Cooperative Multihop Power Line Communications

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***Abstract*—Data communication over power line networks has a number of similarities with communication using wireless transmission. This (probably) goes back to fact that neither power lines nor wireless channels were designed for carrying communication signals. As a result, a number of techniques successfully used in wireless communications have found their way into power line communications (PLC). This has recently been extended to relaying, or more generally, cooperative communications. In this paper, we first show that, different from the wireless domain, cooperative communication does not provide a diversity advantage for typical PLC networks. Secondly, we introduce and compare different approaches of multihop transmission known from wireless communications to PLC. We compare their performances and, supported by numerical results, conclude that cooperative multihop is the preferred choice in terms of end-to-end transmission rate.**

I. Introduction

Background: Power line communications (PLC) has long been used for applications such as voice communication and automation and control. In the late 1990-ies, broadband PLC has become the centre of attention of academic research and industrial development, with notable commercial success in the in-home area network market. The recent worldwide push towards the evolution of the electricity grid into a "smart" grid, for reasons such as the rising demand for electricity, the need for more reliable electricity grids, and the reduction of carbon footprint through integration of renewable and distributed energy generators, etc., has led to a renewed interest in narrowband PLC solutions. Here, narrowband PLC refers to systems that operate below 500 kHz and provide data rates on the order of 100 kbps. These systems have also been referred to as high data-rate narrowband (HDR NB) PLC systems, cf. [1]. Most HDR NB PLC solutions are based on multicarrier modulation such as orthogonal frequency-division multiplexing (OFDM), cf. [2] for an early chip-set, which is also being favoured in ongoing standardizations in the IEEE and ITU-T. For a recent overview on PLC technology including multicarrier modulation we refer to [3].

PLC and wireless communications: The adoption of multicarrier modulation in several recent industrial and international standards is strikingly reminiscent of the success of this modulation format in standardization of modern wireless communication systems. This alludes to certain similarities between PLC and wireless transmission characteristics, such as the frequency-selective nature of the propagation channel, cf. [3, Ch. 2]. Along these lines, other signal processing solutions that have been developed for wireless communications systems have found their way into PLC. These include, for example, multiple-input multiple-output (MIMO) [4], [5], [6], cognitive radio [7], and compressed sensing techniques [8]. The broadcasting nature of the PLC channel, which it also has in common with the wireless transmission channel, has led to research on the application of modern relaying techniques known from wireless communications. For example, [9], [10] describe PLC relaying based on single-frequency networking. Distributed space-time coding and decode-and-forward relaying, originally developed for wireless networks, have been applied to PLC in [11] and [12], respectively. The extension of conventional multihop to cooperative multihop transmission, developed and also referred to as multihop diversity in the wireless domain, has been presented for PLC in [13] and studied further in [8]. We note that "relaying" and "multihop" are referring to the same concept of network nodes assisting each other to transmit a message. In the wireless communication literature, relay transmission often implies two-hop communication, with or without a direct source-to-destination link, while multihop transmission usually assumes more than two hops and no direct link. In the following, we will use these terms in the sense that a multihop transmission consists of a series of relaying steps.

This work: In this paper, we continue the line of recent works investigating the use of wireless relaying techniques in PLC networks. In particular, we proceed with our study in [8] on cooperative techniques for multihop transmission in the context of HDR NB PLC, which, for example, can be used to enable smart grid services in a low-voltage (LV) distribution grid. After preliminaries on PLC network emulation in Section II, we elaborate on the notion of diversity in multihop transmission. In particular, while diversity plays a major role in relay and multihop transmission over wireless channels, we show in Section III that in most PLC networks a diversity gain cannot be achieved. Then, in Section IV, we present different schemes for coding and relay selection in multihop transmission. Those schemes are borrowed from the wireless communication domain and evaluated in terms of achievable end-to-end rate in a PLC line network in Section V. Our results demonstrate that, despite the proven absence

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of a diversity advantage, cooperative multihop transmission provides significant rate gains over conventional multihop.

II. PLC Network Model

The approaches for modeling PLC channels, more specifically channel transfer functions, can be categorized into two classes: phenomenological and deterministic modeling. The former is based on the measurement of channel transfer functions and their approximation through, e.g., the sum of weighted exponentials; and the latter is based on the application of transmission line theory using simplified models of PLC signal propagation, cf. [3, Ch. 2]. While both have their merits and challenges, the deterministic modeling method is clearly preferred for simulating PLC networks with multiple nodes, and thus for relaying and multihop transmission, since it captures the mutual dependencies between different links in the network (more on this in Section III).

For this reason, we adopt the deterministic approach for emulating PLC transmission channels in this work. More specifically, we apply the two-conductor transmission line formalism to approximate the propagation of PLC signals. Accordingly, considering two nodes in the PLC network with voltages and currents V_i and I_i, $i = 1, 2$, respectively, then these are related through transmission line parameters (ABCD-parameters) as follows:

$$\begin{bmatrix} V_1(f) \\ I_1(f) \end{bmatrix} = \begin{bmatrix} A(f) & B(f) \\ C(f) & D(f) \end{bmatrix} \begin{bmatrix} V_2(f) \\ I_2(f) \end{bmatrix} . \quad (1)$$

Note that all parameters depend on frequency f in general. This leads to the node-to-node voltage transfer function

$$H(f) \triangleq \frac{V_2(f)}{V_1(f)} = \frac{Z_2(f)}{A(f)Z_2(f) + B(f)} , \quad (2)$$

where $Z_2(f) = V_2(f)/I_2(f)$ is the impedance of node 2. Since a PLC link can be described as a cascade of two-port networks usually representing line pieces and parallel impedances, the ABCD-parameters used in (2) are obtained from the multiplication of the corresponding transmission matrices (ABCD-matrices) as given in (1). For line pieces, the entries of these matrices depend on the characteristic impedance Z_0 and propagation constant γ associated with the two-conductor model. Please refer to [3, Ch. 2] for more details.

III. Cooperative Diversity in PLC

The concept of cooperative diversity has been developed in wireless communications as a means to realize spatial diversity in a distributed fashion, cf. [14] and references therein. Cooperating users (wireless devices) create a virtual antenna array and transport their information to a destination, often using relay transmission protocols, e.g., [15], [16], [14]. This concept has been extended to wireless relay networks with multiple hops between transmitter and receiver, in which case it is also referred to as multihop diversity, cf. e.g. [17], [18]. The benefits of cooperative or multihop diversity over conventional multihop transmission are highlighted in [19].

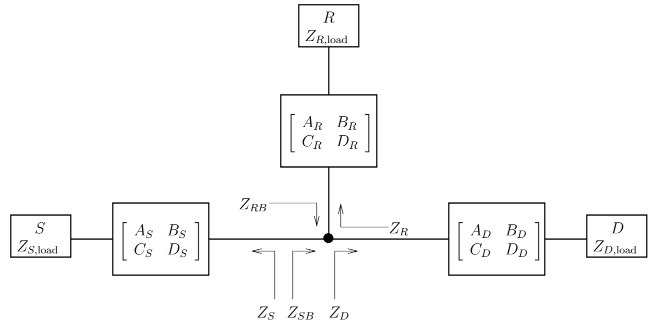

Fig. 1. PLC network with three communication nodes.

Before considering the application of different multihop (diversity) transmission strategies to PLC in the next section, we first wish to shed some light on the issue of "diversity" in multihop PLC. Figure 1 illustrates a PLC network with three communication nodes, namely a source S, a relay R, and a destination D. We also identify the branch point B, which is where the signal paths from S to R and S to D split. The links between those network points are modeled as two-port networks with ABCD-parameters. Using the ABCD-parameters and impedances as defined in Figure 1, we introduce the transfer functions (cf. (2), for brevity, we omit the dependence on frequency f)

$$H_{SB} = \frac{Z_{SB}}{A_S Z_{SB} + B_S} , \quad (3)$$

$$H_{BD} = \frac{Z_{D,\text{load}}}{A_D Z_{D,\text{load}} + B_D} , \quad (4)$$

$$H_{BR} = \frac{Z_{R,\text{load}}}{A_R Z_{R,\text{load}} + B_R} , \quad (5)$$

$$H_{RB} = \frac{Z_{RB}}{A_R Z_{RB} + B_R} , \quad (6)$$

for the different links to and from the branch point B. Then, we can express the transfer functions for the communication links from S to R and D and from R to D as

$$H_{SR} = H_{SB} \cdot H_{BR} , \quad (7)$$

$$H_{SD} = H_{SB} \cdot H_{BD} , \quad (8)$$

$$H_{RD} = H_{RB} \cdot H_{BD} , \quad (9)$$

respectively.

Given the transfer function expressions (7)-(9), we can evaluate the diversity that is achieved with the different cooperative transmission protocols [16]. Considering for example selection decode-and-forward (SDF), the outage probability, which is defined as the probability that the mutual information of SDF falls below a certain target rate, is given by (cf. [16, Eq. (20)][1])

$$p_{\text{SDF}}^{\text{out}} = \Pr[|H_{SR}|^2 < t, |H_{SD}|^2 < t] \times \Pr[|H_{SR}|^2 > t, |H_{SD}|^2 + |H_{RD}|^2 < t] , \quad (10)$$

[1]For the sake of clarity, we do not consider a second source transmission when the relay cannot successfully decode the signal as for SDF in [16]. This leads to a missing factor of 2 in (10) compared to [16, Eq. (20)], but does not affect the discussion about diversity.

where t is a threshold that depends on target data rate and signal-to-noise ratio (SNR). We can lower bound the outage probability (10) by assuming a perfect (i) source-to-relay or (ii) relay-to-destination channel. In the first case, we have

$$p_{\mathrm{SDF}}^{\mathrm{out}} \geq \Pr[|H_{SD}|^2 + |H_{RD}|^2 < t] \ , \qquad (11)$$

and in the latter

$$p_{\mathrm{SDF}}^{\mathrm{out}} \geq \Pr[|H_{SR}|^2 + |H_{SD}|^2 < t] \ . \qquad (12)$$

Substituting (7)-(9) into (11) and (12) gives

$$p_{\mathrm{SDF}}^{\mathrm{out}} \geq \Pr[|H_{BD}|^2(|H_{SB}|^2 + |H_{RB}|^2) < t] \ , \qquad (13)$$
$$p_{\mathrm{SDF}}^{\mathrm{out}} \geq \Pr[|H_{SB}|^2(|H_{BR}|^2 + |H_{BD}|^2) < t] \ . \qquad (14)$$

We observe from (13) and (14) that the performance of the PLC relay channel is determined by the quality of the B-to-D and S-to-B channels. In particular, the diversity order achieved by the relay channel is limited the diversity order of those individual channels.[2] Hence, there is no increase in diversity due to relaying, or multihop in general.

This result can be interpreted in the context of pinhole or keyhole channels known from wireless MIMO transmission [20]. The branch point B is the keyhole through which the signals to two destinations, when S transmits to R and D, or from two sources, when D receives signals from S and R, need to pass. Since in each phase, due to the keyhole property, the diversity order is given by the minimum of the number of sources and destinations [20], [21], a diversity gain as for cooperative wireless transmission is not accomplished.

To illustrate this difference between a three-node PLC network and independent channels between S, R, and D as typically assumed in wireless communication, we consider the PLC transmission scenario as shown in Figure 1 with nodes S, R, and D connected to a main NAYY150SE power cable through NAYY50SE house connection cables. These cables have four conductors (cf. e.g. [3, Fig. 2.16]), and we assume the two-conductor transmission line approximations following [3, Sec. 2.3.3.1] to compute the ABCD-matrices shown in Figure 1. The length of the main supply cable is 1000 m with the branch point B at 500 m. The nodes are connected to the main line through house connection cables of length 30 m. To generate a set of transfer functions load impedances are parallel circuits of a 50 Ω modem impedance and a panel impedance uniformly distributed in $([0,5] + \mathrm{j}[-5,5])\ \Omega$. The transmission frequency is $f = 50$ kHz, and we assume a flat channel (like an OFDM subchannel) so that only spatial (and not frequency) diversity is observed. Figure 2 shows the outage probabilities for SDF and for direct S-to-D transmission versus the transmitter side SNR and a spectral efficiency of 1 bit/s/Hz. Here, repetition coding is applied for direct transmission and for SDF when the relay does not transmit, so the total transmit energy per packet is identical for all scenarios (see [16, Sec. IV]). Also included are the outage-probability curves when the S-to-R, S-to-D, and R-to-D channels are generated as independent and Rayleigh fading with the same average channel gain as the respective PLC channels. These curves are labeled “wireless” in Figure 2. We observe that, interestingly, the curves for direct transmission almost overlap, with the slope of negative one characteristic for Rayleigh fading. While this slope changes to negative two for relaying with SDF in the wireless case, indicating a diversity order of two, it remains the same for PLC relaying. Comparing direct and relay transmission results for PLC, we see a shift towards lower SNRs, which is the multihop power gain. But different from the wireless case, the diversity gain is absent.

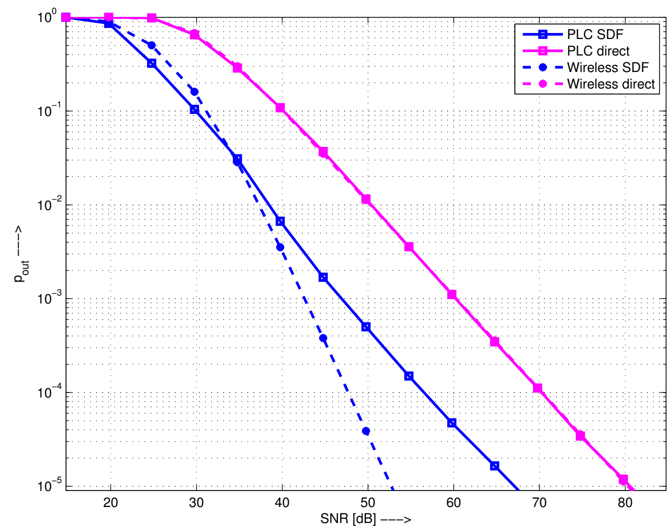

Fig. 2. Outage probability versus transmitter side SNR for PLC and wireless transmission without (i.e., direct transmission) and with a relay using SDF. The wireless channels are all Rayleigh fading with the same average channel gains as the PLC channels. The curves for “PLC direct” and “Wireless direct” practically overlap.

We note that a diversity gain would be achieved if there were redundant paths from source to destination. For example, in a ring network, as considered for airfield ground lighting systems in [10], two separate paths from the source to the destination exist. Also in a mesh network topology, redundant links can exist for parts of or the entire path from source to destination.

As a final remark, we note that different channel gains occurring in (13) and (14) are interdependent. For example, the impedance Z_{SB} seen at the branch point from the source side is the parallel connection of the impedances Z_R and Z_D seen at the branch point to the relay and destination, respectively (see Figure 1). Hence, through Z_{SB} the transfer function H_{SB} in (3) depends on the ABCD-parameters and load impedances of the B-to-R and B-to-D links defining H_{BR} (5) and H_{BD} (4), respectively. Likewise, H_{RB} (6) depends on the ABCD-parameters of the S-to-B and B-to-D links through Z_{RB}, which is the parallel of Z_S and Z_D indicated in Figure 1.

[2]Diversity order is the asymptotic decay of the outage rate over SNR (plotted in log-log scale) for a channel whose gain follows a certain probability distribution. In the context of PLC this means that the channel gain is modeled as a random variable, whose different realizations are experienced for different networks or for the same network due to time-varying impedance values of loads and switching processes, which is alike mobility in wireless networks.

This is another difference to wireless multihop.

IV. Multihop Transmission Strategies

The absence of multihop diversity in PLC transmission (without redundant paths) established in the previous section does not mean that advanced cooperative multihop techniques developed for wireless communication should not be applied to PLC. As shown in Figure 2 the power gains due to multihop transmission can be significant. In this section, we consider different multihop transmission strategies towards maximizing this advantage. As a figure of merit we consider the end-to-end (i.e., S-to-D) achievable rate, which we refer to as end-to-end capacity.

A. Multihop Schemes and End-to-end Capacity

We assume multihop transmission with a time-division protocol such that only one node (source or relay) transmits at a time with a fixed transmit power. Let N the number of hops and n, $n = 1, \ldots, N+1$, denote the node index; i.e., $n = 1$ and $n = N+1$ correspond to source and destination, respectively. The capacity for the link from node n to $n+1$ is denoted by $C_{n,n+1}$. Following [18], [22], we consider three possible multihop schemes.

a) Fixed-rate (FR) multihop: The conventional multihop strategy is that each node on the route retransmits the received message using the same transmission scheme and thus link rate. Hence, the maximum rate that can be achieved over this route is determined by the minimum of the rates achievable on the individual links. We thus can express the end-to-end capacity as

$$C_{\mathrm{FR}} = \frac{1}{N} \min_{n=1,\ldots,N} C_{n,n+1} \,. \tag{15}$$

b) Rate-adaptive (RA) multihop: Given the relatively long coherence time of links in PLC (possibly cyclically static due to time variations with the mains cycle [3, Ch. 2]), transmitters can adjust the rate to follow the link capacity $C_{n,n+1}$. Then, transmission times over different hops along the route depend on the link capacities and a rate R is achievable if

$$R < t_n C_{n,n+1},\ n = 1, \ldots, N \ \cap\ \sum_{n=1}^{N} t_n = 1 \,. \tag{16}$$

The end-to-end capacity follows as

$$C_{\mathrm{RA}} = \left(\sum_{n=1}^{N} \frac{1}{C_{n,n+1}} \right)^{-1} . \tag{17}$$

c) Incremental-redundancy (IR) multihop: Due to the broadcast nature of the PLC channel, multiple nodes can overhear a transmitted signal. Hence, a node along a multihop route will receive the source message multiple times. This allows the receiver to combine those signals to improve the probability of successful detection. While there are different combining strategies, the capacity-optimal approach is to use incremental redundancy, i.e., different nodes send different parity symbols. Similar to the case of RA multihop, a rate is achievable if

$$R < \sum_{\ell=1}^{n} t_\ell C_{\ell,n+1},\ n = 1, \ldots, N \ \cap\ \sum_{n=1}^{N} t_n = 1 \,. \tag{18}$$

The first term of (18) leads to the linear equation system

$$\begin{bmatrix} C_{1,2} & 0 & \ldots & & 0 \\ C_{1,3} & C_{2,3} & 0 & \ldots & 0 \\ \vdots & & & & \\ C_{1,N+1} & C_{2,N+1} & C_{3,N+1} & \ldots & C_{N,N+1} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix}, \tag{19}$$

with $x_n = t_n / C_{\mathrm{IR}}$, from which with the second constraint in (18) the end-to-end capacity is obtained as

$$C_{\mathrm{IR}} = \left(\sum_{n=1}^{N} x_n \right)^{-1} . \tag{20}$$

IR multihop is a truly cooperative technique in the sense that multiple nodes cooperate in the communication over every hop.

B. Relay Selection

The above multihop schemes can be combined with several strategies for relay selection, i.e., the selection of nodes that participate in multihop transmission. In the following, we present three relay-selection strategies that represent different routing paradigms with different overhead-performance trade-offs.

a) Fixed (Fi) selection: The first strategy is to use fixed relay nodes for retransmitting the source packet towards the destination regardless of the instantaneous channel conditions. The relays would be selected to divide the source-to-destination distance approximately evenly. This is a reasonable approach to counter the signal attenuation which increases with distances, but it neglects effects of multipath propagation.

b) Channel adaptive (CA) selection: In this case, one relay is selected at a time based on the progress made towards the destination. In particular, we apply the metric from [23], referred to as information efficiency, which is the product of the distance progress made towards the destination and the link rate. The node that maximizes the information efficiency becomes the next relay. This channel adaptive routing falls into the class of geolocation assisted routing (e.g. [24]) as it requires location and local link-quality information. Since rate adaptation is needed and only one link is considered at a time, it is suited for the RA multihop strategy.

c) Automatic repeat-request (ARQ) selection: An opportunistic routing strategy is to select the node that has successfully decoded the source message first as the next relay. This node identifies itself by being the first to send an acknowledgement. Again, we can assume that due to location information propagation of the message towards the destination is ensured. This method is suited for RA and IR multihop, in which case it implements an ARQ scheme.

TABLE I
MULTIHOP TRANSMISSION STRATEGIES CONSIDERED FOR NUMERICAL RESULTS.

Relay selection	Multihop scheme	Result index
Fixed	Fixed rate	(Fi, FR)
Fixed	Rate adaptive	(Fi, RA)
Fixed	Incremental redundancy	(Fi, IR)
Channel adaptive	Rate adaptive	(CA, RA)
Automatic repeat-request	Rate adaptive	(ARQ, RA)
Automatic repeat-request	Incremented redundancy	(ARQ, IR)

V. RESULTS

To provide a quantitative comparison of the end-to-end rates achievable with the different multihop transmission strategies we consider a PLC line topology similar to the one described in Section III but now with 11 house connection points, i.e., a maximum of $N = 10$ hops. The main power cable supplying the houses has a length of 1000 m and the houses are spaced evenly and connected to the main line through 30 m house connection cables. The power cables are the same as in Section III and 1000 channel realizations are generated by choosing the impedances of the house connection points independently and uniformly from $([0, 5]+\mathrm{j}[-5, 5])\ \Omega$. The first house is the source node and the last house is the destination node, and the other 9 houses can serve as relays for multihop transmission. The transmission frequency band is $f_1 = 10$ kHz to $f_2 = 95$ kHz, and given the frequency response $H_{n,n+1}(f)$ for the link from a node n to $n+1$ determined as in (2), the link rates are computed as

$$C_{n,n+1} = \int_{f_1}^{f_2} \log_2\left(1 + \frac{S_{\mathrm{T}}|H_{n,n+1}(f)|^2}{N_0\Gamma}\right) \mathrm{d}f\ , \qquad (21)$$

where S_{T} is the transmitter-side power spectral density and N_0 is the receiver-side noise power spectral density (both in V^2/Hz, and assumed to be constant over the frequency band), and $\Gamma = 10$ is the margin taking into account the gap between information-theoretic capacity and achievable rate using practical coding and modulation schemes. We parametrize the following results with the transmitter-side SNR S_{T}/N_0.

Figure 3 shows the end-to-end rates for different multihop transmission strategies, i.e., (15), (17) and (20), and the three relay selection schemes, as function of the number of relays and averaged over the 1000 network realizations. Table I summarizes the different combinations of multihop and relay selection schemes considered for the results. The signal-to-noise ratio is $S_{\mathrm{T}}/N_0 = 80$ dB at the transmitter side.

Let us first consider the case of fixed relay selection. For FR and RA coding, the use of relays is beneficial, as higher link rates can be achieved. But the additional number of hops counters this gain and, in fact, the rate declines if too many nodes participate in the multihop transmission. This can be seen from the factor $1/N$ for FR coding in (15). In the case of IR multihop (i.e., cooperative multihop), however, every retransmission is beneficial and there is no penalty for including more nodes in the multihop transmission. When CA

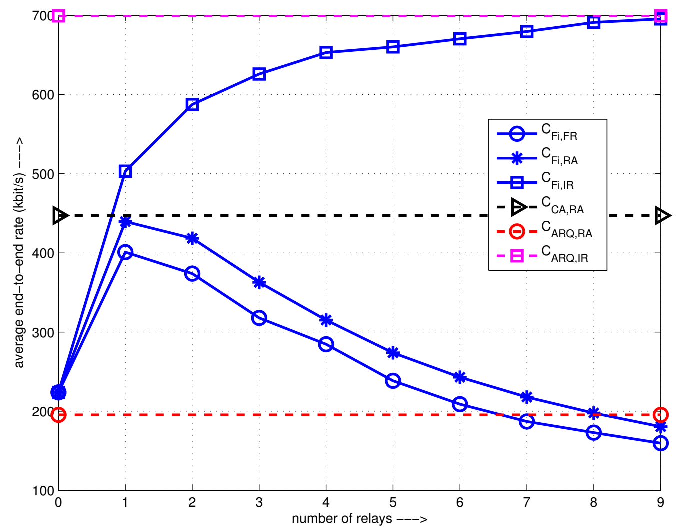

Fig. 3. Average end-to-end rate for a PLC line network with 11 nodes as function of the number of relays (0 relays means direction S-to-D transmission) for different multihop transmission strategies (see Table I). In the case of CA and ARQ relay selection, the number of relays is random and thus horizontal lines are shown.

and ARQ relay selection is employed, the number of hops is a random variable. Therefore, the corresponding average end-to-end rates are shown as horizontal lines in Figure 3. Considering ARQ relay selection, we observe that the rate for RA multihop is relatively low. The reason for this is that opportunistic relay selection leads to relatively many nodes participating in the multihop transmission. Since with every retransmission the next relay node recovers the message from scratch, the end-to-end rate declines. This problem is overcome using IR multihop, since previously received information is accumulated. In fact, ARQ-IR achieves the highest average rate of all strategies. Finally, if CA relay selection is used together with RA multihop, it outperforms ARQ-RA since the advance towards the destination is taken into account in the relay selection step. In summary the results in Figure 3 suggest that IR multihop and thus cooperative multihop is the preferred multihop scheme. It is best combined with ARQ relay selection, since this makes best use of instantaneous link qualities. Since the implementation of IR multihop is complicated by code combining at receivers (see e.g. [18] and [25] for IR with punctured and rateless codes, respectively), CA-RA is a good alternative that only requires rate adaptation for point-to-point links, which is a feature commonly used in PLC.

Figure 4 shows end-to-end rate as function of transmitter-side SNR and for different multihop transmission strategies. Considering fixed relay selection and fixed-rate coding, i.e., Fi-FR, we observe that the curves for 1 and 3 relays intersect. Thus, the optimal number of (evenly-spaced) relays is SNR dependent, with fewer relays favoured for higher SNR as the rate penalty from additional hops outweighs the SNR-gain due to shorter link distances. In contrast to this, IR multihop always

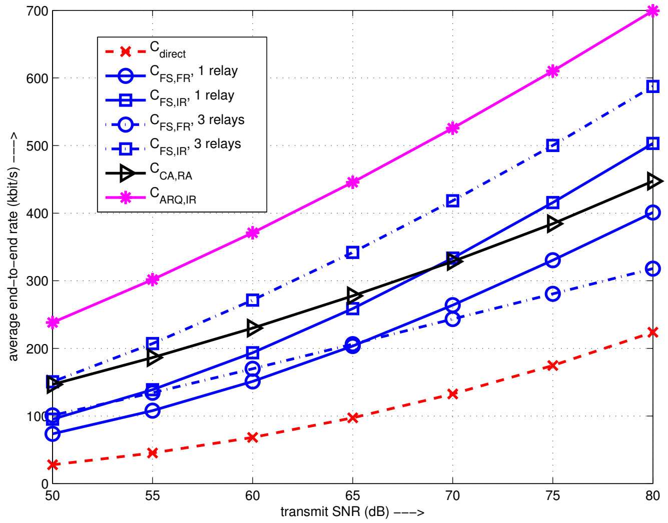

Fig. 4. Average end-to-end rate for a PLC line network with 11 nodes as function of the transmitter side SNR for different multihop transmission strategies (see Table I).

benefits from additional relaying nodes, as more nodes mean shorter hop durations for IR. IR-ARQ is consistently the best strategy, as it combines the benefits of cooperative multihop with an opportunistic relay selection. Finally, CA-RA confirms to be a good choice if non-IR multihop is desired. It favourably combines instantaneous link quality and location information.

VI. Conclusions

In this work, we have studied multihop transmission for PLC. Inspired by results for relaying and multihop in wireless communications, we first focused on the issue of multihop diversity in PLC. We have shown that the typical PLC relay channel consists of two keyhole channels, and thus a diversity gain as observed for wireless relaying is not realized in PLC. We have analyzed several multihop transmission strategies and numerical results for a PLC line network have demonstrated the potential gains due to cooperative multihop in the form of ARQ-IR. Another strategy adopted from the wireless domain, namely channel adaptive relay selection and rate adaptive signaling, shows great promise in terms of achievable rate. Since location information is relatively easy to obtain in PLC networks, we consider it an interesting alternative to ARQ-IR.

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