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Improvements in data transfer rates and energy efficiency through opportunistic relaying in residential power networks

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Abstract

In this research, we look at the feasibility of using half-duplex time-division relay protocols to enhance residential power line communication (PLC) networks in terms of data transfer rate, power consumption, and network reach. We consider a network in which source and destination nodes communicate using an opportunistic protocol in which the relay is used whenever possible in preference to direct transmission either (a) to improve the achievable rate subject to a power spectral density (PSD) mask constraint or (b) to reduce the power consumption subject to both the PSD mask and the rate target constraint. We look at both ODF and OAF, or opportunistic decode and forward and opportunistic amplify and forward. We presume that multi-carrier modulation is being used at the physical layer. To optimize the attainable rate or decrease the total transmitted power for both ODF and OAF, we determine the best resource allocation, meaning the optimal power and time slot allocation, between the source and the relay nodes under these conditions. We demonstrate that the combination issue of power and time slot allocation of DF is particularly difficult to solve, making it difficult to execute the power minimization challenge of ODF. For this reason, we offer a simpler approach that splits the original issue into two convex sub-problems. We demonstrate its near-optimal performance via numerical experiments. Finally, because over home PLC networks the relay can only be placed in outlets, in the main panel, or in derivation boxes, we also study the effect of relay position on performance for each opportunistic protocol. The employment of a statistically representative simulator allows for the utilization of both measured and simulated channel responses in the generation of results. They demonstrate how the placement of the relay and the scale of the network affect the achievable throughput and energy savings. Relay, Multi-carrier Modulation, Power Sharing, Power Line Communication, and Allocation of Limited Resources are some examples of Keywords.

Introduction

Conserving energy is a key consideration in the evolution of cutting-edge communication technology. Ethernet standards like IEEE 802.3az and power line communication (PLC) standards like Home Plug Green PHY (GP) have been created to solve this issue. Multimedia applications, such as high-definition television and 3D virtual reality video games, need not just low power consumption but also a fast transmission rate. Therefore, cutting-edge methods of communication, like multicarrier modulation with bit and power loading algorithms, are required.Cross-layer optimization and cooperative communication techniques. This research looks into the feasibility of using cooperative half duplex time division relay protocols to improve the performance of in-home PLC networks that use multi-carrier modulation at the physical (PHY) layer, such as orthogonal frequency division multiplexing (OFDM), by reducing power

consumption, increasing throughput, and expanding network coverage. The wireless literature has extensively covered the issue of resource allocation in relay networks. Several articles that are relevant to the topic are summarized below. Over flat Rayleigh fading relay channels, [2-4] considers the optimal power and time slot allocation for capac ity maximization. Single-hop parallel Gaussian relay channels (for example, OFDM systems) with a total power restriction have been addressed in [5-10]. In specifically, considering half-duplex amplify and forward (AF) with a total power restriction at the source and relay nodes, the authors of [5] discovered a sub-optimal power allocation. The best answer to the earlier issue is presented in [6]. Half-duplex amplify-and-forward (AF) and decode-and-forward (DF) power allocations were optimized under a source plus relay power limitation of each OFDM sub-channel in. Both of the aforementioned pieces assume that the des tinction node is not in the path of least resistance. Under a total power constraint (source and relay), [8] examines the power allocation for full-duplex [2] DF. When using a combination of AF, DF, and DL for transmission, the best power allocation is calculated in [9], subject to a source plus relay power restriction for each sub-channel. The best power allocation for full and half duplex DF with a total power constraint at the source and destination nodes was determined by the authors of [10]. Multi-relay cooperation, or multi-antenna relays, have been discussed at length in the wireless literature; see, for example, [11,12] and their cited works.

Simulation of a PLC-Based Control System

We take into account a personal area network (PAN) where a relay (R) is used to facilitate communication between nodes in the S and D subnetworks of the PAN (Figure 1). In particular, we assume an opportunistic cooperative protocol for source-to-destination (ST-to-DT) communication, in which the relay is deployed when needed to achieve rate increases or DT power savings, as the case may be. Time division multiple access is used to multiplex data between the source nodes and the relay nodes. There are Tf frames in total, and each frame has two sub-segments with durations and Tf . It is possible that the source cannot directly reach the destination, so the relay is used instead. During the first slot, the source sends its data to the relay and destination nodes, and then it goes silent during the second slot while the relay sends the data it has received to the destination node using the opportunistic cooperative protocol (ODF or OAF). With ODF, the relay uses its own codebook to read the incoming data, re-encode it, and send it on. Figure 2 shows how in OAF the relay solely serves to amplify and convey data. We assume OFDM with M subchannels at the physical layer. Subchannel index, i.e., k Kon, where Kon 0,..., M 1 is the sub-set of used (switched on) sub-channels that allows for satisfying a PSD mask with notches, as is the case in broadband PLC systems [20]; subscripts x and y denote the pairs S,R, or R,D, and k is the sub-channel index, i.e. As a result, the information received at the y-the node in the k-the sub-channel is.

$$z_y^{(k)} = a_x^{(k)} H_{x,y}^{(k)} + w_y^{(k)},\ \{x,y\} \in \{\{S,D\};\{S,R\};\{R,D\}\},\ k \in \mathbb{K}_{\mathrm{on}},$$

where a(k) x is the symbol broadcast by node x on sub channel k in DT, DF, or AF modes, and w(k) y is the noise on that channel. We assume the noise and the transmitted symbols are independent and identically distributed, and that they come from zero-mean, zero-power Gaussian distributions, P(k) w,y and P(k) x,mode. The signal sent by the network nodes is assumed to be constrained by a PSD mask for the whole of this investigation. Additionally, we assume the PSD to be constant across the sub-channels (i.e., P(k) x,mode P k Kon, x S; R, and mode DT; DF;AF) in order to simplify the notation. We emphasize that all the power allocation techniques we'll be looking at in this post hold water when considering a more general non-constant PSD.

ODF is an energy saver

Below, we discuss how ODF can help with both power savings and network expansion. As was said before, the relay is used in ODF if the DF attainable rate is greater than the DT achievable rate. Let's assume we're working with a PSD restriction and a set goal rate while using the relay. We may then have three distinct scenarios. In the first scenario, either DT or DF may be used to achieve the goal rate. If the DF attainable rate is greater than the DT achievable rate, then more energy may be conserved by bringing the DF rate down to the desired level than by doing the same for the DT rate. The second scenario applies when the DT rate is the only one that is subpar. In this situation, the relay may be used to expand the reach of the network. In the third scenario, the achievable rate is less than the desired rate in both modes, but increasing the attainable rate via the usage of the relay may bring it closer to the desired rate. We are able to tackle the issue of calculating the amount of power required by ODF to get a desired rate R when the communication is limited by a power-spectrum-density (PSD) limitation.

$$P_{\mathrm{ODF}} = \min\{P_{\mathrm{DT}}, P_{\mathrm{DF}}\}$$

where PDT and PDF, respectively, denote the minimum power required by the DT and DF modes to achieve a rate R under a PSD constraint. Therefore, PDT is the solution to the problem

$$P_{\mathrm{DT}} = \min \sum_{k \in \mathbb{K}_{\mathrm{on}}} P_{S,\mathrm{DT}}^{(k)}$$
$$\text{s.t.} \quad C_{S,D} = R,$$
$$0 \leq P_{S,\mathrm{DT}}^{(k)} \leq \overline{P} \quad \forall \quad k \in \mathbb{K}_{\mathrm{on}},$$

while PDF is the solution to the problem

$$P_{\mathrm{DF}} = \min \sum_{k \in \mathbb{K}_{\mathrm{on}}} \tau P_{S,\mathrm{DF}}^{(k)} + (1-\tau) P_{R,\mathrm{DF}}^{(k)}$$
$$\text{s.t.} \quad C_{\mathrm{DF}}(\tau) = \min \left\{ \tau C_{S,R}, \tau C_{S,D} + (1-\tau) C_{R,D} \right\} = R,$$
$$0 \leq \tau \leq 1,$$
$$0 \leq P_{S,\mathrm{DF}}^{(k)} \leq \overline{P},$$
$$0 \leq P_{R,\mathrm{DF}}^{(k)} \leq \overline{P}, \quad \forall \quad k \in \mathbb{K}_{\mathrm{on}}.$$

Starting from (9), we note that its objective and its inequality constraint functions are convex, but its equality constraint is not an affine function. Therefore, (9) is not in general a convex problem ([26], pp. 136–137). Nevertheless, we note that the equivalent problem (see [26], p. 67) for the definition of equivalent problems), obtained considering the change of variables

$$P_{S,\mathrm{DT}}^{(k)} = (2^{b_{S,\mathrm{DT}}^{(k)}} - 1)/\eta_{S,D}^{(k)}, \text{ where } b_{S,\mathrm{DT}}^{(k)} = log_2 \left(1 + P_{S,\mathrm{DT}}^{(k)} \eta_{S,D}^{(k)}\right),$$

is best seen as a convex optimization issue. Assuming such a problem exists, its solution is well known and can be found by applying the KKT conditions (refer, for example, to [25]). Thus, the answer to the initial problem (9) is equal to the result of applying the inverse change of variables to the answer to the equivalent problem.

The numerical outcomes

Here, we take a look at how ODF and OAF protocols do in terms of throughput, energy efficiency, and range expansion in private local area networks. To that purpose, we first detail the OFDM system parameters in the "multi-carrier system param eters" section. After that we discuss the locations where the experimental channels have been monitored in the "Experimental channels" section. In the "Statistical channel gen erator" section, we analyze the employment of a statistical channel generator to allow for more general network topologies than were possible with the channel measurements (which were confined to pairs of outlets) and to evaluate performance with the relay located in the MP or in derivation boxes. Finally, we offer and analyze numerical findings in the "Achievable rate improvements with ODF and OAF" and "Power savings with ODF and OAF" sections. Parameters for multi-carrier systems We take into account a multi-carrier scheme using comparable specifications to the HomePlug AV broadband PLC system [30]. Unless otherwise specified, the system operates with M = 1536 sub-channels in the 0-37.5 MHz frequency range. By defining the set Kon of active sub-channels, we may limit the transmission bandwidth to be between 1 and 28 MHz. Keeping with accepted EMC practices [31], we take into account the PSD mask constraint of 50 dBm/Hz. In addition, we assume that both the relay and the destination nodes are subjected to white Gaussian noise with a power spectral density (PSD) of 110 (worst case) or 140 (best case) dBm/Hz.

Channels for Experimentation

Two locations were used to take measurements of the experimental channels. The first example represents a network with a single sub-topology. There are 13 outlets spread over the 100 square feet (6 square meters) of this urban apartment's six rooms, all of which are serviced by the same circuit breaker (CB). The second location illustrates a network with two distinct "sub-topologies" (see Figure 3). An MP and a CB link the two sub-topologies in this two-story, 170 square meter detached home's nine individual rooms. There are a total of

24 accessible outlets (13 on the ground level and 11 on the second). All possible pairs of outlets have been measured in the first location's channels. The ORA configuration will be analyzed via these channels (for more information, see the section under "In-home power line network topology"). At the second location, measurements were limited to the passageways between pairs of outlets from distinct topologies. These pipes will be used for studying ORAD and ORAS setups. The measuring apparatus is described in detail in [32].

ODF and OAF are energy efficient.

Figure 7 compares the power used by DF using the optimum and simplified DF power allocation algorithms (see "Optimal DF power allocation" and "Simplified algorithm for DF power allocation," respectively) to reach a target rate R equal to 20 Mbit/s. As the optimal solution is computationally intensive, we only present results for M = 62 sub-channels and 10 network realizations. The length of the time slot is determined to be t > mr. A PSD of 140 dBm/Hz has been applied to the noise. The MPM relay arrangement is under consideration. Either the power distribution provided by the PSD mask or the answer of the simplified approach may be used as a jumping off point for calculating the best solution. Figure 7 shows that the suggested DF power allocation method produces almost optimum results. In addition, we emphasize that the numerical accuracy of the simulation is responsible for the circumstances when the suggested approach performs somewhat better than the ideal one. As a consequence, we will only provide ODF findings from now on those were achieved with the help of the recommended DF power allocation method. Setting the goal rate equal to the capacity of the DT link (i.e., R = CDT when P(k) S,DT = P k Kon) allowed us to evaluate the efficacy of the suggested ODF power allocation algorithm (see "Simplified algo rithm for DF power allocation") (see also Figure 5). The cumulative distribution function (CDF) of the total transmitted power for DT and ODF (8) is shown in Figure 8 when considering the different relay configurations in a single sub-topology. There will be 110 dBm/Hz of background noise. Figure 8 demonstrates that the SDB is the optimal relay location. It enables a 2.6 dB gain reduction with a probability of 0.8. The BDB relay configuration saves roughly 1.2 dB under the same conditions. When the degree of noise is small, we find that identical outcomes are achieved. With a probability of 0.8, the SDB and BDB configurations reduce power consumption by 2 and 0.9 dB, respectively.

The findings for DT mode and OAF mode are shown in the right sub-plot of Figure 9. The noise floor is also adjusted to -110 dBm/Hz in this example. The ODF-specific outcomes are provided as well (Figure 9left). We compare the two strategies by taking into account 100 different network realizations and setting M equal to 62 in both cases. Figure 9 shows that the BDB is the optimal relay arrangement when using OAF to reduce power consumption. Figure 9 shows that compared to OAF, ODF results in greater power savings. Finally, it's worth noting that the performance behavior of

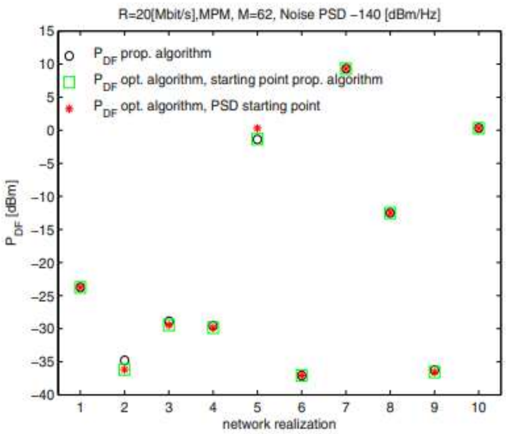

Figure 1 shows the difference between the optimum DF power allocation algorithm's and the simplified algorithm's power requirements for ODF to reach the desired rate R = 20 Mbit/s. Starting from two points—the PSD mask's power distribution and the simplified algorithm's answer—the ideal solution is found using interior-point techniques.

When comparing Figures 8 and 9 on the left, you'll notice that ODF doesn't change much regardless of the number of sub channels M. Now, we'll discuss how a relay may help enhance network coverage (the percentage of connections that achieve the desired data rate). Thus, we think about the MPM, the ORAS, and the ORAD relay in this context.

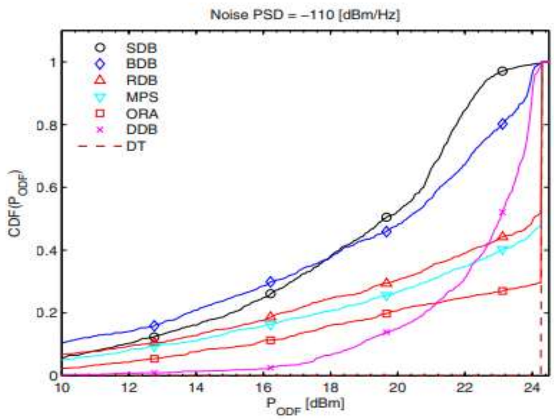

Figure 2 CDF of the total transmitted power using ODF with the relay located according to the various described configurations in single-sub-topology networks, and the DT M = 1536.

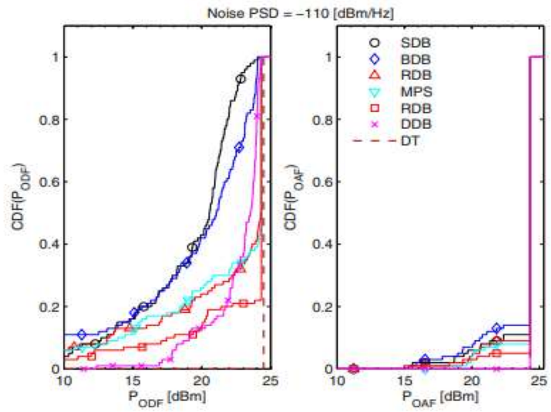

Figure 3 CDF of the total transmitted power using (left) ODF and (right) OAF with the relay located according to the various described configurations in single-sub-topology networks M = 62

setups in a network with two distinct tiers. Since the presence of CBs in the MP causes significant attenuation on the S-D links, we predict that employing the relay will result in a significant increase in coverage area. The following is an example situation we use to test our hypothesis. For example, if a multimedia application from the living room has to be sent to the bedroom on the second story, we may set a minimum needed transfer speed of 100 Mbit/s..

Conclusions

For practical rate increases, power savings, and coverage expansion in home PLC networks, we have looked at the usage of half-duplex time-division ODF and OAF relay protocols. To increase the ODF attainable rate under a PSD limitation, we determined the best allocation of power and time slots. In addition, we offer a streamlined approach based on the resolution of two convex sub-problems to the power minimization issue of ODF subject to a target rate restriction, since the best solution entails a complicated process. We have shown its near-optimal performance via numerical experiments. The algorithms' unusual and specialized use in the home PLC setting has been taken into account. The results demonstrate that ODF is superior than OAF in most respects. Depending on the location of the relay and the scope of the network, significant gains in throughput and reductions in energy consumption are possible. When the relay is located in the derivation box that feeds the source node or in a derivation box that lies on the backbone link between the source and the destination nodes, ODF provides high-reliability rate gains (up to 50%) or power savings (up to 3 dB) in the considered single circuit (single sub-topology) network. The optimum place to put a relay in a network with two branches that meet at the main breaker is where the two branches meet. In this scenario, too, significant gains in rate (as much as 27%), power reductions (as much as 1.9 dB), and coverage extension (as much as 47%) are all possible.

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