Boosting Home WiFi Throughputs via Adaptive DAS Clustering of PLC Extenders

Hisham A. Alhulayyil*†, Jiasi Chen* Karthikeyan Sundaresan‡, Srikanth V. Krishnamurthy*
* *University of California Riverside, USA*, {halhu001}@ucr.edu,{jiasi, krish}@cs.ucr.edu
†*Imam Mohammad Ibn Saud Islamic University, KSA*, halhulayyil@imamu.edu.sa
‡ *NEC Laboratories America, Inc*, karthiks@nec-labs.com

***Abstract*—WiFi-capable PLC (Power Line Communications) plug-and-play extenders are becoming popular to improve WiFi range and coverage in homes and enterprises. As shown in prior work, unlike an Ethernet backhaul, the PLC backhaul may not support high data rates. In addition, clients (users) that are either far or partially occluded from the WiFi-PLC extender they associate with can experience fading and shadowing, which degrades the throughput on the wireless link. Thus, both the PLC and WiFi backhauls will influence a user's end-to-end throughput. In this paper, we seek to exploit the presence of multiple PLC extenders that may be plugged in, by combining their transmissions in a distributed antenna system (DAS), to boost client throughputs in a home setting. Specifically, we design PLC-DAS to determine which PLC extenders are the best candidates for forming a joint DAS transmitter cluster to each client. PLC-DAS is designed based on a real measurement study and not only accounts for the WiFi link qualities from the extenders to the users, but also the PLC link qualities from each extender to a master router which is typically deployed in homes. PLC-DAS is flexible and can maximize the throughput under different fairness objectives. We evaluate PLC-DAS via extensive simulations and show that it can increase the aggregate throughput by up to 4.5x compared to blindly using all WiFi-PLC extenders to form a DAS transmitter, while maintaining a fairness Jain's index value of at least 0.97 with proportional and max-min fairness models.**

I. Introduction

PLC based WiFi extenders that can be plugged into standard power outlets and do not need an Ethernet backhaul are gaining popularity in the market [1] [2] [3]. Typically deployed in homes and enterprises, a master PLC unit connects to the main router and acts as a bridge that connects clients associated with WiFi-PLC extenders to this main router, thus enabling access to the Internet, as shown in Fig. 1. It has been shown that WiFi-PLC extenders improve the WiFi coverage in the area of deployment [4]. However, while WiFi-PLC can potentially improve the WiFi coverage, users can still suffer from bad or unstable WiFi links. For example, in indoor deployments, users occluded (no direct link) from WiFi-PLC extenders can see throughput degradation due to deep fading and shadowing. Such effects have been shown to be common in indoor environments [5]. Specifically, a home WiFi-PLC user can experience varying WiFi link qualities across the areas in the home (*e.g.*, poor coverage in the garage when all the WiFi-PLC extenders are in various bedrooms inside the home).

A well studied approach to mitigate WiFi link degradation is via the usage of Distributed Antenna Systems (DAS) [6]. The idea is to simultaneously transmit the data from multiple

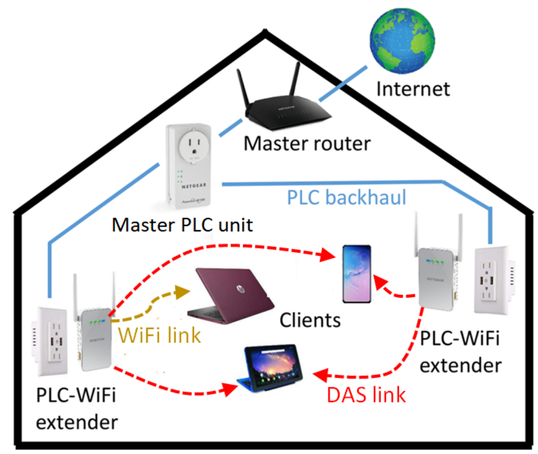


Fig. 1: Powerline communications extend WiFi coverage through existing interior power lines in a home.

(distributed) antennas, the signals from which traverse different paths and thus, when combined at the receiver reduce the likelihood of packet losses. DAS systems have been shown to improve both the quality and the stability of WiFi links [7].

The key question that we ask in this paper is whether the different PLC extenders can be clustered together to form a DAS transmitter to improve the robustness to indoor fading, and thereby improve the throughputs achievable by clients, regardless of their locations within a home. However, as discussed in what follows, there are several issues that make the task of forming such a DAS cluster non-trivial because of the composition of the PLC and WiFi parts of the network. Specifically, as shown later, if PLC extenders are blindly clustered to form a DAS transmitter, the client may even suffer a throughput degradation compared to when it uses a single extender. Below, we discuss why this could be the case.

DAS clustering of extenders could reduce PLC side throughput. Realizing a DAS cluster [8] [9] requires that a plurality of antennas are synchronized when they transmit the data. While this is inherently satisfied when the antennas are connected to a data source via high-bandwidth backhauls (*e.g.*, fiber), in the scenario of interest, the different PLC extenders are likely to have different backhaul capacities on the links to the master router (from where the packets are delivered to the extenders). Thus, in order to synchronize packet transmissions, the extenders with higher PLC capacities (faster) will need to await the delivery to the slowest PLC extender (the one with the lowest PLC capacity to the master router). In other words, the throughput achieved on the PLC part of the link might in fact decrease compared to what might be achieved on this part, if the client were to connect to a single extender. One must ensure that the gains achieved due to DAS clustering more than offset this decrease; a blind approach to clustering could thus degrade the throughput compared to simply having the client connect to a single extender.

Large propagation delays from the different extenders can be detrimental to DAS. Even when the transmitters are synchronized with regards to when they perform their transmissions, there will be variations in propagation delays between the different antennas (WiFi-PLC extenders) and the client. If there is a large difference in these delays, we observe that combining the signals fails, which can adversely affect the throughput. Thus, it is critical that the extenders have similar propagation delays to the client in order to ensure that the gains expected from DAS are derived; otherwise, the throughput might (again) degrade instead of being enhanced.

Contributions. In this paper, our key contribution is the design of a framework that we call PLC-DAS to adaptively choose the right set of extenders to transmit to a client, based on its location. This choice is made based on the PLC capacities to the different extenders, and their positions relative to each other and the client (reasons discussed later).

The design of PLC-DAS is driven by a set of experiments that we conduct to understand the above issues. Specifically, we perform extensive WiFi experiments using WARP boards [10] to understand the achievable gains from employing DAS as well as the level of synchronization required to combine the signal from the different antennas. We also conduct experiments on the PLC backhaul using commodity PLC TP Link TL-WPA8630 PLC extenders. The study sheds light on the interaction between the PLC extenders and how the PLC backhaul is shared, which influences the delays from the master router to the various extenders.

As our main contribution, we design a framework, PLC-DAS, that incorporates a measurement-driven online algorithm to determine the right set of antennas to transmit to a client which is at a given location. Specifically, the algorithm results in the client choosing a primary extender to associate with, based on the PLC capacities from the master router to the various potential extenders, as well as the wireless link qualities to the extenders. Next, other extenders are chosen for joint transmissions along with this primary extender, based on their PLC link capacities and their propagation delays to the client (relative to the primary extender), to form a DAS cell.

We perform extensive evaluations of PLC-DAS using realistic PLC and wireless channel models derived from experiments with realistic home configurations. We consider various fairness models and show that PLC-DAS not only boosts individual client throughputs, and therefore the overall network throughput that is shared across clients in a home, but can also provide max-min or proportional fairness. This is achieved by reducing discrepancies across client throughputs due to better robustness to fading effects, compared to baselines that do not use DAS or apply DAS blindly.

A summary of our contributions in this paper are:

- We perform real experiments to gain an understanding of the feasibility of employing DAS on top of a PLC network.
- We leverage the insights obtained from the measurement experiments to design PLC-DAS. We show that the algorithms within PLC-DAS, which drive the choice of the appropriate antennas to form the DAS cluster to maximize the throughput (or fair throughput) for the client, have polynomial time complexity and can be practically deployed.
- We perform extensive simulations based on realistic channel models and real home layouts to show that PLC-DAS outperforms other baselines approaches that dictate how clients associate with extenders (without DAS or via a blind application of DAS). PLC-DAS achieves up to a 62.7% increase in aggregate throughput compared to a non-DAS baseline in which each user associates with the PLC extender that offers the best end-to-end throughput; this is the best baseline in terms of the achieved aggregate throughput. The results also show that PLC-DAS provides better fairness across users that share the in-home WiFi capacity, with both max-min and proportional fairness models.

II. PLC Background in Brief

The MAC 1901 protocol governs backhaul access in PLC networks. It is similar to 802.11, with some differences in terms of the complexity, fairness and performance [11]. It can be configured to operate using a CSMA (throughput-fair) or a TDMA (time-fair) mode. It supports different QoS classes by granting the flows with higher priority a larger number of time slots in the TDMA mode. Most large vendors such as Cisco, Netgear and TP-Link, support both medium access modes with a PHY rate up to 2024 Mbit/sec [12], which makes PLC extenders attractive for expanding the network without needing pre-existing infrastructure.

Most current PLC extenders are empowered by a WiFi interface that increases the network range. This is especially attractive in areas where the main router's signal is low or poor, causing lowered data rates. The WiFi link between the PLC extender and the end user (also referred to as a client) is controlled by the 802.11 protocol. Since 802.11 shares the medium in throughput-fair manner, users connected to the same WiFi-PLC extender will have similar throughputs, and extenders operating on the same WiFi channel will have to share the frequency associated with that channel [13].

III. Measurements

In this section, we describe our experiments on real testbeds, to get an understanding of the issues relating to realizing DAS in the PLC-WiFi home setting. Specifically, our measurements relate to three aspects: (a) first, we seek to understand the variations in the rate across various PLC links; (b) second, we seek to quantify the gains that might be expected with DAS without using any precoding [14] [15] (note that precoding cannot be

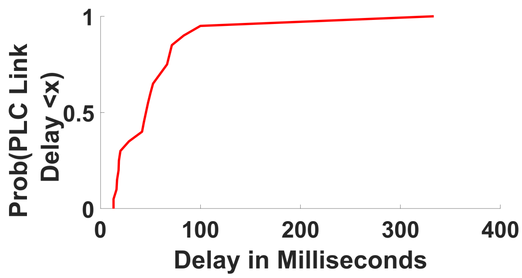


Fig. 2: CDF of latencies experienced on different PLC links.

applied since we are using plug and play WiFi extenders as our antennas); and (c) finally, we seek to understand the extent to which time synchronization needed across the multiplicity of signals for them to be combined successfully at the receiver.

A. Feasibility of PLC as a backhaul for DAS

While in general, the PLC backhaul is time-shared across the various extenders, when a DAS transmission is to be enabled, the same data is multicast to the extenders that belong to the DAS cluster, *i.e.*, there is no time-sharing of the backhaul for that transmission. The feasibility of multicasting on the PLC backhaul has been previously demonstrated [16], [17]. By creating multicast groups – one group for each DAS cell – we can send the data simultaneously to multiple extenders. However, the latency incurred by each packet transmission to the plurality of PLC extenders in the multicast group varies. In Fig. 2 we show, from our real measurement study, the distribution of these latencies across twenty extenders in a two-bedroom apartment in the USA. The setup is as follows: for each power outlet, we include a PLC extender and laptop, which connects to a master router connected to a server, as shown in Fig. 1. Specifically, the laptop client is connected by a Gigabit Ethernet cable to the PLC extender, for this experiment only (the high capacity of the cable ensures that any degradation in user throughput is because of limited PLC link capacities, not because of the Ethernet connection). The extender is connected over PLC backhaul to the main PLC unit, which in turn is connected to the master router and server over Ethernet. We transmit a saturated downlink TCP flow from the server to laptop clients. We repeat the experiment with twenty different outlets (different PLC links) and we use *iperf3* [18] to measure the throughput/delay on each PLC link.

The measurement results suggest that transmissions on different PLC links experience different delays. Because of this, the delay (and consequently throughput on the PLC network) incurred by a DAS transmission is governed by the delay of the slowest extender in its multicast group. In fact, the difference in the delays as seen by the experiments could be as much as 3$\times$ between pairs of extenders. We reiterate here that the transmissions from the extenders need to have fine-grained synchronization in order to enable a successful DAS transmission; thus, those extenders which receive the packet earlier, will need to await the laggards prior to performing the transmission (no such wait is necessary when there is a single extender performing the WiFi transmission). In other words, the PLC capacity for a DAS transmitter is dictated by the capacity of the lowest PLC link in its multicast group and is given by:

$$p_i = \min_{\{j \in A : x_{ij} > 0\}} c_j \tag{1}$$

where p_i is the DAS transmitter PLC link capacity for user i, j is the index of extender in the multicast group (DAS cell), c_j is the capacity of the extender, A is the set of extenders in that DAS cell, and x_{ij} is a binary variable indicating whether user i is connected to extender j in the DAS cell. This showcases the importance of carefully choosing PLC extenders when forming DAS transmitter; blindly grouping or choosing all extenders could cause the end-to-end throughput of the users to degrade due to this artifact on the PLC side. Later, in our simulation experiments to evaluate PLC-DAS, we emulate the depicted distribution of PLC link delays from Fig. 2.

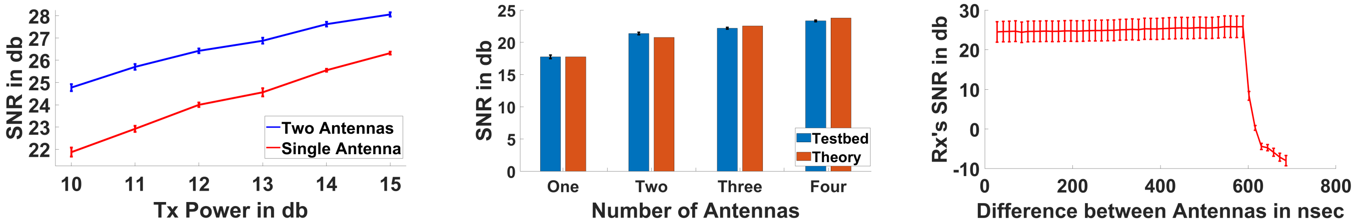
B. DAS side issues

Next, we implement DAS and conduct experiments on the WARP [10] platform to quantify DAS' gains in terms of SNR improvement. In a nutshell, we find that this gain is logarithmic with the number of antennas (extenders) as we show later in this section. We also examine how DAS performs with different transmission powers; specifically, when transmission powers change (increase or decrease), the receiving node experiences different received powers, and we investigate whether this has an impact on DAS gains or not. This emulates different proximities of a client to the DAS transmitters.

Experimental setup: We first describe the set up for our experiments.

DAS with two antennas. We use two WARP V3 nodes, one of which acts as the transmitting node (Tx node) and one as the receiving node (Rx node). The Tx node has two SMA output ports. Each SMA port has one antenna attached to it (total two antennas). The Rx node has only one antenna. No precoding [14] [15] is applied as discussed earlier to reflect scenarios with off-the-shelf PLC extenders. We run our experiments with twenty different topologies in which we change both the Rx (client) and Tx antennas' locations. We examined the benefits of constructive signal combining of DAS at the Rx node, with varying Tx powers (from 10 dB to 15 dB). With each Tx power level, we send one hundred transmissions. In order to ensure that the reported average SNR covers a wide range of values, we send two thousand OFDM symbols with each transmission, which is the maximum number of symbols the WARP node can buffer [19], encoded with BPSK modulation. The Rx node captures the superposed transmitted signal from the two transmit antennas and attempts to decode the received combined signal. When the decoding process is successful, the payload is retrieved. After that, the average SNR is determined by computing the Error Vector Magnitude (a.k.a Relative Constellation Error or RCE).

DAS with more antennas. To construct DAS clusters with more antennas, we use ”Y” shaped splitters to increase the number of Tx antennas. Each splitter has two ends. The first end is attached to the Tx node and the other end is used to connect two antennas. We connect one splitter to each SMA output port (there are two of them) and, consequently,



(a) DAS gain as a function of Tx power when 1-2 Tx antennas are used.

(b) DAS gain when 2, 3, or 4 antennas are used.

(c) The effect of non-synchronized transmissions for two Tx antennas.

Fig. 3: DAS experiments showing feasibility of PLC as a backhaul for DAS, DAS performance gains, and DAS synchronization issues.

increase the number of Tx antennas to up to four. The Rx node has only one antenna. As with the two antenna case, we run our experiment with twenty different topologies in which we change the locations of both the Tx and Rx (client) antennas. With each change in the locations of the Tx and Rx antennas, we perform one hundred transmissions. The average SNR value across all the runs and the different topologies is then computed.

Results on gains with DAS: Our experiments show that DAS with two antennas, on average, provides a 3 dB increase in the signal-to-noise ratio (SNR) when two antennas are used. This is found to be true across a range of transmission powers as shown in Fig. 3a.

The result in Fig. 3b shows a logarithmic increase in SNR value at the Rx node as the number of the Tx antennas increases. A 3 dB increase is observed with two antennas. With three antennas, the total DAS gain is about 4.75 dB. The total DAS gain with four antennas is 6 db. Specifically, the results show that the the average resulting SNR due to DAS can be modeled by:

$$w_i = 10\log(\sum_{j}^{|A|} 10^{snr_j^i/10}) \tag{2}$$

where w_i is the resulting average SNR from DAS, i refers to the index of a specific user, and j is the index of the antenna. A is the set of Tx antennas and snr_j^i is the SNR value user i experiences from antenna j alone. We find that [20] reports the same observations as we do here.

Synchronization: Our final experiment seeks to quantify the level of synchronization needed across a set of transmitter antennas in DAS, in order to guarantee a constructive signal combining at the receiver. Here, we use use one Tx node with two antennas. Then, we induce delays at one of Tx antennas (prior to transmission) at the granularity of nanoseconds to see how this impacts the received SNR at a Rx node. Specifically, the signal is modulated using BPSK and stored in a buffer corresponding to the Tx antennas. Then, we stagger the transmissions of one of the Tx antennas to induce differences in times when the signals are received by the Rx node. The two transmitted signals mix and superpose in the air before arriving to the Rx node. The Rx node receives the mixed signal and starts decoding it. Once the decoding process succeeds, the average SNR is computed.

The result of our experiments, shown in Fig. 3c, suggest that if the difference in transmission times between two signals is equal to or larger than 600 ns (nanoseconds), the SNR starts to sharply decline. This happens because the cyclic prefix serves as a guard interval against inter-symbol interference (ISI). In our experiment, the cyclic prefix of each OFDM symbol is equal to 600 ns. Once the time difference between the two signals exceeds the length of the cyclic prefix, ISI is more likely to be severe. This result suggests that extenders that are chosen to serve in one DAS cell must tightly synchronize their transmission times to less than 600 ns.

IV. Problem Statement & Solutions

Our goal is to maximize the aggregate throughput (with different types of fairness objectives) of WiFi-PLC users in a home setting. In order to do this, in §IV-A we propose a system model based on the insights from §III. Then we formulate the problem of maximizing the total utility (discussed later) of the WiFi-PLC network. We decompose this problem into two sub-problems, DAS cell formation and WiFi time assignment, and propose an algorithm in § IV-B to solve these. Our solution can optimize throughput with respect to different fairness functions (specifically, max-min fairness and proportional fairness).

A. Problem Statement

The network consists of a PLC backhaul with a WiFi air interface. Each user connects to the master router over a concatenated PLC-WiFi link. A group of PLC links can deliver data to more than one PLC extender on the PLC backhaul. We refer to such a grouping of PLC extenders as a DAS cell or a DAS cluster. Since we consider a home network in this work, we assume a single WiFi contention domain (multiple interfering contention domains such as in enterprises is left for future work). Therefore, there is minimal inter-domain interference, and each DAS cell serves a single user at a time, by simultaneously transmitting the same data over the WiFi interface to the end user. Multicast is be used to efficiently deliver the data to all PLC extenders in each DAS cell, rather than inefficiently sending the same data via unicast to each extender in that group [16], [17].

Our objective is to maximize the total network utility, where utility is defined as a function of the throughput. We formulate this optimization problem in Problem 1 below. The notations used in these formulations are summarized in Table I; note that

Variable	Description
α	The fairness factor.
A	Set of PLC-DAS extenders.
c_j	The PLC capacity of extender j
$f(.)$	A function that takes the SNR value in dB and returns the corresponding WiFi modulation scheme rate
γ_j	The delay difference between the primary extender and extender j
λ_i	The WiFi time allocation for user i
p_i	The capacity of the PLC backhaul for user i
snr_j^i	The SNR value experienced by user i from extender j
U	Set of users.
υ_i	bitrate of user i.
$u(\cdot)$	utility function defined in (11)
w_i	The cumulative DAS-SNR for user i
x_{ij}	Binary variable indicating whether extender j serves user i.

TABLE I: Table of Notation

in this paper, *rate* refers to the PHY bit rate of the WiFi or PLC links, while *throughput* refers to the achieved bit rate a user could enjoy on a PLC or WiFi link given a time allocation.

Problem 1. *Overall Formulation*

$$\max_{x_{ij},\lambda_i} \quad \sum_{i=1}^{|U|} u(\upsilon_i \lambda_i) \tag{3}$$

$$\textit{s.t.} \quad \upsilon_i = \min(f(w_i), p_i), \quad \forall i \in |U| \tag{4}$$

$$w_i = 10\log\left(\sum_{j=1}^{|A|} (10^{(snr_j^i/10)}) x_{ij}\gamma_j\right) \tag{5}$$

$$p_i = \min_{\{j\in A: x_{ij}>0\}} c_j, \quad \forall i \in |U| \tag{6}$$

$$\sum_{j=1}^{|A|} x_{ij} \geq 1, \quad \forall i \in |U| \tag{7}$$

$$\sum_{i=1}^{|U|} \lambda_i = 1 \tag{8}$$

$$x_{ij} = \begin{cases} 1 & \textit{if extender } j \textit{ serves user } i \\ 0 & \textit{otherwise} \end{cases}, \forall i \in |U|, \forall j \in |A| \tag{9}$$

$$\gamma_j = \begin{cases} 1 & \textit{if extender j and the primary extender are out of the sync by} > \textit{600 ns} \\ 0 & \textit{otherwise} \end{cases}, \forall j \in |A| \tag{10}$$

The objective (3) is to maximize the total utility of all users. The utility function u is defined as the α-fair utility function as a function of each user's throughput $\upsilon_i\lambda_i$:

$$u(\upsilon_i\lambda_i) = \begin{cases} \frac{(\upsilon_i\lambda_i)^{1-\alpha}}{1-\alpha} & \alpha > 0, \alpha \neq 1 \\ \log(\upsilon_i\lambda_i) & \alpha = 1 \end{cases} \quad \forall i \in |U| \tag{11}$$

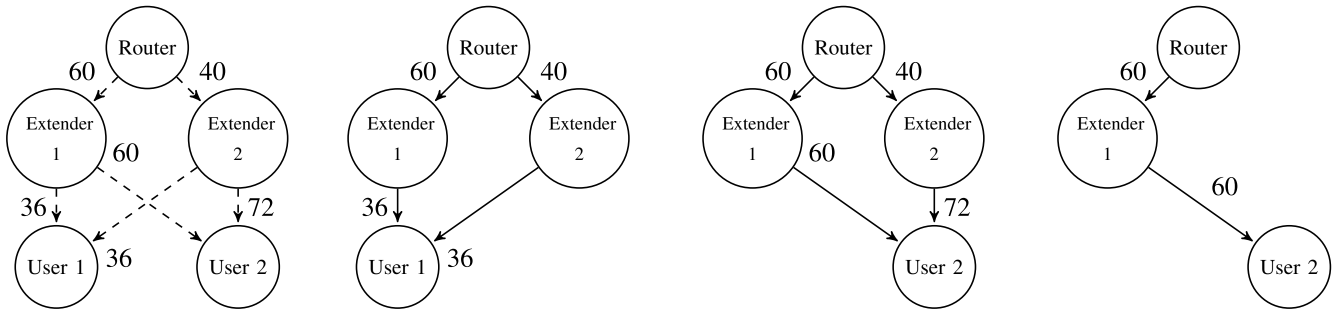
where for $\alpha = 0$, the system prioritizes efficiency (*i.e.*, the aggregate throughput), and as α increases, the system prioritizes fairness (*i.e.*, users have an equal share of the throughput). Constraint (4) says that the achievable end-to-end bitrate of user i is the minimum of its PLC and WiFi link segments. Constraint (5) specifies the aggregate WiFi SNR a user receives from all the extenders in its DAS cell. Constraint (6) quantifies the capacity of the PLC backhaul for user i as the minimum of the extenders to which it is connected (for DAS), due to multicast. Constraint (7) states that each user must connect to at least one extender. Constraint (8) states that the total time allocation must sum to 1. Constraint (9) says that x_{ij} is a decision variable which is equal to 1 when user i is connected to extender j, and 0 otherwise. Finally, constraint (10) is a system parameter that describes whether the extenders are synchronized within less than 600 ns. The variables in this optimization problem are λ_i, the WiFi time allocation for user i, and x_{ij}, which specifies whether user i is connected to extender j.

Toy example: To illustrate our problem, we next describe a toy example. We will show that creating DAS cells naively, such as by associating to the extender that gives the highest RSSI or to the extender that offers best end-to-end throughput, may not result in the the optimal solution, and thus solving our optimization problem is non-trivial. Fig 4a shows our example network topology with the possible PLC and WiFi links for user 1 and user 2. The edges between the router and the two extenders represent the bitrate of each PLC link, if each PLC link was used in isolation. The edges between the extenders and the two users represent the WiFi links if only one WiFi link was active.

First, consider the case for user 1 in Fig. 4b. When the two extenders form a DAS cell, user 1 will enjoy a WiFi link with bitrate of 48 Mbps, and an overall end-to-end throughput of $\min(48, 40) = 40$ Mbps. If user 1 naively decides to associate with extender 1 alone, because it gives the best end-to-end throughput (36 Mbps), using DAS still yields a higher throughput. DAS gives a higher throughput because (a) the WiFi signal from the two extenders combined is better than what user 1 can achieve with an extender individually, and (b) this boost in WiFi signal more than compensates for the reduced rate on the PLC backhaul due to multicast.

On the other hand, user 2 will suffer if both extenders are naively used to form a DAS cell, as shown in Fig. 4c. The reason is that user 2 will experience a hit in throughput from including extender 2, because the PLC link for extender 2 is poor quality (40 Mbps), so adding it decreases the multicast backhaul rate to 40 Mbps, throttling the end-to-end throughput to 40 Mbps as well. A naive solution for user 2 is to connect to the extender that offers the highest RSSI, which is extender 2. However, this assignment is suboptimal since the PLC link segment (extender 2's PLC link) has a capacity of only 40 mbs, throttling the end-to-end throughput of user 2 regardless of the high quality of its WiFi link. The optimal end-to-end throughput for user 2 is achieved through the configuration shown in Fig. 4d, where user 2 connects to extender 1 only.

Problem Decomposition: We next describe how to decompose problem 1 into two sub-problems. First we formulate the problem of DAS antenna selection (*i.e.*, DAS cell formation), where we solve Problem 2 for x_{ij}. We refer to this as Problem 2. We then formulate the problem of WiFi time allocation, where we solve Problem 3 for λ_i. We first describe



(a) Maximum achievable rates of each PLC and WiFi links in isolation.

(b) Maximum achievable throughput (rate) for user 1. The resulting DAS-SNR is 17 dB which maps to 48 Mbps. Total throughput is $\min(48, 40) = 40$ Mbps.

(c) Maximum achievable throughput (rate) for user 2. The resulting DAS-SNR is 28 dB which maps to 72 Mbps. Total throughput is $\min(72, 40) = 40$ Mbps.

(d) Maximum achievable throughput (rate) for user 2. Total throughput is $\min(60, 60) = 60$ Mbps.

Fig. 4: Toy example of different possible DAS cell formation solutions.

Problem 2 below, which is defined for each user i:

Problem 2. *PLC-DAS Extender Selection*

$$\max_{x_{ij}} \quad \min(f(w_i), p_i) \tag{12}$$

$$\textit{s.t.} \quad w_i = 10\log\left(\sum_{j=1}^{|A|}(10^{(snr_j^i/10)})x_{ij}\gamma_j\right), \quad \forall i \in |U| \tag{13}$$

$$p_i = \min_{\{j\in A: x_{ij}>0\}} c_j, \quad \forall i \in |U| \tag{14}$$

$$\sum_{j=1}^{|A|} x_{ij} \geq 1, \quad \forall i \in |U| \tag{15}$$

$$x_{ij} = \begin{cases} 1 & \textit{if extender } j \textit{ serves user } i \\ 0 & \textit{otherwise} \end{cases} \tag{16}$$

$$\gamma_j = \begin{cases} 1 & \textit{if extender } j \textit{ and the primary extender are out of sync by} > 600 \textit{ ns} \\ 0 & \textit{otherwise} \end{cases} \tag{17}$$

The objective (12) in Problem 2 says that we want to maximize the throughput of a given user i (during a given time duration). The constraints in this problem match those in problem (1) relating to x_{ij}.

Next we formulate the problem of solving for the time allocations $\{\lambda_i\}$ in Problem 3 below:

Problem 3. *WiFi time allocation with α-fairness*

$$\max_{\lambda_i} \quad \sum_{i=1}^{|U|} u(\upsilon_i \lambda_i) \tag{18}$$

$$\textit{s.t.} \quad \sum_{i=1}^{|U|} \lambda_i = 1 \tag{19}$$

The utility function $u(\cdot)$ in (18) is defined in (11), and the objective is to maximize the summation of user utility with respect to the time allocations λ_i. Constraint (19) states that the total time allocation across users is equal to one. Note here that this formulation is general enough to capture a wide spectrum of fairness definitions, depending on the value of α.

In the special case of $\alpha = 1$ in (11), we have the proportional fair utility function as the objective, as written below in Problem 4:

Problem 4. *WiFi time allocation with proportional fairness ($\alpha = 1$)*

$$\max_{\lambda_i} \quad \sum_{i=1}^{|U|} \log(\upsilon_i \lambda_i) \tag{20}$$

$$\textit{s.t.} \quad \sum_{i=1}^{|U|} \lambda_i = 1 \tag{21}$$

The constraints of Problem 4 are the same as Problem 3.

We seek to understand whether the solutions to the decomposed problems also solve the overall problem. Theorem 1 below shows this.

Theorem 1. *A solution to Prob. 2 and Prob. 4 is also a solution to Prob. 1 when $\alpha = 1$.*

Proof: Denote a solution to Prob. 1 as $(\lambda_i^{**}, x_{ij}^{**})$. Denote a solution to Prob. 2 as x_{ij}^* and a solution to Prob. 4 as λ_i^*. The constraints of Prob. 1 are equal to the union of the constraints of Probs. 2 and 4, and hence their feasible sets are equivalent. It remains to examine their objective functions. The claim is that (λ_i^*, x_{ij}^*) is also a solution to Prob. 1.

Since x_{ij}^* maximizes $\upsilon_i(x_{ij})$ according to the definition of Prob. 2, we know that $\upsilon_i(x_{ij}^*) \geq \upsilon_i(x_{ij}^{**})$ for all i, which implies that $\sum_i \log(\lambda_i^{**}\upsilon_i(x_{ij}^*)) \geq \sum_i \log(\lambda_i^{**}\upsilon_i(x_{ij}^{**}))$. The RHS maximizes (3) for $\alpha = 1$, and so the LHS must equal the RHS. Next, since λ_i^* maximizes Prob. 4, we have that $\sum_i \log(\lambda_i^*\upsilon_i(x_{ij}^*)) \geq \sum_i \log(\lambda_i^{**}\upsilon(x_{ij}^*)) = \sum_i \log(\lambda_i^{**}x_{ij}^{**})$, where the equality comes from the RHS-LHS argument above. Since $\sum_i \log(\lambda_i^{**}x_{ij}^{**})$ maximizes (3), we can replace the first inequality with equality. Therefore, (λ_i^*, x_{ij}^*) achieves the same optimal value in (3) as $(\lambda_i^{**}, x_{ij}^{**})$, and hence is also a solution to Prob. 1.

■

A similar proof holds for Prob. 1 and Probs. 3, 2.

B. Algorithms for DAS Cell Formation and WiFi Time Allocation

In this section, we describe our algorithms to solve Problems 2, 3, and 4. This is done in two steps: (1) DAS cell formation via antenna selection, and (2) WiFi time allocation. The first step of DAS cell formation is solved via Algorithm 1. Algorithm 1 assigns each user to the extender (primary extender) that gives the highest end-to-end throughput. Then, it adds additional extenders to create a DAS cell for each user. Algorithms 2 and 3 allocate time to each user to achieve max-min fairness or proportional fairness, respectively.

Algorithm 1 DAS Cell Formation

Inputs: Set of users U, set of extenders A, PLC capacity c_j, SNR value snr_j^i,
Output: User assignments x_{ij}
Variables: user index i, extender index j, end-to-end bitrate b_{ij}

1: **for** $i \leftarrow 1$ to $|U|$ **do**
2:     **for** $j \leftarrow 1$ to $|A|$ **do**
3:         $b_{ij} \leftarrow \max(\min(f(snr_j^i), c_j))$
4:     $\bar{j} \leftarrow argmax_j(b_{ij})$
5:     $x_{i\bar{j}} \leftarrow 1$
6:     $\upsilon_i = b_{i\bar{j}}$
7: **for** $i \leftarrow 1$ to $|U|$ **do**
8:     **for** $j \leftarrow 1$ to $|A|$ **do**
9:         **if** $\gamma_j == 1$ **then**
10:             **if** $x_{ij} == 0$ **then**
11:                 **if** $c_j > \upsilon_i$ **then**
12:                     $x_{ij} \leftarrow 1$
13:                     $w_i \leftarrow 10 \log \left(\sum_{j'=1}^{|A|} (10^{\frac{snr_{j'}^i}{10}}) x_{ij'} \right)$
14:                     $\upsilon_i \leftarrow \min(f(w_i), p_i)$
15:                 **else** $x_{ij} \leftarrow 0$

Step I: First, Algorithm 1 iterates over all users $i \in U$ and extenders $j \in A$, and finds the extender that gives the best end-to-end throughput for each user (lines 1 to 6). Then, it checks if there is any other extenders that can be added to create a DAS cell for each user (lines 7 to 15). It does so by first checking if the PLC capacity of the extender to be added (x_{ij}) is greater than the bitrate the user currently has (υ_i) (line 11). Second, it checks if adding that extender will result an improvement in the WiFi link (lines 13 and 14).

Step II: After determining the DAS cells, we next determine how to allocate time resources fairly across users. Our methods to achieve max-min and proportional fairness are presented in Algorithms 2 and 3, respectively. In the former, we try to maximize the throughput of the user with the minimum throughput in the system. This can be achieved by granting more airtime to the users with poor throughputs. Therefore, users are allocated time based on their achievable bitrates relative to the maximum achievable bitrate across all users. Such an allocation can easily be shown to result in equal throughputs for all users.

Algorithm 2 Max-Min Fairness

Inputs: Set of achievable users' throughputs $\{\upsilon_i\}$
Output: Max-min time allocation for each user $\{\lambda_i\}$
Variables: user index i

for $i \leftarrow 1$ to $|U|$ **do**
    $\lambda_i = \frac{\max_{i'}(\upsilon_{i'})}{\upsilon_i}$

Algorithm 3 attempts to solve Problem 4, for proportional fairness. The objective (20) aims to maximize the summation of the log utility, $\log(\upsilon_i \lambda_i)$. Since x_{ij} is fixed in Problem 4 (it was computed in Step I above), Problem 4 has a closed form solution for λ_i, where where all the users have equal time shares (*i.e.*, equal λ_i) [21]. Consequently, we divide the total time 1 by the total number of users in the system, $|U|$.

Algorithm 3 Proportional Fairness

Inputs: Set of achievable users' bitrates $\{\upsilon_i\}$
Output: Proportional fair time allocation for each user $\{\lambda_i\}$
Variables: user index i

for $i \leftarrow 1$ to $|U|$ **do**
    $\lambda_i = \frac{1}{|U|}$

Algorithm Complexity: Step I of our algorithm runs in $\mathcal{O}(|U||A|^2)$, where $|U|$ is the number of users and $|A|$ is the number of the PLC extenders. The runtime of the Step II of our algorithm is $\mathcal{O}(|U|)$. Thus the total runtime for both steps is given by $\mathcal{O}(|U||A|^2)$.

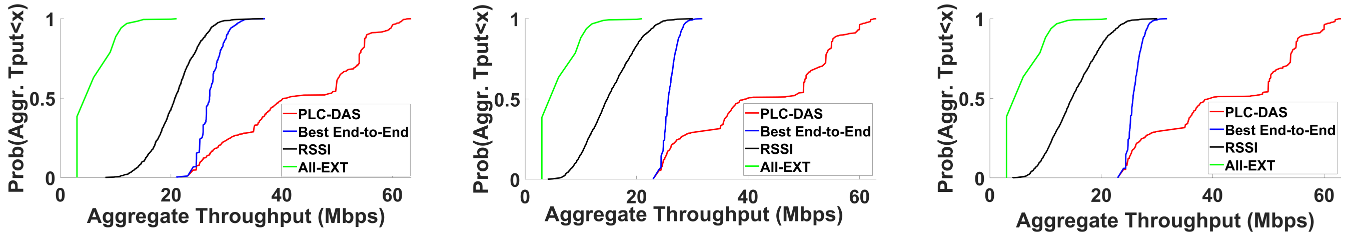
V. Evaluations

To capture a diverse variety of home settings, we perform extensive simulations. We make the simualtion set ups realistic by using the experimental measurement results reported in Section III, both on the PLC and the WiFi (DAS) parts of the network.

A. Simulation Details

PLC-DAS Simulation Framework: We implement PLC-DAS entirely from scratch in MATLAB [22] since other simulating tools do not have models of realistic PLC backhauls. PLC-DAS runs on a Lenovo T460p machine running a 64-bit Windows 10 operating system. We develop code to simulate 2D homes with different areas. This helps us understand how PLC-DAS behaves in a variety of settings, spanning a small studio apartment to an average home in the USA [23]. Specifically, we simulate four to eight WiFi-PLC extenders and five to twenty users. Each extender is placed randomly in the home area and assigned a capacity from the distribution we observed in our measurements in Section §III. Later we show that our home models yield results that are similar to the results when real home layouts and WiFi-PLC extender locations from Pinterest [24] are considered.

The number of users (5-20) and their locations in the house layout are chosen randomly. The WiFi links between users

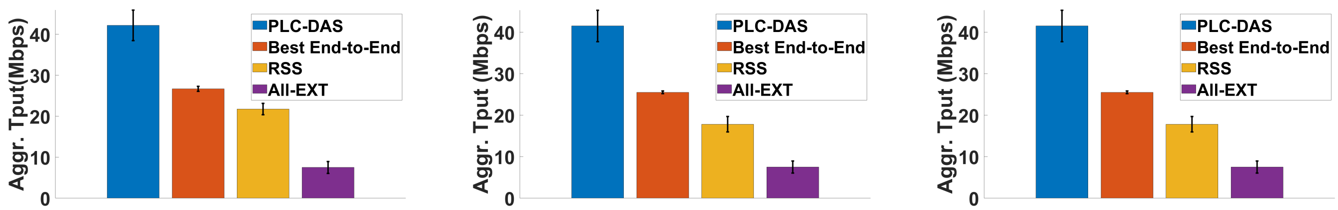


(a) Aggregate throughput with proportional fairness.

(b) Aggregate throughput with max-min fairness.

(c) Aggregate throughput with throughput fairness.

Fig. 5: CDF of aggregate throughput with different fairness models.



(a) Proportional fairness aggregate throughputs.

(b) Max-min fairness aggregate throughputs.

(c) Throughput-fair aggregate throughputs.

Fig. 6: Average aggreate throughput. The results show how PLC-DAS outperforms other baselines.

and extenders are assigned SNR values based on the physical distance between each user relative to each extender, as well as the shadowing and fading impacts for indoor users as reported in [25]. The resulting average SNR values that users could experience when using DAS is then computed based on our findings in Section §III. Subsequently, each averaged SNR value is mapped to a modulation scheme based on the SNR-to-modulation translations provided in [26]. Each modulation scheme is capable of encoding a specific number of bits within each OFDM symbol. Therefore, each SNR value is mapped to a specific bitrate that the corresponding modulation scheme can provide [27].

Baselines: We evaluate PLC-DAS against three baselines: (a) Best End-To-End (BETE), (b) Received Signal Strength (RSS) and (c) All-Extenders (All-EXT). The BETE baseline assigns users to the single extender that provides the highest end-to-end throughput over the concatenated WiFi-PLC link. The RSS baseline assigns a user to the extender with the highest quality WiFi link. without considering the PLC backhaul capacity. This reflects the assignment policy that currently exists on off-the-shelf WiFi-PLC extenders. Lastly, we consider the case when all accessible extenders are used to form a DAS cell (All-EXT). The All-EXT baseline demonstrates the pitfalls when DAS cells created blindly with out considering PLC link capacity differences.

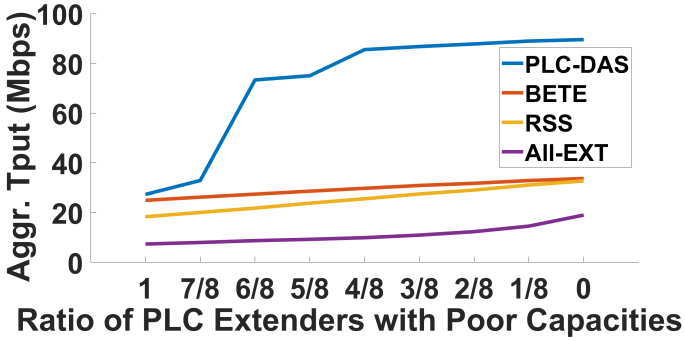
Performance Matrics: Our metrics of interest are: (a) the aggregate network throughput that PLC-DAS can deliver compared to the other baselines and, (b) the fairness achieved with PLC-DAS versus other baselines, with respect to our three fairness models viz., proportional fairness (PF), max-min fairness (MM) and throughput-fair (TF). As discussed in §IV-B, PF allocates time slots equally to each user, and MM seeks to maximize the throughput of the user with the minimum throughput. higher rates.

B. Results

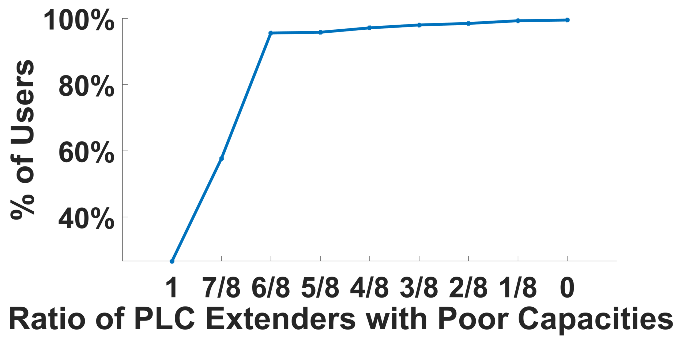
Throughput gains with PLC-DAS: First we compare PLC-DAS against the three baselines, in terms of aggregate throughput with the different fairness models. The CDFs in Figs. 5a, 5b and 5c show that PLC-DAS outperforms all the baselines in all trials. In Fig. 6a we show the aggregate throughputs when using PF. *We find that PLC-DAS with PF outperforms all the three baselines and yields average throughput improvements of 58%, 112% and 462%, over BETE, RSS and All-EXT, respectively. Similarly, when MM and TF throughputs are maximized, as seen in Fig. 6b and Fig. 6c respectively,* PLC-DAS *outperforms the baselines BETE, RSS and ALL-EXT on average by 62.7%, 103% and 457%, respectively.*

The RSS baseline yields a higher throughput under PF compared to MM (by 22%). This is because PF allocates an equal time shares to all users. On the other hand, MM maximizes the throughput of the user with the worst throughput, *i.e.*, it provides larger time allocations to users with poor rates, compared to users with good rates, and consequently suffers from a lower aggregate throughput.

The All-EXT baseline suffers with all fairness models. When all extenders are considered for a DAS cell, the extender with the poorest PLC capacity (the slowest), becomes the bottleneck that limits the throughput for that cell. The poorest extender will always be the last extender to receive data on the PLC backhaul and other extenders have to wait for it before transmitting the data over WiFi to the end user, thus increasing the delay and decreasing the throughput.



(a) The effect of PLC backhaul on the total throughput of PLC-DAS



(b) The effect of the PLC backhaul on the percentage of users benefiting from PLC-DAS.

Fig. 7: PLC backhaul impact.

Fairness: We use Jain's fairness index [28] to evaluate the fairness of PLC-DAS in comparison to the three aforementioned baselines. The closer Jain's index value is to 1, the more fair. *The Jain's fairness index results in Table II show that* PLC-DAS *provides a better or at least comparable fairness to all other baselines, except for All-EXT. Unlike other baselines,* PLC-DAS *shows a balance between fairness and maximizing the aggregate throughput*. While PLC-DAS might not be able to benefit some users because either (a) they are not in locations that are amenable to DAS, or (b) because they are already obtaining the best throughput at their locations by connecting to a single primary extender, PLC-DAS can improve the individual throughputs of users with poor throughputs. This alleviates variations across user throughputs thereby enhancing the fairness index.

The reason that All-EXT exhibits the highest fairness index is because all extenders a user can associate with are included for the DAS cluster corresponding to that user. The extender with the poorest PLC link capacity in the home will now dominate the backhaul throughput, and the throughputs of all users will degrade to the capacity determined by that poor extender. Consequently, the individual throughputs for these users become similar and are poor. This boosts the Jain's index for All-EXT, but at the expense of severely decreased user throughputs. MM and TF always yield the highest index of 1. This is because these models try to achieve equal throughputs for all users. This improves fairness but again, at the cost of higher throughputs. Importantly, PLC-DAS maximizes the

	PF	MM	TF
PLC-DAS	0.97	1	1
BETE	0.93	1	1
RSSI	0.78	1	1
ALL-Exts	1	1	1

TABLE II: Jain's fairness index

aggregate throughput while scoring a fairness index of at least 0.97 across different fairness models.

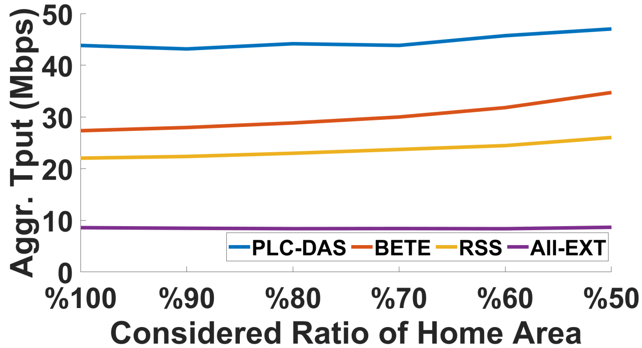
The remaining results in this section reflect the PF model unless stated otherwise. We omit the results with the other two models (results are similar in spirit with what was reported thus far) due to space constraints.

The impact of the PLC backhaul on gains with PLC-DAS**:** Next, we examine how the different PLC link qualities affect the aggregate throughput gain of PLC-DAS. We simulate a WiFi-PLC network in a home setting with eight PLC extenders, all with good links (a PLC link is classified as good if its capacity > 50 Mbps [29]). Subsequently, we flip one of the good PLC links to a poor link (capacity≤ 50 Mbps). We continue this process, *i.e.*, keep flipping good PLC links, one at a time until all the PLC links are poor. At each switch from a good to a poor link, we simulate the experiment one thousand times and then we take the average of the aggregate throughputs.

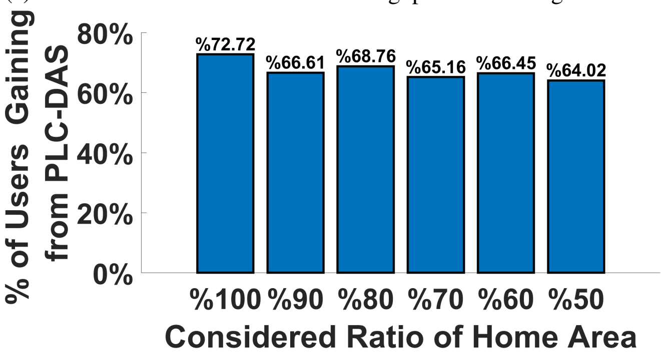
The results of this experiment, captured in Fig. 7a, show that PLC-DAS still offers an improvement (albeit small) in terms of aggregate throughout even when PLC backhaul is all poor (ratio=1). PLC-DAS *shows an improvement of 1.9 times compared to BETE and up to 7.4 times over All-EXT when 75% of the PLC links are poor (ratio=6/8). This demonstrates that* PLC-DAS *is very effective in improving throughput even with a mostly poor PLC backhaul.* This is because some users can exploit the good PLC extenders to form DAS clusters. Beyond this point however, as the ratio of poor to good quality PLC links increases, the penalties incurred due to PLC backhaul links causes the overall throughput to drop sharply; almost no client benefits from using DAS in such cases.

Impact of the home area (large house vs. small studio): In this next set of experiments, we consider homes with sizes similar to an average US house. The goal is to understand the gains with PLC-DAS in homes of different areas. In each case, we consider four to eight extenders with five to twenty users, and randomly generate one thousand different topologies with regards to user locations. The results in Fig. 8a show that when the home area is decreased by 50%, PLC-DAS, BETE, and RSS improve their aggregate throughputs compared to the original larger home area. In contrast, the fraction of users benefiting from PLC-DAS when the home area is decreased by 50% declines by 8.7% ,compared to when the whole home area is considered (ratio=100%), as shown in Fig. 8b. This is driven by users who are now connected to their primary PLC extender with excellent WiFi link segments, because they are now closer due to the reduced home area. Consequently, *the gains from* PLC-DAS *are reduced in smaller homes; larger houses, however, yield much higher throughput gains.*

Realism of our home layouts: Finally, we show that



(a) Home area effect on the total throughput when using PLC-DAS



(b) Home area effect on the percent of users benefiting from PLC-DAS.

Fig. 8: Home area impact.

	Aggregate Throughputs with PF (Mbps)	
	Real House Layouts	Randomly Generated Layouts
PLC-DAS	40	42.1
BETE	25.5	26.7
RSS	21	21.7
All-EXT	9.3	7.5

TABLE III: Aggregate throughput comparison between real house layouts and randomly generated layouts

the randomly generated house layouts and extender locations realistically reflect real-life home settings. We consider ten real house layouts with electrical diagrams obtained from [24]. We study the electrical wiring on these layouts and extract the physical locations of the power outlets, with up to 20 power outlets observed per home based on the electrical diagrams. Each power outlet is a potential location where a WiFi-PLC extender can be plugged in. We run our simulation with ten real-life house layouts. We simulate four to eight extenders and five to twenty users. Extenders are assigned capacities as per the distribution observed in Section §III. Then we compute the average aggregate throughputs and the fairness indices. We repeat the experiment, but this time with the house layouts and extender locations generated randomly with our approach. *Tables III and IV show that our randomly generated topologies yield very similar results to real house layouts and extender locations.* This provides confidence that our simulations reflect realistic home settings.

	Jain's Fairness Index with PF	
	Real House Layouts	Randomly Generated Layouts
PLC-DAS	0.97	0.97
BETE	0.95	0.94
RSS	0.85	0.84
All-EXT	1	1

TABLE IV: Fairness comparison between real house layouts and randomly generated layouts

VI. Related Work

In this section, we describe relevant related work.

WiFi User Association: The authors of [30], [31] develop user association policies in WiFi networks to optimize a performance metric (*e.g.*, throughput) with some fairness models. Our work differs for multiple reasons. First, these efforts assume an Ethernet backhaul of a higher capacity than the WiFi links. The PLC backhaul may not satisfy this property, *i.e.*, the PLC segment could be the bottleneck rather than the wireless link. Second, they do not consider the use of DAS.

Distributed Antenna Systems: There are several efforts on creating DAS clusters, either to improve robustness or energy efficiency (*e.g.*, [32]–[35]). These efforts however, do not consider the impact of the backhaul on DAS transmissions as we do here.

PLC: There are efforts like [36]–[39] on broadband PLC networks. They do not consider concatenated WiFi-PLC links.

Hybrid WiFi-PLC: Vidyut [40] considers using electrical wiring to deliver a synchronization signals to wireless APs to improve performance in MIMO deployments. However,they are not concerned with the characteristics of the PLC backhaul. Apicharttrisorn *et al.* [29] measure the performance of PLC extenders equipped with HomePlug AV2, which are WiFi-compliant extenders. In [41], the authors study if a PLC backhaul can serve as a backbone for WiFi in home settings. None of these studies however, consider DAS deployment. The authors of [13] propose a framework to assign users to the appropriate extenders with the objective of maximizing the aggregate throughput in hybrid WiFi-PLC networks. However, they do not consider using DAS as a mechanism for providing better indoor coverage.

VII. Conclusions

In this paper we propose PLC-DAS, a framework to maximize the total network throughput in WiFi-capable PLC networks by using distributed antenna systems or DAS. PLC-DAS intelligently chooses the best set of WiFi-PLC extenders for each user, that gives the highest end-to-end throughput for that use. The challenge we handle is that we ensure that we eliminate PLC backhaul links of inferior qualities when creating the DAS cluster; otherwise, we show that this can degrade the user throughput instead of improving the same. We formulate the problem of choosing the set of extenders that yields the highest throughput and propose variations that account for different fairness models. Our problem formulation is driven by real experiments on PLC and DAS testbeds. We subsequently design a set of algorithms to build a framework

PLC-DAS, which significantly boosts the achievable throughputs of users within homes. We show via simulations that PLC-DAS significantly outperforms non-DAS and naive DAS baselines in terms of aggregate throughput while scoring high in terms of the Jain's fairness index (at least 0.97).

VIII. Acknowledgments

This work was partially supported by the NSF NeTS grant 1528095. The authors would also like to thank Dr. Thyaga Nandagopal of NSF who initially suggested the problem of realizing DAS over PLC.

References

[1] D. Dzung, I. Berganza, and A. Sendin, "Evolution of powerline communications for smart distribution: From ripple control to ofdm," in *2011 IEEE International Symposium on Power Line Communications and Its Applications*. IEEE, 2011.

[2] *Power Line Communication (PLC) Systems - Global Market Trajectory & Analytics*. Global Industry Analysts, Inc, 2020.

[3] *Power Line Communication Market - Global Industry Analysis, Size, Share, Growth, Trends and Forecast 2016 - 2024*. Transparency Market Research, 2021.

[4] "Best wi-fi extenders of 2019: top devices for boosting your wifi network," https://www.techradar.com/news/the-best-wi-fi-extenders.

[5] G. Bianchi, S. Di Domenico, M. De Sanctis, L. Liberati, V. Perrotta, and E. Cianca, "Unveiling access point signal instability in wifi-based passive sensing," in *ICCCN '17*. IEEE.

[6] Y. Zhang, H. Hu, and J. Luo, *Distributed antenna systems: open architecture for future wireless communications*. CRC Press, 2007.

[7] S. Pato, J. Pedro, J. Santos, A. Arsénio, P. Inácio, and P. Monteiro, "On building a distributed antenna system with joint signal processing for next generation wireless access networks: The futon approach," in *7th Conference on Telecommunications, Portugal*, 2008.

[8] J. Li, K. Xiong, J. Cao, X. Yang, and T. Liu, "Energy efficiency in rf energy harvesting-powered distributed antenna systems for the internet of things," *Sensors*, 2020.

[9] H. Ouassal, T. Rocco, M. Yan, and J. A. Nanzer, "Decentralized frequency synchronization in distributed antenna arrays with quantized frequency states and directed communications," *IEEE Transactions on Antennas and Propagation*, 2020.

[10] "Warp project." [Online]. Available: http://warpproject.org

[11] C. Vlachou, A. Banchs, J. Herzen, and P. Thiran, "On the mac for power-line communications: Modeling assumptions and performance tradeoffs," in *(ICNP '14*.

[12] L. Yonge, J. Abad, K. Afkhamie, L. Guerrieri, S. Katar, H. Lioe, P. Pagani, R. Riva, D. M. Schneider, and A. Schwager, "An overview of the homeplug av2 technology," *Journal of Electrical and Computer Engineering*, 2013.

[13] H. A. Alhulayyil, K. Apicharttrisorn, J. Chen, K. Sundaresan, S. Oymak, and S. V. Krishnamurthy, "Wolt: Auto-configuration of integrated enterprise plc-wifi networks."

[14] T. Koike-Akino, A. F. Molisch, C. Duan, Z. Tao, and P. Orlik, "Capacity, mse and secrecy analysis of linear block precoding for distributed antenna systems in multi-user frequency-selective fading channels," *IEEE Transactions on Communications*, 2011.

[15] J. Park and B. Clerckx, "Multi-user linear precoding in massively distributed polarized antenna systems under imperfect csit," *IEEE Transactions on Vehicular Technology*, 2020.

[16] F. Chiti, R. Fantacci, D. Marabissi, and A. Tani, "Performance evaluation of an efficient and reliable multicast power line communication system," *IEEE Journal on Selected Areas in Communications*, 2016.

[17] A. Maiga, J.-Y. Baudais, and J.-F. Hélard, "Increase in multicast ofdm data rate in plc network using adaptive lp-ofdm," in *ICAST '09*. IEEE.

[18] "Tcp/udp bandwidth measurement tool," https://iperf.fr/.

[19] M. Matsui, T. Nakagawa, R. Kudo, K. Ishihara, and M. Mizoguchi, "Blind frequency-dependent iq imbalance compensation scheme using cma for ofdm system," in *2011 IEEE 22nd International Symposium on Personal, Indoor and Mobile Radio Communications*. IEEE.

[20] D. G. Brennan, "Linear diversity combining techniques," *Proceedings of the IRE*, 1959.

[21] J. Chen, M. Chiang, J. Erman, G. Li, K. Ramakrishnan, and R. K. Sinha, "Fair and optimal resource allocation for lte multicast (embms): Group partitioning and dynamics," in *2015 IEEE Conference on Computer Communications (INFOCOM)*. IEEE, 2015, pp. 1266–1274.

[22] MATLAB, *version 9.6.0.1072779 (R2019a)*. Natick, Massachusetts: The MathWorks Inc., 2019.

[23] "Highlights of annual 2019 characteristics of new housing," www.census.gov/.

[24] "Pinterest." [Online]. Available: https://www.pinterest.com/

[25] J. Lei, R. Yates, L. Greenstein, and H. Liu, "Wireless link snr mapping onto an indoor testbed," in *First International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities*. IEEE.

[26] M. Dangi and M. K. Porwal, "Analyses of snr threshold for minimum ber in various modulations schemes and development of an adaptive modulation scheme," *IJISET–Int. J. Innov. Sci. Eng. Technol*, 2015.

[27] D. J. Urban, "Application of 4k-qam, ldpc and ofdm for gbps data rates over hfc plant," *NCTA Technical Papers*, 2013.

[28] R. Jain, A. Durresi, and G. Babic, "Throughput fairness index: An explanation," in *ATM Forum contribution*, 1999.

[29] K. Apicharttrisorn, A. O. F. Atya, J. Chen, K. Sundaresan, and S. V. Krishnamurthy, "Enhancing wifi throughput with plc extenders: A measurement study," in *Passive and Active Measurement*, 2017.

[30] A. P. Jardosh, K. Mittal, K. N. Ramachandran, E. M. Belding, and K. C. Almeroth, "Iqu: Practical queue-based user association management for wlans," ser. MobiCom '06. ACM.

[31] M. AMER, A. Busson, and I. Guérin Lassous, "Association optimization in wi-fi networks: Use of an access-based fairness," ser. MSWiM '16.

[32] J. Joung, Y. K. Chia, and S. Sun, "Energy-efficient, large-scale distributed-antenna system (l-das) for multiple users," *IEEE Journal of Selected Topics in Signal Processing*, 2014.

[33] X. Chen, X. Xu, and X. Tao, "Energy efficient power allocation in generalized distributed antenna system," *IEEE Communications Letters*, 2012.

[34] D. Castanheira and A. Gameiro, "Distributed antenna system capacity scaling [coordinated and distributed mimo]," *IEEE Wireless Communications*, 2010.

[35] T. Niiho, M. Nakaso, K. Masuda, H. Sasai, K. Utsumi, and M. Fuse, "Multi-channel wireless lan distributed antenna system based on radio-over-fiber techniques," in *LEOS '04*. IEEE.

[36] M. Zimmermann and K. Dostert, "Analysis and modeling of impulsive noise in broad-band powerline communications," *IEEE transactions on Electromagnetic compatibility*, 2002.

[37] J. Lin, M. Nassar, and B. L. Evans, "Impulsive noise mitigation in powerline communications using sparse bayesian learning," *IEEE Journal on Selected Areas in Communications*, 2013.

[38] M. E. M. Campista, L. H. M. K. Costa, and O. C. M. B. Duarte, "Improving the data transmission throughput over the home electrical wiring," in *LCN '05*. IEEE, 2005.

[39] V. Degardin, M. Lienard, A. Zeddam, F. Gauthier, and P. Degauquel, "Classification and characterization of impulsive noise on indoor powerline used for data communications," *IEEE Transactions on Consumer Electronics*, 2002.

[40] V. Yenamandra and K. Srinivasan, "Vidyut: Exploiting power line infrastructure for enterprise wireless networks," ser. SIGCOMM '14. ACM, 2014.

[41] N. Roy, D. Kleinschmidt, J. Taylor, and B. Shirazi, "Performance of the latest generation powerline networking for green building applications," ser. BuildSys'13. ACM.