WIRELESS RELAYING WITH PARTIAL COOPERATION BASED ON POWER-LINE COMMUNICATION

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ABSTRACT

In this paper we investigate the use of Power-Line Communication (PLC) to assist cooperative wireless relaying. We consider a communication scheme that uses the power-line to initialize and synchronize wireless amplify-and-forward (AF) relays and to broadcast information between the relays. Based on the analysis of transfer function and noise measurements of PLC channels in office and residential environments we propose a transmission scheme for the inter-relay-communication over power-lines and assess the influence of this scheme on wireless relaying. The use of PLC leads to a very flexible way of enhancing wireless communications by plugging in additional relays where they are needed – without additional wiring.

1. INTRODUCTION

In wireless networks spatial diversity and spatial multiplexing gains are achieved by multiple antennas at the transmitter and at the receiver. Using *cooperative relaying strategies* [1], [2], [3] these gains are also possible for single antenna nodes. Spatial multiplexing is mandatory to achieve the high bandwidth efficiency that is necessary for future Gigabit/sec wireless communication systems. Practical cooperative relaying schemes for spatial multiplexing gains usually need the exchange of information between the relays; in this paper we consider a cooperative relaying scheme that is associated with a considerable signaling overhead between the relays and we study the possibility to use PLC for this overhead.

The considered scenario is shown in Fig. 1: a room (e.g. a conference room) with nodes that need high-speed wireless data communication. Fixed infrastructure AF relays assist the communication between the nodes (N_r: number of relays). The wireless nodes are equipped with a single antenna; they form an ad-hoc network using OFDM under a two-hop relay traffic pattern. We assume that the wireless nodes can be divided into N_a source/ destination pairs; the transmission from a source node to its associated destination node includes two channel uses: one for the uplink transmission from the source to all relays and one for the downlink transmission when each relay broadcasts an amplified (but not decoded) version of its received signal to the destination nodes.

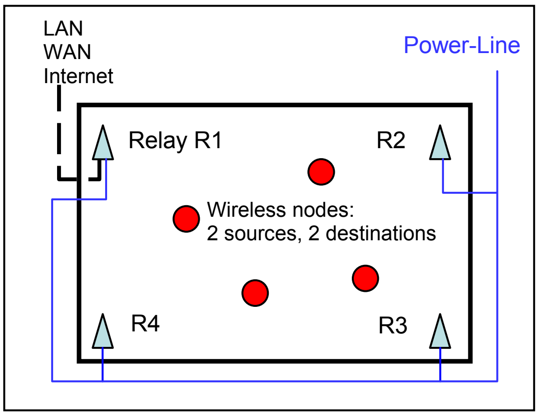

Fig. 1. Scenario: Wireless multiuser zero forcing relaying assisted by PLC between the relays.

The AF relay gains are assigned such, that the interference between different source/ destination links is nulled by coherent combining of the broadcasted signals; we refer to this scheme as *multiuser zero forcing (ZF) relaying* [3], [4]. This essentially realizes a distributed spatial multiplexing gain with single antenna nodes, enabling high data rates. But for mulituser ZF relaying all relays have to be synchronous and in an initialization phase every relay has to broadcast its channel state information (CSI) regarding all wireless nodes (uplink and downlink CSI) to all other relays; in [4] is shown, how this information can be acquired. The CSI has to be updated from time to time, because otherwise it becomes outdated. In the following we investigate, if synchronization and initialization/ updating of the wireless relays can be done using PLC. We assume that every relay is supplied by a power outlet and therefore the power-line can be used for communication between the relays (PLC backbone). In addition it is also possible to connect a relay to a backhaul (e.g. a LAN, WAN etc.) over the power-line (see Fig. 1); in this case the relay acts as an Access Point for the wireless nodes. The wireless source and destination nodes are not necessarily connected to the power-line and communicate only over the wireless medium; they do not cooperate, e.g. there is no joint decoding.

The analysis of the PLC backbone is based on extensive measurements of the transfer function and the noise of the PLC channels - for office and residential environments. The channel capacity of these indoor PLC channels is determined at frequencies between 1 MHz and 30 MHz. A PLC transmission scheme is proposed and the expected jitters are analyzed, because they determine the suitability of PLC for the relay synchronization.

2. MEASUREMENTS

Based on own measurements we review in the following some properties of indoor PLC channels that are needed in the remaining of the paper. More information about PLC measurements and the properties of PLC channels can be found e.g. in [5], [6] and the references therein. To determine the characteristic properties of indoor low-voltage system PLC channels, measured transfer functions and measured noise power density spectra (PDS) of the channels are used. Transfer functions are measured by a network analyzer, noise power density spectra by a spectrum analyzer. Couplers are used to connect the measurement devices to the power-line.

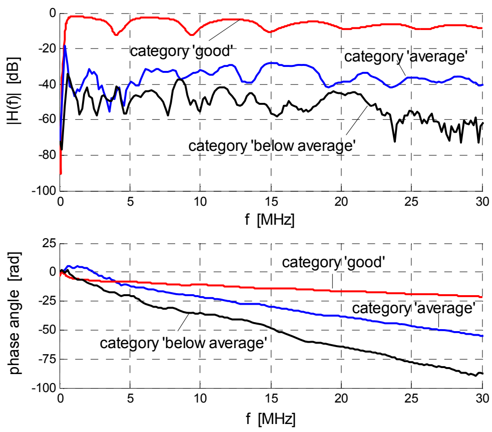

Fig. 2. Transfer functions of 3 measured PLC channels.

The measured transfer functions show high differences regarding the frequency-selectivity and the average attenuation. Fig. 2 shows three examples of measured PLC transfer functions, roughly classified according to the average attenuation in the categories ‘good’, ‘average’ and ‘below average’. The PLC channels in one room (or in adjacent rooms) usually belong to the categories ‘good’ or ‘average’; in our measurement campaign ‘below average’ PLC channels are typically found in case of connections between not adjacent rooms. The characteristics of PLC transfer functions depend on different factors: the cable length of the power-line between the two power outlets that define entry and exit point of the PLC channel, the included phase conductors and fuse circuits, and multipath propagation because of reflections (Fig. 3).

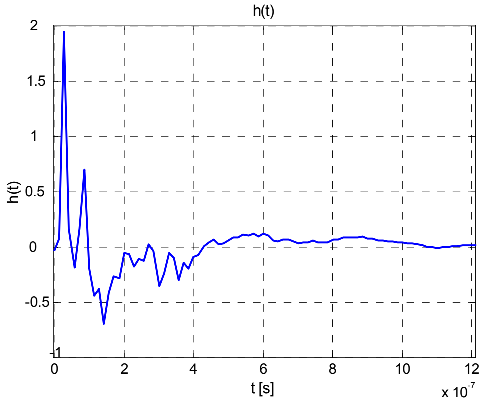

Fig. 3. Impulse response of a PLC channel (relatively short duration; category ‘good’).

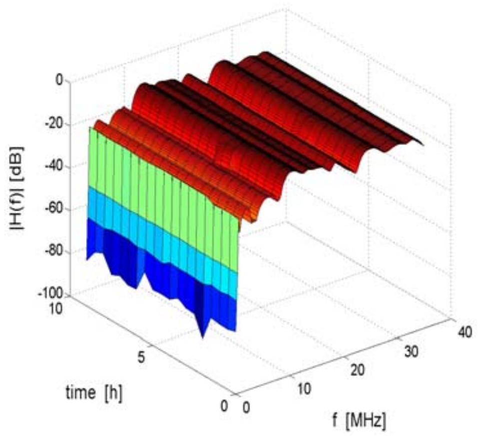

Fig. 4. Variations over time (8 h) of the amplitude spectrum of a PLC transfer function.

Such reflections are generated, e.g., at open-ended power outlets or at devices connected to the power-line with their loads not matched to the frequency-dependent impedance of the power-line network. Fig. 4 shows an example of the variations within 8 h of the amplitude spectrum of a measured PLC transfer functions. According to our measurements the transfer functions of PLC channels are quasi-static; they vary only slowly over time except for modifications of the power-line topology next to the considered PLC channel (e.g. a device plugged in). In Fig. 5 and Fig. 6 noise measurements for PLC channels are shown. The use of electrical devices is one reason for noise at the power-line (Fig. 5 shows the influence of a dimmer as an example). Other reasons are narrowband interferers – e.g. (medium/ short wave) radio transmitter and radio stations. The curve 2 in the lower part of Fig. 5 shows a typical noise power density spectrum (PDS) of a PLC channel. Distinct narrow band interferences can be found.

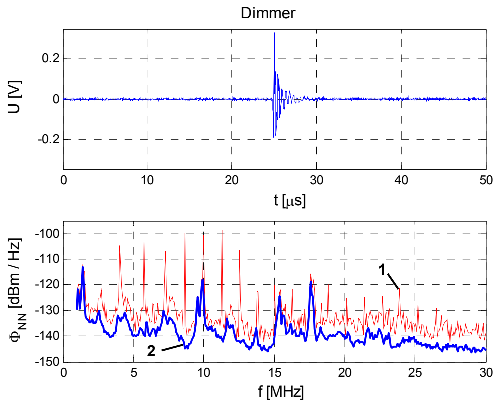

Fig. 5. Part of periodical time function of a dimmer and measured noise power delay spectrum of a PLC channel with a dimmer (1) and without (2).

In Fig. 6 the variations of the PDS within 24 h is shown. All in all it can be seen that transfer function and noise PDS of a PLC channel are frequency-selective, strongly depending on the location and vary only slowly over time; in addition, impulsive noise can be expected (upper part of Fig. 5) and is modeled in the following by its spectral behaviour.

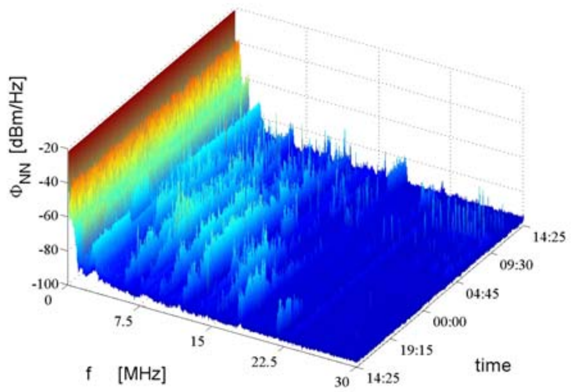

Fig. 6. Variations over time (24 h) of a measured noise power density spectrum (PDS) of a PLC channel.

2.1. Channel capacity

In Europe the maximum permitted radiation for unshielded cables is restricted by standards (because of electromagnetic compatibility (EMC) reasons). In this paper a low transmit power density of $\Phi_{TT}(f)$ = 1.38e-8 V^2/Hz (constant for the considered bandwidth B) is assumed, that meets regulations applied e.g. in Switzerland (for details see [5]). This corresponds to a transmit power of 8 mW at 50 Ω and a bandwidth of B = 29 MHz (1 MHz … 30 MHz). To determine the capacity of a channel, a measured transfer function and a measured noise PDS are used. The channel is separated into N narrowband flat fading sub-channels of bandwidth $\Delta f = B / N$ where N is the number of samples of the measured transfer function $H(k\Delta f)$ and of the measured noise PDS $\Phi_{NN}(k\Delta f)$:

$$C \approx \Delta f \cdot \sum_{k=1}^{N} \log_2 \left(1 + \frac{\Phi_{TT}(k\Delta f) \cdot |H(k\Delta f)|^2}{\Phi_{NN}(k\Delta f)} \right) \quad (1)$$

The noise of each sub-channel k is approximated as AWGN of variance $\sigma_k = \Phi_{NN}(k\Delta f) \cdot \Delta f$. The samples of the power density of the transmitted signal $\Phi_{TT}(k\Delta f)$ are found using water-pouring.

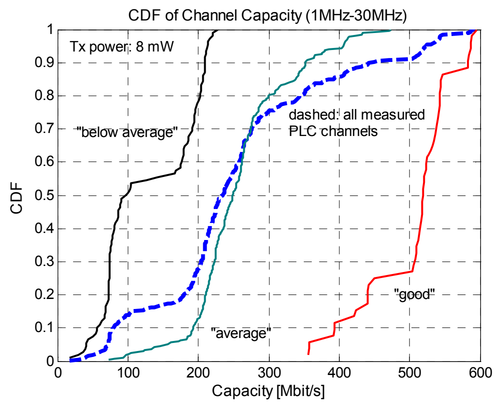

Fig. 7. Measured PLC channels: Cumulative distribution function of channel capacity.

Fig. 7 shows the CDFs of the channel capacity of 430 measured PLC channels. The dashed curve shows the CDF for all measured channels, the other 3 curves show the CDFs of the 3 categories of the transfer functions.

3. PLC BACKBONE FOR WIRELESS RELAYING

3.1. Relay initialization and updates of CSI

Wireless multiuser ZF relaying: every relay broadcasts its CSI regarding the wireless source/ destination nodes to all other relays using the power-line.

Each of the N_r relays has to estimate $2N_a$ complex channel taps per OFDM sub-carrier (one uplink and one downlink tap per source/ destination pair). We assume 8 bytes per complex channel tap, including coding for error protection. Each relay broadcasts this estimated CSI to all other relays using PLC. If a relay does not receive the CSI of all other relays, a protocol scheme is assumed that reduces the number of assisting relays to these relays that have all CSI of each other. The data transmitted over PLC adds up to 16 $N_r N_a$ bytes.

We consider the following example: number of wireless source/ destination pairs $N_a = 3$; number of relays $N_r = 10$, update of CSI every 10 ms. This leads to a sum data rate of 48 kB/s = 0.384 Mbit/s. If the wireless source/ destination nodes use 128 OFDM sub-carriers, and if the channel taps of every sub-carrier has to be transmitted (usually it is enough to transmit much less – depending on the resolvable channel paths), the (maximum) sum rate for PLC is 49.152 Mbit/s. Because the information is broadcasted between the relays, every PLC channel between two relays has to support this sum rate.

As Fig. 7 shows, for more than 98 % of all measured PLC channels the channel capacity is higher than 50 Mbit/s; even in the category 'below average' there are more than 92 % with a capacity high enough to support the necessary data rate. For N_r=10 relays there are $\binom{10}{2} = 45$ different PLC channels. In the considered example in average one relay (2% outage, 45 channels) is affected. But 9 relays remain (not 8) because if a link between two relays does not support the rate, then it's enough that one of these relays does not assist the communication between the wireless sources and destination nodes. The remaining 9 relays are enough to enable multi-user zero-forcing because at least 7 relays are necessary to support 3 source/ destination pairs [3], [4].

3.2. PLC transmission scheme

Because PLC channels are highly frequency-selective OFDM is a suitable transmission scheme (see also [6]). In addition, for OFDM it is possible to leave particular frequencies unused, e.g. because of high attenuation/ disturbances or due to EMC reasons. Furthermore the relays use OFDM for the wireless communications. Our measurements show durations of the channel impulse response of up to 3 µs; so an OFDM symbol duration of 10 µs (Δf_{sc} = 100 kHz sub-carrier spacing) seems appropriate and is used exemplarily in the following; the OFDM guard time should be at least 3 µs. As an example we consider 288 OFDM sub-carriers with 100 kHz spacing (frequency range 1 MHz … 28.8 MHz). Fig. 8 shows the symbol error rate (SER) vs. receiver SNR for OFDM transmission - 4-QAM on all sub-carriers - over the 'below average' channel shown in Fig. 2. A measured noise PDS of this channel is used to generate colored noise; perfect CSI is assumed at the receiver; 20 dB receive SNR corresponds for this PLC channel to about 2.3 mW transmit power. For this value the uncoded OFDM achieves almost a symbol error rate of SER = 1e-2. Because the PLC channel is quasi-static, pre-coding schemes at the transmitter using a-priori CSI could be used for peer-to-peer transmissions; but we are considering broadcasting between all relays, therefore these schemes are not feasible, because it is not possible for one relay to adapt to all channels of the other relays.

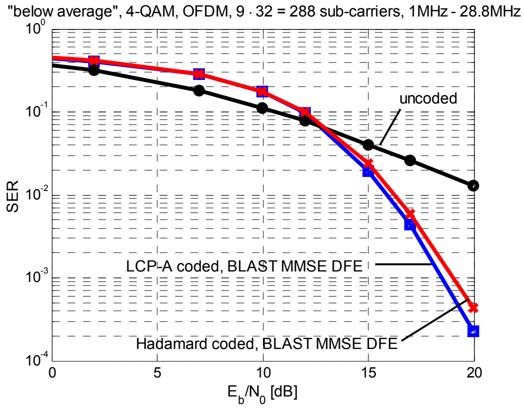

Fig. 8. SER performance: OFDM, 4QAM, channel 'below average'

Our approach is linear pre-coding using unitary matrices; no CSI at the transmitter is necessary. For the simulation results in Fig. 8 we divided 288 symbols (one per sub-carrier) in 9 blocks with 32 symbols and used a (32x32) Hadamard pre-coding matrix and a (32x32) LCP-A matrix defined in [7], which is known to achieve the full frequency diversity gain. At the receiver an interference compensation technique has to be used, because the channel fading in combination with the pre-coding matrices introduces inter-symbol interference [7]; for the simulations we used a BLAST MMSE-DFE [8]. A Forward Error Correction (FEC) code in addition to the linear pre-coder can be used to protect against impulsive noise (not applied in the presented simulation results). The LCP-A matrix shows the best performance and achieves SER = 2e-4 for 2.3 mW at a data rate of 57.6 Mbit/s (4-QAM is used for all simulations); considering the 3 µs guard time the data rate still amounts to 40.32 Mbit/s. This seems more than enough for the communication between two relays, even if a relay acting as an Access Point is connected to a backhaul over power-line (see Fig. 1).

3.3. Synchronization of wireless relays over PLC

Now we investigate, if the PLC OFDM can be used to assist the synchronization process of the relays; the synchronization is necessary to enable a coherent combining of the (wireless) signals that arrive from the relays at the destination nodes. Usually, carrier synchronization in an OFDM system is accomplished by locking on an un-modulated carrier which is used as a pilot tone. The phase of a local oscillator can be derived from the received signal by a PLL (Phase Locked Loop); the local oscillator has an average frequency exactly equal to that of the RF carrier. A second-order loop can be used to eliminate a constant phase offset. Therefore we use a zero-mean stationary random process with variance σ_ϕ^2 as a model for the remaining carrier phase jitter (see [9], [10], [11]). According to [9] the jitter variance at sufficiently high SNR is given by:

$$\sigma_\phi^2 \sim N/S \cdot B_N / W \qquad (2)$$

W is the signal bandwidth, B_N the one-sided noise bandwidth of the loop used in synchronization (PLL).

In Fig. 9 the CDFs of the SNR values of all OFDM sub-carriers for all measured PLC channels and for all channels in the three categories are given. More than 20 % of all OFDM sub-carriers show a SNR value of less than 12 dB (the 'below average' channels even lower than 0 dB) – according to [9] 12 dB SNR translates to a high jitter variance $\sigma_\phi^2 \approx -15$ dB.

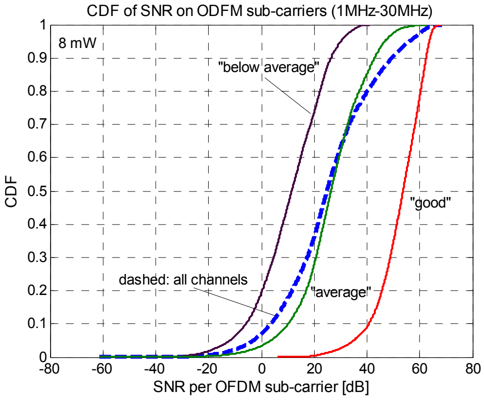

Fig. 9. Measured PLC channels: CDF of SNR per OFDM sub-carrier.

But in Fig. 10 is shown that more than 98 % of the PLC channels show at least one OFDM sub-carrier with more than 20 dB SNR; even in the category 'below average' for more than 96 % the SNR is at least 20 dB. If these sub-carriers can be used as pilot tones for synchronization, the jitter variance is low ($\sigma_\phi^2 \approx -23$ dB [9]). Therefore the relays can use a pilot tone in the PLC OFDM to establish a synchronization of the symbol timing; if the jitter is low and very narrow PLL filters are used then even the wireless carrier phase synchronization can be assisted by the PLC reference signal.

4. CONCLUSIONS

In this paper we studied the feasibility of using PLC to assist cooperative wireless relaying. Based on a measurement campaign of indoor PLC channels we analyzed the channel capacity and proposed an OFDM transmission scheme that can be used for synchronization and inter-relay-communication over power-line, even using low transmit power to meet given regulations. We conclude that PLC is a promising candidate to enhance wireless relaying schemes that are based on inter-relay-communication. The overhead due to the inter-relay-communication does not affect the wireless part; costs are reduced because additional wiring is not needed; and relays can be plugged in wherever needed.

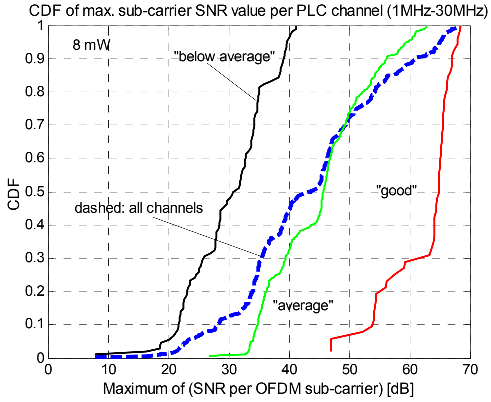

Fig. 10. CDF of maximum SNR values; for every PLC channel only the OFDM sub-carrier with highest SNR is considerd.

5. REFERENCES

[1] I. Hammerström, M. Kuhn, A. Wittneben, " Cooperative diversity by relay phase rotations in block fading environments," *Proc. SPAWC 2004*, pp. 5, July 2004.

[2] R. U. Nabar, O. Oyman, H. Bölcskei, A. Paulraj, "Capacity scaling laws in MIMO wireless networks", *Proc. Allerton Conf. Comm., Contr. and Comp.*, pp. 378–389, Oct. 2003.

[3] A. Wittneben, B. Rankov, "Distributed Antenna Systems and Linear Relaying for Gigabit MIMO Wireless," *Proc. IEEE VTC'04 Fall*, Los Angeles, USA, Sept. 2004.

[4] A. Wittneben, I. Hammerström, "Multiuser zero forcing relaying with noisy channel state information", *Proc. IEEE WCNC 2005*, Mar. 2005, to appear.

[5] M. Götz, M. Rapp, K. Dostert, "Power line channel characteristics and their effect on communications system design," *IEEE Comm. Mag.*, April 2004.

[6] E. Del Re, R. Fantacci, S. Morosi, R. Seravalle, "Comparison of CDMA and OFDM techniques for downstream power-line communications on low voltage grid", *IEEE Trans. On Power Delivery*, Vol 18, no. 4, Oct. 2003.

[7] Y. Xin, Z. Wang, G. B. Giannakis, "Space-time diversity systems based on linear constellation precoding," *IEEE Trans. on Wireless Comm.*, vol. 2, no. 2, pp. 294-309, 2003.

[8] G. D. Golden, G. J. Foschini, R. A. Valenuela, P. W. Wolniansky, "Detection algorithm and initial laboratory results using V- BLAST space-time communication architecture," *Electronic Letters* (vol. 17, Nov. 1998).

[9] L. E. Franks, "Carrier and bit synchronization in data communication – a tutorial review," *IEEE Trans. on Comm.*, Vol. com-28, No. 8, August 1980.

[10] T. Pollet, M. Moeneclaey, I. Jeanclaude, H. Sari, "Carrier phase jitter sensitivity for single-carrier and multi-carrier QAM systems," *Proc. Symp. On Comm. and Vehicular Techn. in the Benelux*, 1994.

[11] H. Steendam, M. Moeneclaey, "Synchronization sensitivity of multicarrier systems," *European Trans. on Comm*, ETT special issue on Multi-Carrier Spread Spectrum, Vol. 15, No. 3, May – June 2004, pp. 223-234.