study the impact of different components of a power distribution network (e.g. phases, breakers and distribution/trunk lines). Figure 1 shows CDF of throughputs observed for those cases.

Case 1: We observed that the performance of a PLC link operating on same breaker and same distribution line is mainly affected by the location of PLC nodes with respect to the interfering electrical appliances. Highly attenuating device impedances or severe device interferences can lead to significant performance degradation (we observe ~6.5 fold decrease in throughput).

Case 2: PLC nodes connected to same (or different) phase but different breakers operate over lower throughputs as compared to same phase, same breaker case (~20-30% decrease in observed throughput)[2]. This is because signals experience higher attenuations while passing through the breaker circuitry located between the PLC nodes.

[1]Kamran Ali did this work during his internship at Hewlett Packard Labs.
[2]We have excluded the cases of high interference from electric devices.

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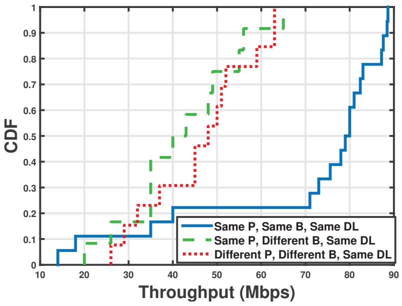


Fig. 1: CDF of throughputs observed in different cases.

Case 3: PLC performance significantly drops (~ 18-30 folds throughput decrease) when nodes are located at different distribution lines. Distribution lines can make PLC connectivity often impossible, due to transformers in between.

Electrical devices connected to power lines also impact PLC performance, either by introducing adverse multipath attenuations or creating in-band interference. Moreover, we observe that although different devices can cause similar degradation in PLC throughput, their impact on the PLC spectrum can be very different, which can be observed from their tonemaps.

B. PLC Channel Reciprocity

Asymmetry of PLC links depends upon the location of PLC nodes compared to branch circuits or other connected electrical devices. We observe that for more than 50% of the links, the tonemaps of forward and reverse links, on average, differ by more than 1 bit per subcarrier. In terms of measured throughput, the maximum difference in asymmetric links is observed to be 15 Mbps.

C. PLC Temporal Dynamics

In order to study temporal dynamics, we measure performance of a PLC link for 2 days (48 hours) period. We observe that throughput between most PLC links remained quite stable (the standard deviation of throughput is below 1.5 Mbps, more than 60% of the time), which shows that throughput performance of most PLC links remains quite consistent over time. Such *pseudo-stationary* nature of PLC links can minimize the channel probing overheads, for example, during spectrum sharing (III-C) or multi-hop routing (III-B).

III. Design Guidelines & Solutions

A. PLC Network Topology

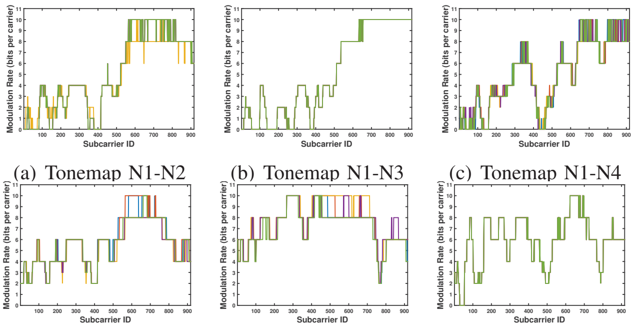
As we discussed before, our results have shown that PLC performance significantly drops (or connectivity is impossible), when PLC nodes are located at different distribution lines. Hence, PLC-Net should have at least one PLC Internet gateway node for each distribution line. PLC performance also drops when nodes are located at different breakers. We propose that deploying multiple gateways to different breakers per distribution line can allow for PLC devices to dynamically change their gateways based on channel conditions. We leave the examination of this trade-off as future work.

B. Case for Multi-hop Routing

Direct link communication in PLC networks can often be impossible or show very low throughput, either due to highly location dependent multipath attenuations and/or interference from appliances. We explore if multi-hop routing can improve throughput and connectivity in a large building settings, such as enterprises, through real world experiments using the optimized link state routing protocol (OLSR) [7]. Our results show that mesh routing can significantly boost PLC-Net performance in scenarios where direct PLC links perform very poorly and multi-hop communication is required. (e.g. when communication is affected by electrical devices).

C. Spectrum Sharing in PLCs

HPAV devices contend for the whole spectrum during communication. Our analysis of the tonemaps obtained for several different links in our testbed shows that different PLC links in the same neighborhood can experience significantly different channels, which happens mainly due to highly location dependent multipath characteristics.



(a) Tonemap N1-N2 (b) Tonemap N1-N3 (c) Tonemap N1-N4
(d) Tonemap N2-N1 (e) Tonemap N2-N3 (f) Tonemap N2-N4

Fig. 2: Tonemaps of 12 links among 4 neighboring PLC nodes.

For example, Figure 2 shows snapshots of the tonemaps of 6 different links in a network of 4 PLC nodes deployed in our test environment. If we consider the last 200 subcarriers (717-917) for all the links of node N1, we observe the modulation is at least 6 bits per carrier (cf. Figures 2(a), 2(b), 2(c)). On the other hand, the last 200 subcarriers for all the links of node N2, show lower modulation, which can be as low as 2 bits per carrier (cf. Figures 2(d), 2(e), 2(f)). A spectrum sharing (SS) strategy could allow both N1 and N2 to transmit at the same time to their neighbors (e.g. N1-N3 and N2-N4) using only their high-performance subcarriers. Similar observations hold for other links (tonemaps not shown here), where certain subcarriers can not carry data (0 modulation) and others can allow high modulations.

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