Enhancing WiFi Throughput with PLC Extenders: A Measurement Study

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Abstract. Today, power line communications (PLC) based WiFi extenders are emerging in the market. By simply plugging an extender to a power outlet, a user can create a second access point which connects to a master AP/router using the power line infrastructure. The underlying belief is that this can enhance the throughput that a user can achieve at certain locations (closer to the extender) and potentially increase wireless capacity. In this paper, we conduct an in-depth measurement study to first see if this belief always holds true, and if it does, the extent to which the end-to-end throughput improves. Our measurement study covers both homes and enterprise settings, as well as single and multi-user (or multi-device) settings. Surprisingly, we find that in 46% of cases in an office environment, using a PLC extender does not result in an increase in throughput, even when a single client accesses the network and is located close to the extender. This is because unlike in the case of an Ethernet backhaul, the PLC backhaul could consist of poor quality links (49% of the time in an office environment). We also find that the further away the extender is from the master router, the more likely this possibility becomes. We find that sharing of the PLC backhaul across devices could also be undesirable in some cases, and certain users should connect directly to the master AP in order to improve total throughput. Our study sheds light on when these effects manifest themselves, and discusses challenges that will need to be overcome if PLC extenders can be effectively used to enhance wireless capacity.

1 Introduction

Today there are a number of power line communications (PLC) based WiFi extenders from different vendors on the market (e.g., TP-Link, Netgear, Zyxel, Linksys, and Amped). A user can plug in these extenders (we call them PLC extenders or EXT) into power outlets and they interface with an access point (AP) or router that has access to the Internet (we call this the master router or MRT) using power lines, to essentially act as (additional) APs. By using these plug-and-play extenders in homes or enterprises, users can conceivably improve the quality of their wireless links; this is because clients can now potentially

M.A. Kaafar et al. (Eds.): PAM 2017, LNCS 10176, pp. 257–269, 2017.
DOI: 10.1007/978-3-319-54328-4_19

connect to an extender which is closer and clear of obstructions than to an AP that is obstructed or far away.

Objectives: In this paper, we conduct an in-depth measurement study to see if the better quality wireless links translate to real throughput gains with PLC extenders. We also seek to quantify these gains (or losses if they occur) and determine the root causes for these. We perform this measurement study despite the common belief that these extenders are beneficial because of two motivating observations. First, the throughputs achievable on power lines are not deterministic; in other words, the throughputs achievable between the master router and different PLC extenders could be different. Second, if multiple client devices (or users) share the PLC backhaul, there could be contention on the backhaul that results in degraded performance.

Take aways: In brief, the key take aways of our measurement study are as follows: **(1)** While using a PLC extender does provide throughput benefits in majority of the cases, it does not always do so. In some cases, even with a single client, a throughput degradation is observed compared to connecting to the master router, even if the client is much closer to the extender. **(2)** The sharing of the PLC backhaul among multiple connections (to a plurality of clients) could hurt the overall performance of the network. The overall performance could improve if some of the clients connect directly to the master router as opposed to the closest PLC extender (which provides the strongest WiFi signal). In addition to the above key take aways, our study provides an understanding of how many other factors such as the distance and the number of walls between the extender and the master router, as well as the configuration of the electrical distribution circuits, influence performance.

Our work in perspective: To the best of our knowledge, our work is the first study on the effectiveness of PLC extenders in providing enhanced throughputs in homes and offices. The work also sheds light on the factors that influence whether or not throughput gains can be realized and can thus influence future work on configuration solutions for integrated PLC/WiFi networks. Unlike in traditional WiFi networks wherein the performance on an underlying backhaul (such as Ethernet) is assumed to be commensurate with that of the WiFi links, care must be taken in terms of accounting for PLC idiosyncrasies.

2 PLC Background and Related Work

The PLC Channel: In the US, broadband PLC operates in the 1.7–80 MHz band. It is similar to wireless communications in that the PLC signal is attenuated with distance due to cable branching/losses. While a wireless signal is obstructed by walls and floors, a PLC signal is degraded by (a) noise generated by electrical apparatuses sharing the cables and (b) electrical components, e.g. transformers, that sit between end points. At the MAC layer, although both PLC and WiFi standards (IEEE 1901 and 802.11) use CSMA/CA to avoid collisions when multiple stations share the same channel, IEEE 1901 uses deferral counters to prevent collisions from happening so that congestion windows of the stations do not grow rapidly.

PLC-based WiFi Extenders: PLC extenders on the market couple PLC's AV2 and WiFi's 802.11 to take advantage of existing power lines and enhance WiFi performance and coverage to end users. Recent products typically support HomePlug AV2 and 802.11ac (which operates in the 5 GHz band). However, according to a recent survey [3], 2.4 GHz WiFi access points are still dominant in homes and offices. As a result, in this paper, we focus on networks using 2.4 GHz 802.11n for front-end access and AV2 as a backhaul.

Related work: To the best of our knowledge, we are the first to do an in-depth measurement study on the use of PLC extenders towards improving WiFi coverage or performance. Below, we briefly summarize related work.

Hybrid networks: In [6,9], the authors consider a network where clients have two interfaces viz., a PLC interface and a WiFi interface. They propose metrics for comparing the performance on the two interfaces and consider methods to use them jointly as parallel links. They do not perform measurements on commercial PLC extenders, which concatenate PLC and WiFi links, as we do.

PLC vs WiFi: There has been work to compare the WiFi MAC and the IEEE 1901 MAC that is used with PLC [7]. However, this does not yield any insights on why PLC extenders may be useful (or not) in enhancing WiFi throughputs.

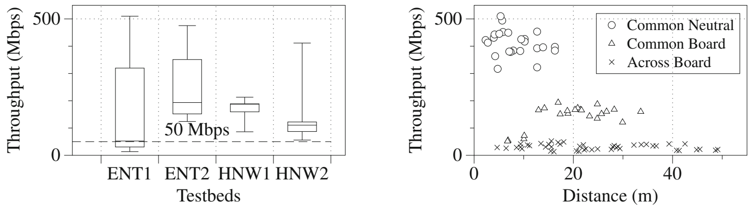
PLC studies: There are also a number of studies on PLC. For example, [2,5] provide insights on current PLC standards (AV2). However, they do not consider the use of PLC in building extenders to improve WiFi coverage or throughput. There have also been efforts to enhance PLC performance either by tuning MAC parameters [8] or by using an application level learning based framework [1]. However, again these efforts do not consider interactions between PLC and WiFi.

3 The Influence of Power Line Configurations

Measurement Setup: Our equipment consists of a commercial WiFi router (Netgear Nighthawk AC1900), six commercial PLC extenders (TP-Link TL-WPA8630), and four clients (Lenovo Ideapad 300S). We perform measurements

Table 1. Properties of the four testbeds

Name	Description	Area (m^2)	Walls	Floors	Client locations	PLC extenders
ENT1	Multi-room office	350	14	1	87 (hallways)	6
ENT2	Single-room lab	213	0	1	20 (room)	4
HNW1	Two-story house	245	10	2	8 (bedrooms)	3
HNW2	One-story apartment	170	6	1	6 (bedrooms)	4



(a) Throughput Ranges of the Four Testbeds

(b) Impact of Power Distribution on PLC Throughput (ENT1)

Fig. 1. PLC-only throughputs in typical home and work environments.

in four environments: a 10-room office space (ENT1), a large single-room laboratory (ENT2), a two-story home (HNW1), and a one-story apartment (HNW2); further details are omitted due to space limitations. Clients are placed roughly uniformly in each environment, and by default choose a WiFi access point with the highest RSSI. Further details of the measurement environments are provided in Table 1. We perform 10-minute `iperf3` tests between the PLC extenders or clients, and the master router, to measure the total achievable (saturation) TCP throughputs between each pair. We also experiment with web browsing and video streaming applications to showcase application performance. On all four testbeds, we measure the pairwise throughput between unoccupied power outlets.

We classify connections based on the achieved throughput into two classes viz., good and bad PLC connections (Table 2). Since the maximum throughputs achievable over WiFi to nearby extenders is 50 Mbps, we set this as the threshold to delineate good and bad PLC connections.

Table 2. Network conditions

PLC condition	Throughput (Mbps)
Good	≥50
Bad	<50

Results and analysis: Our results are shown in Fig. 1(a). We find that in all but the ENT1 testbed, the achievable saturation throughputs are higher than the threshold. We then look at the power circuit diagrams of ENT1 to determine when the saturation throughputs are lower than the threshold. We find that if two power outlets connect to circuits that use a common neutral line, they have very high throughput (around 400 Mbps). If two power outlets connect to the circuits that belong to the same distribution board but different neutral lines, the throughput between them drops to less than 200 Mbps. Most importantly, if two power outlets connect to circuits that belong to different distribution boards, the throughput becomes lower than 50 Mbps, causing the PLC connection to become a bottleneck. The reason for the above is that in order to go between the distribution boards, the connection has to traverse an electrical transformer which attenuates a range of frequencies also used by PLC [10].

Our studies reveal that (Fig. 1(b)) *even if* the distance between two power outlets is relatively small (they are in close proximity), it is still possible that the PLC throughput between them is very low. However, the larger the distance between two power outlets, the more likely it is that they can only sustain a lower PLC throughput between them. Note here that these effects are not seen in the other three testbeds since they use a single distribution board.

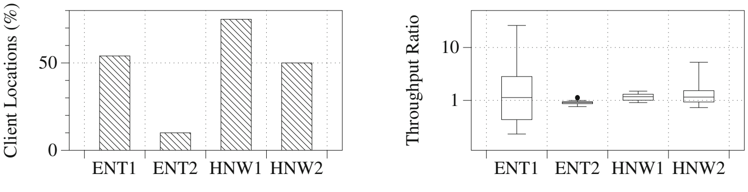
4 Single-User Studies

In this section, we investigate whether PLC extenders can improve throughput compared to a WiFi-only scenario, when there is only a single client. We evaluate throughput gains in typical home and enterprise environments, including the impact of distance between routers, extenders, and clients, density of extenders, and attenuation from walls and floors. Our main finding is that PLC can improve average throughput, particularly when there are multiple walls, but careful placement/activation of the extenders is necessary to achieve these gains.

4.1 Throughputs with PLC Extenders

We first examine the improvements in client throughputs in each of our four test environments (Table 1). We measure the end-to-end throughput between the router and the client, when (a) the client associates with the default PLC extender or (b) directly with the master router. We find that the improvements due to PLC extenders depend on the environment, with higher gains in multi-room and multi-story environments (and lesser gains in single large rooms).

When and to what extent do PLC extenders help? The percentage of client locations where the PLC+WiFi throughput exceeds the WiFi-only throughput are plotted in Fig. 2(a). The results suggest that in office, home, and apartment environments, PLC extenders help in the majority of client locations, but not in the laboratory environment. To showcase the gains in these environments, we plot the ratio of the PLC+WiFi (connection via a PLC extender) to WiFi-only (connection to the master router) throughput in Fig. 2(b). In ENT1, which is large and contains many walls obstructing the WiFi signal from the main router, the PLC extenders can potentially provide very high throughput gains of up to 30x. In contrast, in ENT2 where there are no walls, the



(a) % of Client Locations Where PLC+WiFi > WiFi-only (b) Ratio of PLC+WiFi to WiFi-only throughput

Fig. 2. Throughput gains from PLC extenders over WiFi-only.

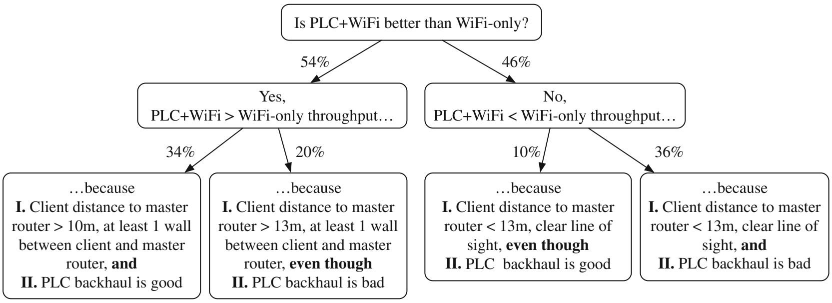
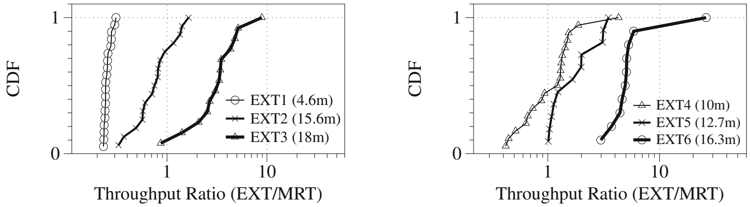


Fig. 3. Reasons why PLC extenders help (or not) compared to WiFi-only (ENT1).

throughput gains are negligible, since the WiFi signal from the master router is strong. The HNW1 and HNW2 environments contain a mix of walls and floors, and can thus benefit from PLC extenders, but not to the extent as in the ENT1 case. Interestingly, we note that in HNW1, despite the master router and PLC extenders being spread over two floors, the throughput gains are minor. This is because the master router WiFi signal can easily penetrate a single floor, suggesting that PLC extenders may be more beneficial in the multiple-wall rather than multiple-floor scenarios.

Reasons for throughput gains from PLC extenders. To delve further into the office environment (ENT1) where PLC can be most helpful, we analyze the reasons for the throughput gains. Specifically we ask the following questions. Can PLC extenders help even when the PLC backhaul quality is poor? Are there cases where good PLC backhaul is not helpful, because the WiFi-only throughput is very high?

For each client location, in addition to the end-to-end throughput, we measure the throughput of the PLC backhaul, and classify it as good or bad according to Table 2. Figure 3 summarizes our results. In 34% of cases, we have the expected scenario where throughput gain results from a poor (direct) master WiFi and a good PLC backhaul connection. However, in 20% of cases, even a poor-quality PLC backhaul connection can help if the WiFi link to the master



(a) Poor PLC backhaul (b) Good PLC backhaul

Fig. 4. Impact of PLC extender backhaul and router distance on throughput gain.

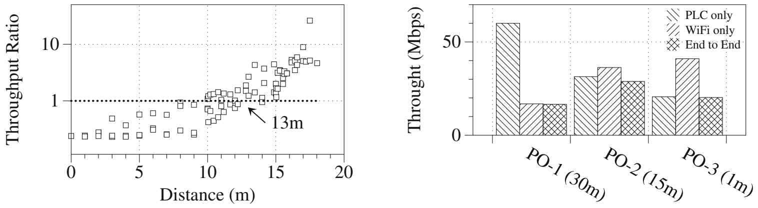
router is poor (due to at least one obstructing wall). We also see the opposite scenario where in 10% of locations, a good-quality PLC backhaul link does not help because the WiFi link to the master router is still very good (due to the clear line of sight).

4.2 Impact of Distance

In reality, users who purchase off-the-shelf PLC devices may not have access to electrical diagrams and thus may be unable to infer which PLC connections are good or bad as we did in Sect. 3. Therefore, we next examine benefits from PLC extenders given easy-to-estimate quantities such as physical distance. We conduct an in-depth study in the office environment (ENT1). Our main findings are that (1) throughput gains improve with distance between the router and the extender, especially when the extender has a good PLC connection to the router, (2) the location of the extender must be chosen based on both the PLC backhaul throughput and the PLC extender's WiFi throughput, in order to ensure that neither hop becomes the bottleneck for end-to-end throughput.

Throughput changes with distance from the master router: We first examine the impact of distance of the PLC extender from the master router. If the extender is close to the router, we expect the throughput gains for the client to be minimal, because the master router's WiFi signal will be already strong. However, as the distance between the extender and the router increases, the master router's WiFi quality will degrade, and the PLC extenders should help, especially when the PLC backhaul is good. In Fig. 4, we plot the CDF of throughput gains of each client when they associate with their default extender (highest received signal strength or RSS) in lieu of the master router. Figure 4(a) indicates that even a poor-quality PLC backhaul yields throughput gains if (and only if) the extender is quite far (18 m or further) from the router. When the PLC backhaul is good however, we see a throughput gain when the extender is as close as 12.7 m away from the router (Fig. 4(b)).

Since the default association of the client is to a nearby extender, we expect that the impact of distance on throughput gains enjoyed by clients to be similar to that in our aforementioned study with just the extenders. In Fig. 5(a), we



(a) Client Distance from Router vs. Throughput Ratios (EXT/MRT)

(b) Client Distance from Extender

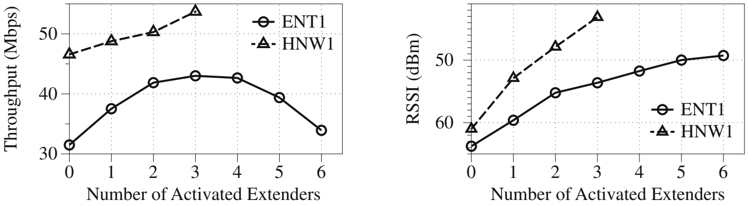
Fig. 5. Impact of distance from the master router on throughput.

plot the relationship between client distance from the master router and the throughput gain. We observe that the client begins to see a throughput gain at distances that are greater than ~13 m, across all extenders (with good or bad PLC backhaul connections).

Impact of distance between a client and its extender: In this set of experiments, we seek to answer the question: Given a client that is located very far from the master router, where should the extender be placed to maximize throughput? Placing the extender close to the client will result in good WiFi signal quality but may result in a poor PLC backhaul quality, especially if the outlet is on a different distribution board than the master router. On the other hand, placing the extender close to the router to ensure good PLC backhaul quality may result in a poor quality WiFi link between the client and the extender (low signal strength). We place a client 35 m from the master router and examine cases where it associates with three possible power outlets. We plot the PLC backhaul throughput, the extender WiFi throughput, and the end-to-end throughput in Fig. 5(b). The closest power outlet to the client (PO-3) is suboptimal because a poor PLC backhaul bottlenecks the end-to-end throughput. On the other hand, the power outlet (PO-1) with the best PLC backhaul quality is also suboptimal, because it has a poor WiFi connection to the client. The extender that maximizes end-to-end throughput is PO-2, which has both good (but not best) PLC backhaul and extender WiFi throughputs. In summary, the PLC extender must be carefully placed between the client and router to balance PLC and WiFi throughput bottlenecks. Since it may be difficult for a casual user to measure and optimize extender placement, a reasonable approach may be to provide simple guidelines for extender placement, and focus on the appropriate client association strategy. A simple strategy might be to consider the end-to-end throughput as a metric for association instead of the WiFi signal strength.

4.3 Can More Extenders Help?

Next we ask: Are more extenders always helpful, or is there decreasing marginal utility? To measure this, we activate each of the six extenders one-by-one in decreasing order of throughput gain. For each client location, the client associates with either the master router or the activated PLC extenders based on the default



(a) Throughput (Mbps) (b) RSSI (dBm)

Fig. 6. Single client: Impact of number of PLC extenders on throughput.

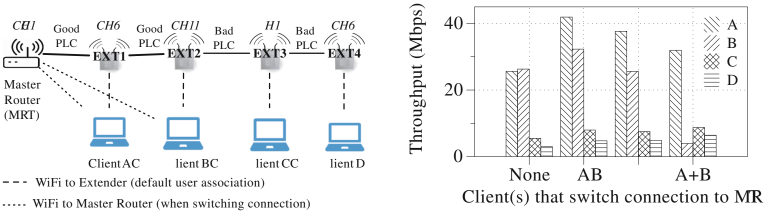
association policy (highest RSSI). We plot the average throughput across all client locations versus the number of activated PLC extenders in Fig. 6(a). In the house environment (HNW1), as expected, increasing the number of extenders improves the client throughput, due to better spatial coverage of WiFi signal throughout the home. However, in the office environment of ENT1, adding too many extenders actually decreases average throughput. This is because some outlets in the office environment have poor PLC backhaul quality. Clients see higher RSSI values (Fig. 6(b)) and associate with the new extenders, but since the last three extenders have poor PLC backhaul, the clients inadvertently associate with an extender with poor end-to-end throughput. Therefore, before adding PLC extenders, it is important to consider both the PLC backhaul quality and the WiFi signal strength in the deployment environment; otherwise, poor PLC connectivity may result in reduced network throughput.

5 Multi-user Studies

Building on our studies in Sect. 4, we next examine if the benefits of using PLC extenders carry over when there are multiple clients or users present. Our main findings are: (1) to relieve PLC backhaul contention and improve throughput for clients far from the master router, some clients close to the master router should connect directly to it, possibly at the expense of their own throughputs; and (2) in an office setting (ENT1), adding new PLC extenders may decrease average client throughput because the extenders choose the same WiFi frequency to avoid contention with existing WiFi APs.

5.1 Sharing PLC Backhaul

In the single-user scenario, we found that in 54% of locations in the office environment (ENT1), a client can benefit by connecting to a PLC extender. However, in the multi-user scenario, the client's benefit from connecting to a PLC extender may be reduced due to increased PLC backhaul contention. Should clients close to the master router connect to it, relieving contention on the PLC backhaul for the remaining clients on PLC? If this causes a reduction in the switching client's throughput, does the resulting gain of the other clients provide a net benefit?



(a) Experimental setup (b) Throughput

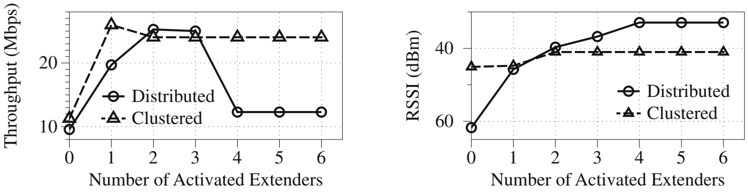
Fig. 7. Clients switch connection to master router.

To investigate this, we consider four clients in the office environment (ENT1) which can potentially associate with four PLC extenders, as shown in Fig. 7(a).[1] In the single-user case, a client far away from the master router (client D) received 12 Mbps when connecting to a PLC extender, but in the multi-user case when three other clients also connect via PLC extenders (clients A, B, C), its throughput drops to 2.98 Mbps. What if the client closest to the master router (client A) switches? If that case, we see that all clients increase their throughputs, as shown in Fig. 7(b). However, if a client slightly further away from the master router switches (client B), it slightly sacrifices its own throughput to benefit the other clients.

If switching one client helps, does switching both clients help? We find that switching both clients (A, B) to the master router lowers total throughput due to increased contention on the master router's WiFi. This suggests that when multiple clients are present, a few clients close to the master router should connect to it in order to reduce PLC backhaul contention and improve throughput for distant users; however, switching too many clients[2] causes contention between the master router's clients and lowers total throughput. We envision that an iterative approach where clients closest to the master router are sequentially switched could help effectively identify the optimal set that should be switched.

5.2 Can More Extenders Help?

In the single-user case, increasing the number of PLC extenders sometimes resulted in suboptimal throughput, due to clients associating with extenders with poor PLC backhaul. We investigate whether this holds in the multi-user case, and what additional complexities arise from inter-client interference. We expect that the benefits of additional extenders depends on the spatial configuration of the clients, and so we setup clients in two configurations: *distributed*, where a client is placed at each of the four corners of the office (ENT1), and *clustered*, where all the four clients are situated in the middle of the office area. We activate each of the six extenders one-by-one in decreasing order of average RSSI.



(a) Average Throughput (b) Average RSSI

Fig. 8. Multiple clients: Impact of number of PLC extenders on average throughput.

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[1] To focus on PLC backhaul contention and avoid WiFi interference issues, we configure the WiFi channels of the PLC extenders for maximum frequency reuse.

[2] In our testbed, one switching client is optimal.

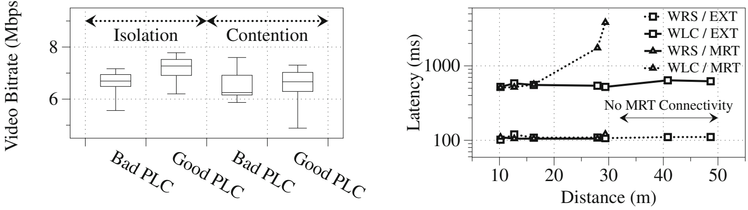
In Fig. 8(a), we plot the average client throughput versus the number of PLC extenders. Initially, we see that the first 1–2 extenders increases average throughput, because clients experience higher RSSI (Fig. 8(b)) and the PLC backhaul is good. However, in *distributed* configurations, further adding PLC extenders can result in decreased average throughput (e.g., from 25 Mbps to 12 Mbps when a fourth extender is added). This is because in addition to poor user association policies discussed previously, the additional extenders choose the same WiFi frequency band to avoid interfering with existing office WiFi networks, causing inter-client interference.[3] In the *clustered* configuration, adding more PLC extenders is unhelpful because clients associate with the first 1–2 extenders with higher RSSI and ignore later extenders.

In conclusion, although more PLC extenders results in higher client RSSI, it does not necessarily lead to higher throughput. Two main factors directly impact the performance of PLC+WiFi: frequency reuse and user association. PLC extenders may not be helpful in environments with multiple existing WiFi networks, as the PLC extenders try to avoid interfering with external APs, choosing the same frequency band and decreasing the throughput of their own clients. For client association, as in the single-user case, clients may need to consider the quality of the PLC extender's backhaul connection when deciding which extender to associate with.

6 Applications

In the previous sections, we studied saturation throughput of PLC+WiFi networks. In this section, we wish to understand how PLC extenders impact application performance. To do this, we conduct experiments with two popular applications viz., video streaming and web browsing (hosted on local machines).

Video Streaming: Dynamic adaptive streaming over HTTP (DASH) is one of the most common video streaming protocols in use today. However, previous studies have shown that multiple clients sharing a bottleneck link unfairly choose



(a) Video bitrates (b) Web browsing latency

Fig. 9. Video and web browsing performance

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[3] For example, in our setup, existing WiFi networks use channel 1 and 6, so all PLC extenders choose channel 11.

video bitrates that allow some clients to monopolize the link, and also experience a high degree of instability [4]. In our study, we find that not only does this issue manifest over PLC links, but in addition the magnitude of the video bitrate and frequency of bitrate switches depends on the quality of the PLC backhaul.

In our setup, we stream an 8-minute 1080p DASH video[4] encoded at four different bitrates (1.6, 2.4 4.8, 8 Mbps) to two clients[5]. To see the impact of the PLC backhaul, one client is associated with a good PLC extender, and the other with a bad PLC extender. The video bitrates are plotted in Fig. 9(a) across ten trials. In the multi-user case, both clients are negatively impacted by PLC contention, decreasing the average video bitrate and increasing the average number of switches compared to the single-user case. Moreover, both metrics have higher variance. In particular, the good-PLC client suffers a higher variance despite enjoying a higher video bitrate on average, than the bad-PLC client. This is because it occasionally suffers from very low bitrates due to contention on the PLC backhaul. Similarly, the good-PLC client enjoys a fewer number of bitrate switches on average but occasionally sees a large number of bitrate switches (not shown due to space limitations).

Web Browsing: How does good and bad PLC impact page load time? In contrast to video streaming applications, which suffer from reduced video bitrates when the PLC backhaul is poor, we find that web-browsing clients can still enjoy low page load times even when they are located far from the master router.

To show this, we load the Top 100 Alexa websites on a client and record two metrics: (a) web response start (WRS), the latency between when the browser requests the page and when it receives the first web object, (b) web load complete (WLC), the latency between when the browser requests the page and when it receives the last web object. We evaluate this in the office environment (ENT1), and place the client close to each extender to focus on impact due to PLC backhaul quality. In Fig. 9(b), we plot the WRS and WLC as a function of the client's distance from the master router. If the client connects to the PLC extenders we can see that no matter the client's distance from the master router, the WRS and WLC are nearly constant. However, if the client connects to the master router, it experiences relatively high WLC after 29 m. Notably, at the two user locations that are most distant from the master router (40 and 48 m), the client loses WiFi connectivity to the master router and can only load the webpage via the PLC extenders. This suggests that for web browsing, PLC extenders can be beneficial even if the quality of the PLC backhaul link is poor.

7 Conclusions

In this paper, we perform an in-depth measurement study of the benefits of commercial PLC extenders to improve WiFi throughputs. We find that PLC extenders can be most beneficial in multi-room environments (e.g., office spaces),

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[4] https://peach.blender.org/.

[5] http://dashif.org/reference/players/javascript/.

but can also suffer from degraded throughput due to more complex power line configurations resulting in poor-quality PLC backhaul. Our results suggest that more sophisticated client association policies (instead of highest RSSI by default) and frequency planning around existing WiFi APs, taking into account the quality of the PLC backhaul, could potentially help realize maximum benefits from PLC+WiFi. We intend to investigate these avenues as future work.

Acknowledgments. This work was partially supported by the NSF NeTS grant 1528095.

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