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Opportunistic Relaying in In-Home PLC Networks

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***Abstract*—We consider the use of a relay to provide capacity improvements and range extension for in-home power line communication networks. In particular, we focus on opportunistic relaying where the relay is exploited only if it provides improved capacity w.r.t. the use of direct transmission between the source and the destination. The relay applies a decode and forward scheme and the channel is shared in a time division multiple access mode. The performance is studied in statistically representative in-home power line communication (PLC) networks via the use of a statistical topology model together with the application of transmission line theory for the computation of the channel transfer function among network nodes. The statistical topology model allows determining the capacity improvements as a function of the relay position. Furthermore, we determine the optimal time slot duration for each considered relay configuration, as well as we propose the use of a globally optimal time slot duration that maximizes the average network capacity. The numerical results show that significant capacity improvement can be obtained via opportunistic relaying in in-home PLC networks. The gains are more significant for low SNR scenarios and for networks composed by sub-networks each connected to the main panel via a circuit breaker that introduces signal attenuation.**

I. INTRODUCTION

Nowadays, there is an increasing need of distributing multimedia contents to different users in the same domestic environment. Power line communication (PLC) modems provide wide band transmission in home networks. Several internet service providers distribute internet access via a home gateway connected to several power line communication modems. The communication protocol between different modems and the gateway is usually based on time division multiple access (TDMA), as for instance it is done by the HomePlug standard [1]. The presence of multiple PLC modems can be exploited to implement cooperation. That is, the communication between two modems can benefit from the presence of another modem that acts as a relay.

In this paper we study the performance improvement that can be potentially offered by relaying in home PLC networks. Both throughput enhancement and range extension can be achieved with the use of a relay.

Some early work on this area has been done in [2] where it was presented a network management system that exploits the presence of relays in a TDMA fashion. Later, in [3] it was suggested to extend the transmission range and to reduce the transmission delay in PLC networks with repeaters using distributed space time codes (DSTC).

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Our study starts from the description of typical in-home power line topologies and wiring structures. As it will be shown, in-home topologies have a regular structure where the outlets belonging to nearby rooms are connected to the same derivation box. The derivation boxes are fed by the main panel. Multiple floor houses can be partitioned in a number of subnetworks each fed by the main panel. Each sub-network is connected to the main panel by a circuit breaker (CB). It follows that potentially each outlet, or derivation box, or even the main panel, can be a location where to position a relay. In order to assess performance as a function of the relay position, we describe a statistical topology model that has been derived from the observation of real scenarios. Channel impulse responses are computed using transmission line theory on realizations of the topology with the presence of a random number of loads (appliances).

We investigate the use of the cooperative opportunistic decode and forward (ODF) protocol presented in [4]. The physical layer deploys multi-carrier modulation, and the medium access control is based on TDMA. The relay is opportunistically used only if it provides increased capacity w.r.t. the use of direct communication between the source and the destination. We focus on single phase in-home power line networks. We consider both the optimization of the time slot duration of the source and the relay for each network realization, and the use of a globally optimal time slot duration that maximizes the average network capacity. We investigate the effect of the relay position considering various configurations. Finally, we consider in-home networks that comprise sub-networks connected to the main panel via a CB. Since the CB introduces attenuation, range extension and improved capacity is obtained by positioning the relay at the main panel.

The paper is organized as follows. In Section II, we first describe the topology model. Then, we describe the opportunistic relay protocol and the relay configurations that we consider. In Section III, we show numerical results that allow evaluating the effect of the relay configuration on performance and establishing the best configuration. The conclusions are then reported in Section IV.

II. RELAY NETWORK ARCHITECTURE AND PROTOCOL

As previously stated, we are interested in seeing whether capacity improvements for in-home PLC networks are attainable with the use of cooperative communications. To this end, we first describe the key characteristics of an in-home power line infrastructure. This allows understanding how relaying can be practically applied. Then, we describe the transmission protocol.

A. In-home Wiring Infrastructure

In-home PLC infrastructures are characterized by a regular wiring topology composed of two layers. Fig. 1 shows a typical topology arrangement. Outlets are usually placed at the bottom layer and are grouped and fed by the same "super node" referred to as derivation box. All the outlets fed by the same derivation box are nearby placed, namely, inside the same room. Therefore, the location plan can be divided in elements that contain a derivation box with the associated outlets. We refer to this area elements as "clusters". Observations of real scenarios suggest to match each cluster to a room or a small number of nearby rooms.

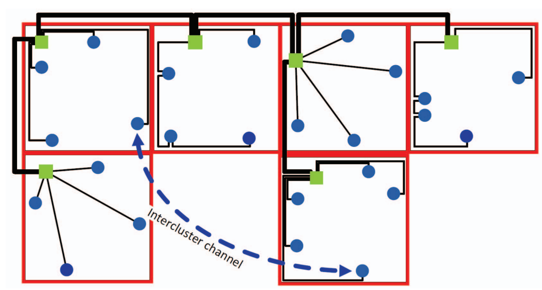

Figure 1. A typical in-home topology layout showing derivation boxes (square marker) and connections with outlets (dot markers).

Different clusters are usually interconnected through their derivation boxes with dedicated cables. These set of interconnections make up the second layer of the layout structure. In the in-home network we can identify pair of outlets that belong to the same cluster whose channels are referred to as intracluster channels. Conversely, the channels associated to pair of outlets that belong to different clusters are referred to as intercluster channels. In Fig. 1, an intercluster channel example is shown.

The main panel plays a special role. In fact, the main panel connects the in-home network with the energy supplier network. Furthermore, there exist two types of in-home networks. The first can be referred to as a single section network, e.g., in single floor houses. The second comprises multiple sections (or sub-networks), that are fed by the main panel through different circuit breakers, e.g., in multiple floor houses. In this second case the topology can be divided into sub-topologies interconnected through the CBs.

Now, the communication between different pair of outlets can be improved with the assistance of a relay. In principle, the relay can be positioned in any outlet, or derivation box, or even in the main panel. Before describing the relay configurations that we consider, we first present the relaying protocol.

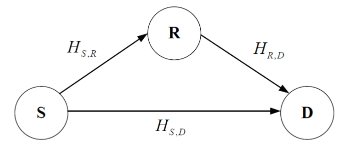

Figure 2. Cooperative relay system model.

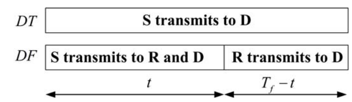

Figure 3. DT and DF modalities and corresponding time slots allocation.

B. Opportunistic Decode and Forward Protocol

We consider a network composed by a source (S), a relay (R) and a destination (D) node as shown in Fig. 2. Multiplexing is accomplished via TDMA, where the time is divided in frames of duration T_f. Each frame is divided into two time slots whose durations are t and $T_f - t$. The communication between S and D follows the opportunistic decode and forward (ODF) protocol presented in [4]. In ODF the sender sends data to the destination according to two modalities, direct transmission (DT), or decode and forward (DF). In DT, S transmits to D occupying all the time frame T_f. In DF mode, S transmits its data to both R and D during the time slot t, then in the second slot $T_f - t$, R decodes and forwards the same data to D using an independent codebook while the source is silent [5]. Finally, D decodes the message combining the data received in both time slots from both the source and the relay. Fig. 3 shows the DT, the DF modalities and the corresponding time slots allocation.

At the physical layer, we assume a multi-carrier system with M sub-channels. The channel between each pair of nodes is denoted as $H_{x,y}(k)$, where the subscripts x and y denote the pairs {S,R}, {S,D} or {R,D}, and k is the sub-channel index, i.e., $k \in \{0, \dots, M-1\}$.

We evaluate the performance of the ODF protocol under the assumption of additive white Gaussian noise (AWGN). Therefore, with a frame of normalized duration $T_f = 1$, the capacity of ODF can be expressed as [4]

$$C_{ODF}(t) = \max\{C_{DT}, C_{DF}(t)\}, \quad (1)$$

where C_{DT} and $C_{DF}(t)$ respectively denote the capacity of DT and DF modes. They are given by

$$C_{DT} = C_{S,D} \quad (2)$$

$$C_{DF}(t) = \min\{tC_{S,R}, \quad tC_{S,D} + (1-t)C_{R,D}\}. \quad (3)$$

In (2) and (3) we denote with $C_{S,D}$, $C_{S,R}$ and $C_{R,D}$ the capacity of the links S-D, S-R and R-D respectively. Assuming a large number of sub-channels, they are given by [6]

$$C_{x,y} = \frac{1}{MT} \sum_{k=0}^{M-1} log_2 (1 + SNR_{x,y}(k)),$$
$$\{x,y\} \in \{\{S,D\};\{S,R\};\{R,D\}\}, \quad (4)$$

where

$$SNR_{x,y}(k) = \frac{P_a(k)|H_{x,y}(k)|^2}{P_w(k)}, \quad (5)$$

is the signal over noise ratio in sub-channel k for the link x-y, T is the sampling time, whereas $P_a(k)$ and $P_w(k)$ respectively denote the transmitted and the noise power in sub-channel k.

From (1)-(3) it is interesting to note that the direct link is used whenever the capacity $C_{S,D}$ is greater than $C_{S,R}$. This is true for any t. In the remaining cases, to see whether the communication follows the DT or the DF mode, we need to compute C_{DT}, $C_{DF}(t)$ and compare them as in (1).

In order to maximize the capacity (1), we note that the capacity of DF mode (3) is a function of the time slot duration t. Therefore, the optimal slot duration can be found maximizing the capacity $C_{DF}(t)$ [7], i.e.,

$$t_{opt} = \underset{t\in[0,1)}{\operatorname{argmax}} \left\{C_{DF}(t)\right\}. \quad (6)$$

To solve (6), we observe that the arguments of the minimization in (3) are linear functions. Two cases are then possible. When $C_{R,D} \leq C_{S,D} \leq C_{S,R}$, the optimal time slot duration t_{opt} is equal to 1, thus the DT scheme is still the best choice. Conversely, when $C_{S,D} < C_{R,D} < C_{S,R}$, the optimal time slot duration is given by the intersection of the linear functions in (3), i.e., $t_{opt}C_{S,R} = t_{opt}C_{S,D} + (1 - t_{opt})C_{R,D}$.

C. Desciption of the Considered Relay Configurations

In this paper we only focus on source-destination (S-D) channels defined between pair of outlets that do not belong to the same cluster, i.e., intercluster channels. As reported in [8], these channels experience higher attenuations than intracluster channels. Thus, they can have more benefit from the help of a relay. Clearly, these benefits are also dependent on the relay location. To this end, we consider strategical locations for the relay. In particular, we position the relay either in the derivation boxes or in the main panel. These choices have been made because both positions can be considered strategical, since each derivation box feeds a group of outlets and the main panel feeds a group of derivation boxes. The former configuration is referred to as "all derivation boxes" (ADB), while the latter as "main panel" (MP).

Furthermore, since intercluster channels involve communications between outlets of different clusters, their backbones, i.e., the shortest paths between the source and the destination, are always characterized by the presence of at least the derivation boxes of the source and destination clusters. Thus, we analyze the performance using a relay in the derivation box of the source and in the derivation box of the destination. We refer to these two sub-cases as "source derivation box" (SDB) and "destination derivation box" (DDB), respectively.

Placing the relay in the derivation boxes can be practically complex, hence we also position the relay in a randomly selected outlet not belonging to the source and destination clusters. We refer to this configuration as "outlet relay arrangement" (ORA).

Finally, as the numerical results will show, we point out that placing the relay in the main panel provides significant performance improvements for "cross-breaker channels", e.g. channels associated to outlets that belong to different floors of a multiple sub-topology layout. These improvements are significant when the CBs introduce high attenuations. In fact, since the main panel is always a cross-way node for all the cross-breaker channels, CB attenuations have a strong impact in performance. Therefore, relaying can be a valid solution for this configuration.

III. Numerical Results

We herein study the statistics of the capacity for the opportunistic relay scheme. The numerical results have been obtained using the statistical topology generator presented in [8]. We briefly summarize it here for completeness.

A. Statistical Topology Model

According to experimental evidences, we have derived a statistical topology generation algorithm, where a location plan with a given area A_f is made up of $N_c = \lceil A_f/A_c \rceil$ clusters of area A_c. Without any loss of generality we distribute outlets only along the cluster perimeter. We choose the number of outlets inside each cluster as a Poisson variable of intensity $\Lambda_o A_c$. So the outlets are distributed as the arrivals of a Poisson process along the cluster perimeter. We have also added a random number of loads, such as lamps or computer transformers, whose impedances have been collected via measurements. The probability that no loads are connected to an outlet is p_v.

In Table I, we report the values for all the parameters used by the bottom-up simulator [8]. In particular, we consider the home area and the cluster area as uniform distributed random variables. We do so in order to present results that gather the heterogeneity of the whole in-home scenario.

Table I
PARAMETER SET FOR THE BOTTOM-UP GENERATOR

Parameter	Value
A_f (m^2)	$\mathcal{U}(100, 300)$
Λ_o $(outlets/m^2)$	0.5
A_c (m^2)	$\mathcal{U}(15, 45)$
p_v	0.3

Another issue is the efficient channel transfer function computation via the bottom-up approach. To this respect, in [9] we have proposed a solution based on a scalar version of the ABCD matrix method. More in detail, we propose to firstly remap the topology as a function of the source and destination position. Then, we split the resultant layout in elements referred to as units, which gathers a certain number of branches and loads. Finally, we compute the channel transfer function as the product of the voltage ratios between input/output ports of all the units. With this methodology the channel transfer function computation is efficient even for complex topologies, where time-domain algorithms fail or become too complex.

B. Performance Results

The channel frequency responses $H_{x,y}(k)$, $\{x,y\} \in \{\{S,D\};\{S,R\};\{R,D\}\}$ are computed in the band 1-30 MHz, with a sampling frequency resolution of $24.414\,kHz$, that corresponds to the sub-channel spacing of the HomePlug standard [1]. The capacity according to (4) is computed assuming uniformly distributed power across the sub-channels with a power spectral density (PSD) of $-50\,dBm/Hz$ for both the source and the relay. In order to evaluate the improvements in different application scenarios we consider AWGN with two PSD levels, i.e., $P_w = -140\,dBm/Hz$ and $P_w = -110\,dBm/Hz$, respectively.

We generate $N = 1000$ topologies. For each topology we randomly pick a pair of outlets belonging to different clusters. We place the relay in any possible location according to the configurations described in Section II-C. Hence, we apply the opportunistic decode and forward algorithm of Section II-B obtaining the optimal time allocation $t_{opt}(c,i)$ for each topology realization i and relay arrangement $c \in \{ADB,\ SDB,\ DDB,\ ORA,\ MP\}$. As an example of the resultant $t_{opt}(c,i)$ distribution, in Fig. 4 we show the probability density function (PDF) of $t_{opt}(SDB)$.

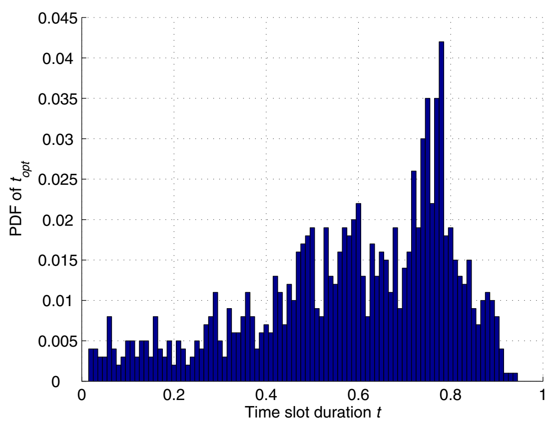

Figure 4. Probability density function of the optimal time slot allocation for the SDB configuration.

We point out that in the computation of the channel frequency response we assume modems with an input impedance of $50\,\Omega$ for both the transmitter/receiver and the relay. Therefore, it should be noted that the presence or absence of the relay affects the frequency response between a certain pair of outlets. In Fig. 5 we plot the complementary cumulative distribution functions (CCDF) of the S-D link, when no relay is used. Hence, we compare the capacity of the pure S-D link to that obtained with each relay configuration. The curves show that the best performance is obtained with the SDB configuration optimizing the time slot duration.

In Table II, we report the average values of capacity for the pure S-D link ($C^p_{S,D}$), for the S-D link when the relay is inserted but not used ($C^r_{S,D}(c)$ for $c = ADB$, SDB, DDB, ORA, MP) and for the S-D link when the relay is opportunistically used ($C_{ODF}(c)$). Clearly, for each topology realization t has been optimized as in (6). The fourth and the sixth column of Table II for the moment should be disregarded. The results show that the insertion of the relay may cause a decrease in capacity since it is viewed as a new load by the network. However, the capacity generally improves when the relay is used. In particular, the SDB configuration is the best performer and it turns out to be beneficial for 100% of the networks, as shown in the fifth column of Table II.

Table II
NUMERICAL RESULTS FOR INTERCLUSTER NETWORKS

$P_w = -140dBm/Hz$ and $C^p_{S,D} = 359.97Mbps$					
	Capacities $(Mbps)$			Perc. of DF	
Config.	$C^r_{S,D}$	C_{ODF}	C^g_{ODF}	Networks	t^g_{opt}
ADB	354.93	384.74	361.64	62.5	0.87
SDB	349.11	405.89	374.33	100	0.78
DDB	349.80	362.72	353.85	100	0.99
ORA	359.90	374.05	362.59	30.2	0.87
MP	355.01	384.07	360.56	62.9	0.89
$P_w = -110dBm/Hz$ and $C^p_{S,D} = 134,67Mbps$					
	Capacities $(Mbps)$			Perc. of DF	
Config.	$C^r_{S,D}$	C_{ODF}	C^g_{ODF}	Networks	t^g_{opt}
ADB	131.03	154.22	140.57	62.9	0.77
SDB	126.29	179.02	156.31	100	0.66
DDB	127.16	138.96	131.90	100	0.97
ORA	134.56	142.79	136.84	30.1	0.82
MP	131.08	155.06	140.15	63.8	0.79

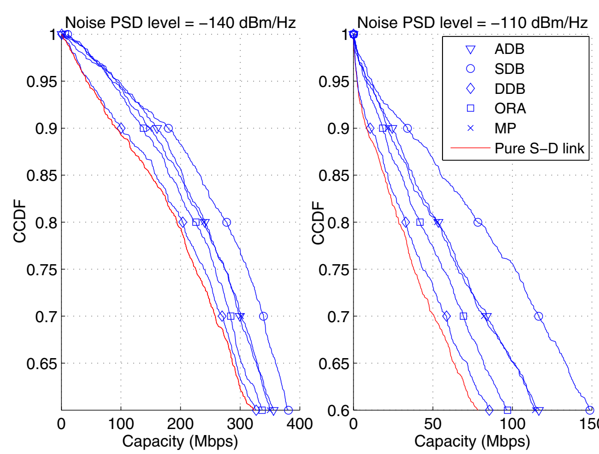

Figure 5. Complementary cumulative distribution function of capacity for different relay arrangements and for two noise levels.

C. Global Time Slot Optimization

The results in the previous section have been obtained optimizing the time slot for each channel realization and relay configuration. We now investigate the possibility to use a single globally optimal time slot duration $t^g_{opt}(c)$ for all topology realizations given a certain relay configuration c. The globally optimal time slot duration $t^g_{opt}(c)$ is the one that maximizes the average capacity. Therefore, we proceed as follows. For each relay configuration c, we consider the capacity of the sub-set of network realizations for which the ODF uses DF transmission only. Then, we compute the average capacity (averaged over the network realizations) and we denote it with $C_{DF}(c,t)$. We show $C_{DF}(c,t)$ in Fig. 6. Finally, we choose the optimum time slot duration for each relay configuration c as the one correspondent to the peak of the capacity curves of Fig. 6, i.e.,

$$t^g_{opt}(c) = \underset{t\in[0,1)}{\text{argmax}}\{C_{DF}(c,t)\}\ . \tag{7}$$

In Table II we report the $t^g_{opt}(c)$ and the average capacity $C^g_{ODF}(c)$ of the opportunistic decode and forward scheme that uses $t^g_{opt}(c)$ when DF is chosen, and $t = 1$ when direct transmission is picked.

The results show that the best performing relay configuration is the SDB. In general the improvement w.r.t. the pure S-D link is not very pronounced when the average SNR is high. For example, in the SDB case the relay improves the S-D link (in the presence of the relay) by 7% when the PSD noise level is $-140\,dBm/Hz$. Whereas, when the PSD noise level is $-110\,dBm/Hz$ the relay significantly improves the S-D link by 24%.

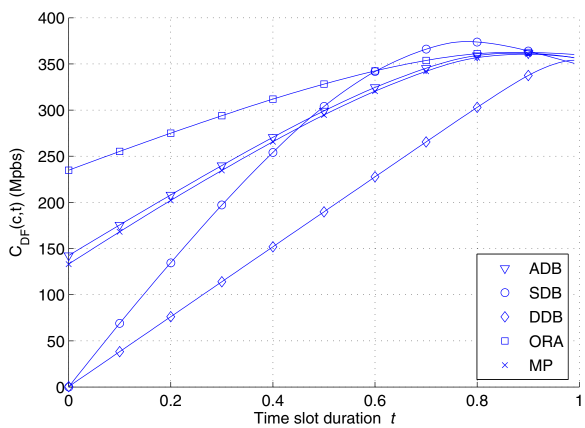

Figure 6. Average capacities $C_{DF}(c,t)$ as a function of the time slot t.

D. Network with Multiple Sub-topologies

In order to simulate the effect of the CB switches in the main panel for a multiple sub-topologies configuration we introduce an attenuation $A = \{0, 10, 20\}\,dB$ in the main panel where the relay is located. We evaluate the average capacity $C_{DF}(CB,t)$ of the cross-breaker channels. In Fig. 7 we plot the average capacity as a function of the time slot duration for the three values of attenuation. In Table III we summarize the results as done for the previous cases. The results show that the globally optimum time slot duration decreases as the attenuation increases. The benefit provided by the relay is higher for channels with higher attenuation.

IV. Conclusions

Significant capacity improvement can be obtained via opportunistic relaying in in-home PLC networks. The relay is beneficial to improve the communication performance among pair of outlets belonging to distinct clusters since they experience channels with high attenuation. In such a case, the best relay position is the derivation box that serves the transmitter node. The capacity gains are even higher for cross breaker channels when we opportunistically exploit a relay positioned in the main panel.

Table III
Numerical results for Interfloor channels

A (dB)	Capacities $(Mbps)$ $C^p_{S,D}$	$C^r_{S,D}$	C_{ODF}	C^g_{ODF}	t^g_{opt}
0	316.13	306.22	354.09	316.87	0.87
10	238.76	229.61	302.02	267.98	0.77
20	169.16	161.02	252.10	221.67	0.69

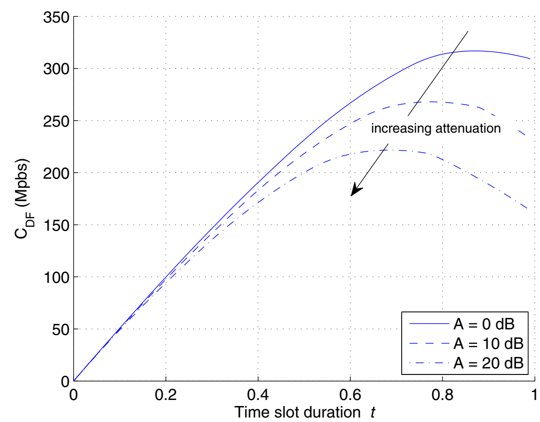

Figure 7. Average capacity $C_{DF}(CB,t)$ for cross-breaker channels as a function of the time slot t.

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