

PLC enhanced wireless access networks: a link level capacity consideration

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Abstract - The integration of Power Line Communication (PLC) is of interest to future broadband communication systems. These communication systems will be mostly wireless but the use of non-dedicated wired infrastructure will help to reduce costs. PLC uses the highly developed infrastructure of the electrical energy distribution network for data transmission. So it is possible to enlarge the capacity of communication systems without additional wiring and additional costs for this wiring – for outdoor applications, for example to bridge the last mile, as well as indoor, for example to establish or enlarge LANs without new data cables. To evaluate the potential of PLC an analysis of the channel capacity of the power line at higher frequencies is needed.

In this paper a detailed analysis of the link level channel capacity of Indoor PLC channels is presented at frequencies between 1 MHz and 30 MHz. This analysis is based on extensive measurements of the transfer function and the noise of these channels - for an office environment as well as for a home environment.

I. INTRODUCTION

In wireless communication systems the use of antenna-arrays leads to Multiple Input Multiple Output (MIMO) radio channels. These radio channels promise high channel capacities for future wireless communication systems [1], [2]. The capacity of such a broadband communication system can be enhanced by the capacity of existing power lines cost-effectively. This leads to heterogeneous networks (Fig. 1). The use of PLC offers a multitude of possibilities for such systems. Besides the utilization of existing and well-developed infrastructure there is for example the fact, that PLC systems work at much lower frequencies than wireless communication systems (in Europe broadband PLC is restricted to frequencies between 1 MHz and 30 MHz). This reduces the costs for transmitter and receiver because it means that the components are cheaper.

On the other hand the maximum permitted radiation for unshielded cables is restricted by strict European standards; at the frequency of 1 MHz the peak value of the

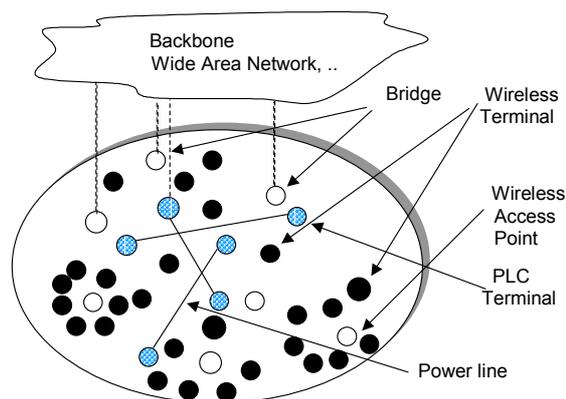


Fig. 1. Heterogeneous network

field strength measured in a distance of 3 m is limited to 40 dB μ V/m. With increasing frequency the allowed peak value decreases up to 27 dB μ V/m at 30 MHz. According to an estimation in [3] this leads to a maximum transmitting power density of about $1.1 \cdot 10^{-6}$ V²/Hz in the average case and about $1.1 \cdot 10^{-8}$ V²/Hz in the worst case. So only a low transmitting power density will be possible for future broadband PLC.

In this paper a transmitting power density of $1.38 \cdot 10^{-8}$ V²/Hz is assumed. This corresponds to a transmitting power of 8 mW at 50 Ω and a bandwidth of 29 MHz (1 MHz ... 30 MHz).

II. MEASUREMENTS

To determine the channel capacity of an Indoor PLC channel of the low-voltage system a measured transfer function and a measured power density spectrum (PDS) of the noise on the channel is used. The transfer function is measured by a network analyser, the power density spectrum by a spectrum analyser. Couplers are used to connect the measurement devices to the power line.

The measured *transfer functions* show big differences in the average attenuation and the frequency selectivity of the attenuation. Fig. 2 shows three examples of measured

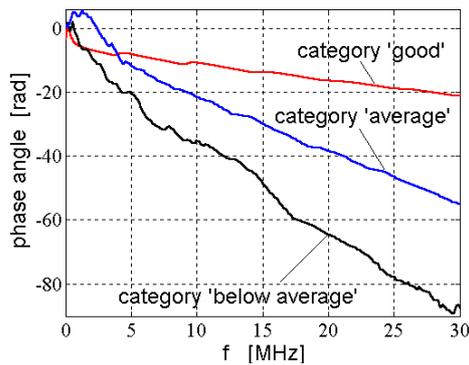
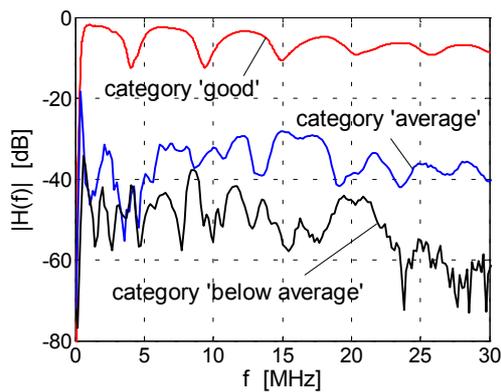


Fig. 2 Three measured PLC transfer functions (amplitude spectrum and phase angle)

PLC transfer functions; they are roughly classified in the categories 'good', 'average' and 'below average'.

With increasing distance between two measured sockets the attenuation of higher frequencies increases more than the attenuation of lower frequencies (low pass characteristic). But the attenuation not only depends on the distance between the used sockets but also on the supply of these sockets. Fig. 3 shows a typical power supply of a house in Germany: it is supplied by three-phase current, i.e. 3 phase conductors (L1, L2, L3) and a neutral conductor (not shown in Fig. 3). A normal socket is connected to one of the three phase conductors and to the neutral conductor (null); in our measurements a PLC signal is transmitted between phase and null. For constant distance the lowest attenuation between two sockets is found if the sockets are supplied by the same phase conductor and protected by the same fuse; the loss increases in the case of different fuses. If different phase conductors supply the sockets usually the attenuation is high. In addition the frequency selective attenuation depends on the environment, which means open-ended sockets and devices that are connected to the power line near the tested pair of sockets. This is a result of the reflections generated at the open-ended sockets and at those devices because their loads are not matched to the frequency dependent impedance of the power line net. So, the characteristics of the transfer function, above all the often-

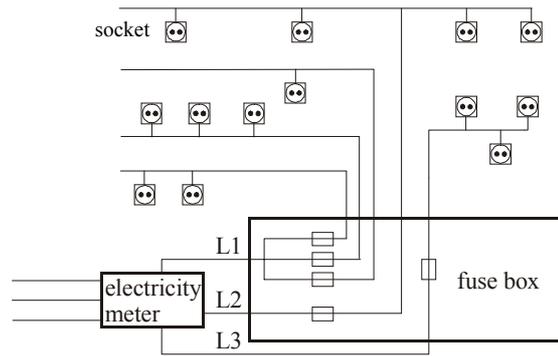


Fig. 3. Power supply of a house

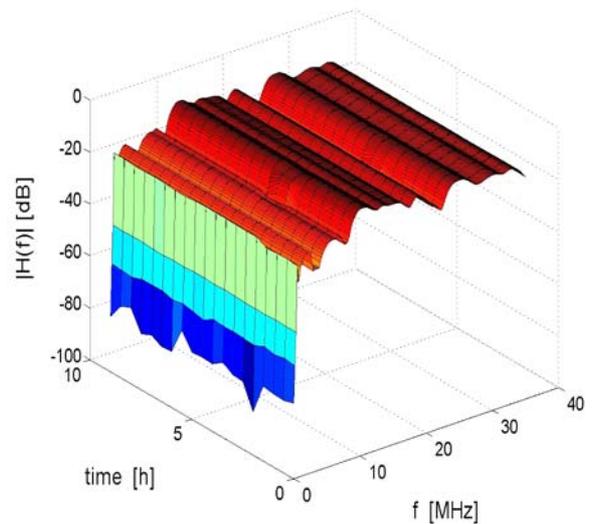


Fig. 4. Variation with time (8 h) of the amplitude spectrum of a PLC transfer function

periodic deep notches in the amplitude spectrum, can be explained by multipath propagation because of reflections [4], [5].

Fig. 4 shows the variation with time of the amplitude spectrum of a PLC transfer function. According to our measurements the transfer function of a PLC channel is quasi-static; it varies only slowly with time except for a modification of the power line topology next to the considered sockets (e.g. an electrical device plugged in near the considered PLC channel).

In Fig. 5, Fig. 6 and Fig. 7 noise measurements of PLC channels are shown. The use of electrical devices (such as a drilling machine, dimmer, vacuum cleaner, hair dryer, ...) is one of the reasons for disturbances on PLC channels (Fig. 5). Other reasons are switching actions and narrowband interferer - e.g. (medium / short wave) radio transmitter and radio stations. Plot 1 of Fig. 6 presents a typical noise power density spectrum of a PLC channel.

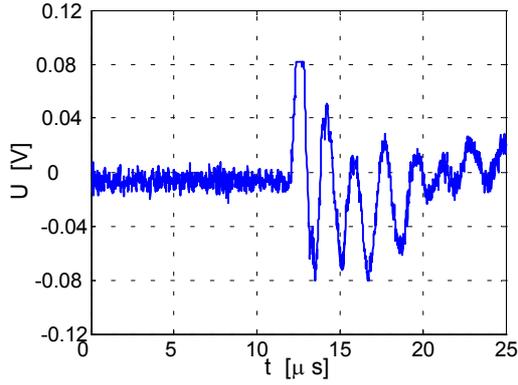


Fig. 5. Measured time function of an electric drilling machine

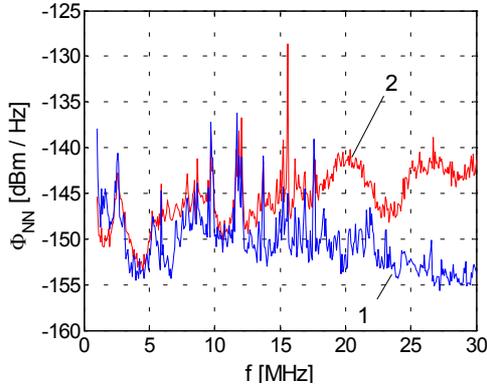


Fig. 6. Measured power density spectrum of the noise of a PLC channel with an electric drilling machine (2) and without (1); averaged over 100 measurements

Distinct narrow band interferences can be found in the spectrum. Plot 2 of Fig. 6 shows the PDS of an electrical drilling machine supplied by a socket next to the measured socket.

In the evening and at night the noise on the PLC channel decreases at some frequencies (Fig. 7), probably because the most electrical devices are not used at this time of the day. At other frequencies the noise increases, partly because propagation conditions in the atmosphere get better for medium and short wave transmissions.

The measurements show that a PLC channel usually has a frequency selective transfer function and frequency selective noise (partly because of strong narrowband interferences).

The transfer functions and the power density spectra of the noise are space-depending and vary (slowly) with time, but the noise power density spectra are more time-variant than the transfer functions, which are quasi-static. Because the attenuation increases with the distance only influences near the PLC channel play a decisive role.

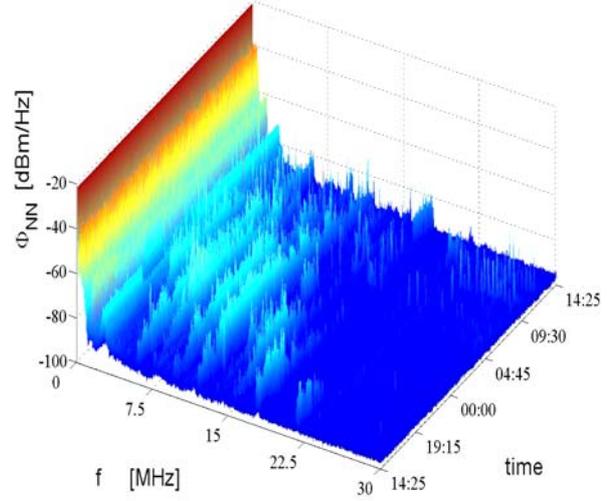


Fig. 7. Variation with time (24 h) of a measured noise power density spectrum of a PLC channel

III. CHANNEL CAPACITY

The channel capacity is a limit to error-free bit rate that is provided by information theory. For a band-limited channel with additive white Gaussian noise (AWGN) it is given by

$$C = B \cdot \text{ld} \left(1 + \frac{S_R}{N} \right) \quad (1)$$

where B is the bandwidth of the channel and S_R/N is the signal-to-noise ratio at the receiver [6]. With the power density spectra of the received signal $\Phi_{RR}(f)$, of the transmitted signal $\Phi_{TT}(f)$ and of the noise $\Phi_{NN}(f)$ the capacity of a channel with the transfer function $H(f)$ can be derived as follows:

$$C = \int_{f \text{ in } B} \text{ld} \left(1 + \frac{\Phi_{RR}(f)}{\Phi_{NN}(f)} \right) df$$

$$C = \int_{f \text{ in } B} \text{ld} \left(1 + \frac{\Phi_{TT}(f) \cdot |H(f)|^2}{\Phi_{NN}(f)} \right) df \quad (2)$$

To determine the instantaneous 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 $H(\nu\Delta f)$ and of the measured noise PDS $\Phi_{NN}(\nu\Delta f)$:

$$C \approx \Delta f \cdot \sum_{\nu=1}^N \text{ld} \left(1 + \frac{\Phi_{TT}(\nu\Delta f) \cdot |H(\nu\Delta f)|^2}{\Phi_{NN}(\nu\Delta f)} \right) \quad (3)$$

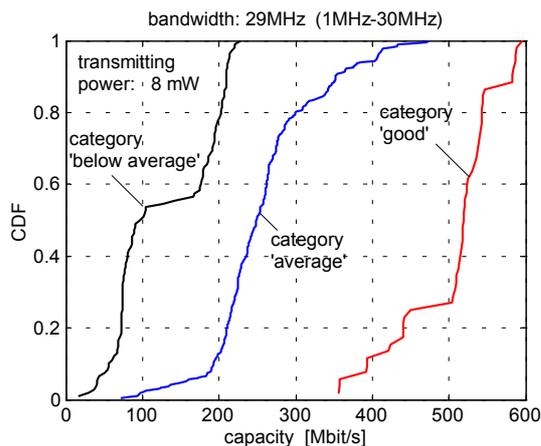


Fig. 8. Cumulative distribution functions of PLC channel capacities; category ‘good’: 61 channels, ‘average’: 259, ‘below average’: 110

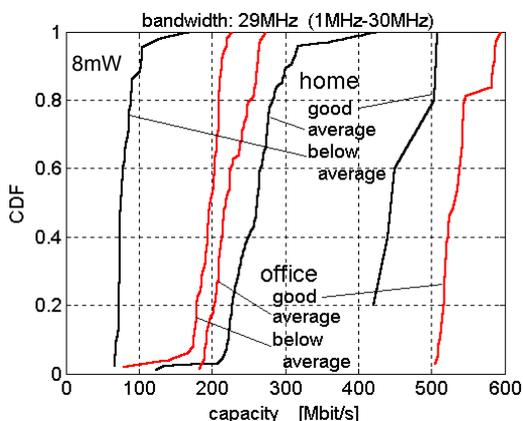


Fig. 9. Comparison of channel capacities of a home (142 channels) and office (166 channels) environment

The noise of each sub-channel i is approximated as AWGN of variance $\sigma_i = \Phi_{NN}(i\Delta f) \cdot 2 \cdot \Delta f$. The samples of the power density of the transmitted signal $\Phi_{TT}(v\Delta f)$ are found using the “water-pouring” approach [7] to maximize (3). The used total power is 0.4 V^2 , i.e. 8 mW at 50Ω (averaged power density of $1.38 \cdot 10^{-8} \text{ V}^2/\text{Hz}$).

Figure 8 shows cumulative distribution functions (CDF) of the instantaneous channel capacity of 430 analysed indoor PLC channels assigned to three categories. The channels were measured in an office environment and in two different residential buildings. The classification into the three categories is done evaluating the attenuation of the transfer functions (Fig. 2 shows three examples). The transfer function is quasi-static and therefore characteristic for a PLC channel. In an office or in an apartment usually all three categories of the transfer function can be found. Normally it is not known if the same phase conductor supplies the two sockets of a PLC channel, or how high the attenuation of the channel is. So, in this paper the

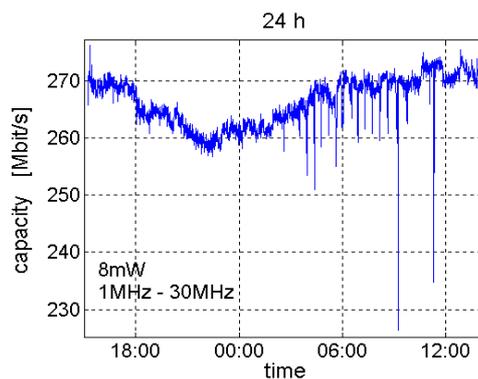


Fig. 10. Variation with time of the capacity of a PLC channel

categorization is used for most CDF plots. Obviously channel capacities of more than 400 Mbit/s are not rare even at a very low transmitting power density (Fig. 8). More than 70 % of the PLC channels with a low attenuation (category ‘good’) have a capacity of more than 500 Mbit/s . Even in the category ‘below average’ about 50 % of the analysed channels have a channel capacity of at least 100 Mbit/s , only 3% less than 38 Mbit/s . The low capacities in this category are caused by high attenuation as a result of long distances or different phase conductors. In the latter case HF-coupling of the phase conductors can reduce the attenuation.

Fig. 9 shows a comparison of the channel capacities in an apartment and in an office. In the apartment most of the measured noise power densities were higher than in the office. So, here the channel capacities of the categories ‘good’ and ‘below average’ are lower. But in the category ‘average’ most of the capacities in the office are lower. One reason is, that for this category the attenuation is higher in the office, because there almost every room has its own fuses in contrast to the apartment. So, for different rooms not only the distance between them leads to the attenuation but also the fact that the sockets are not connected until behind the fuse box (Fig. 3). This results in the big gap (about 250 Mbit/s) between the capacities of the ‘good’ and the ‘average’ transfer functions, because there is no pair of sockets with a long distance between them that is protected by the same fuse. This type of channels can be found in the apartment; a part of the transfer functions there belong to the category ‘average’ at the border to ‘good’. Therefore there is no such clear gap between the capacities of ‘good’ and ‘average’ transfer functions in the apartment.

For PLC a partitioning in indoor and outdoor frequencies is considered: up to about 10 MHz outdoor PLC, then indoor PLC. This leads to indoor channel capacities of about 66 % of the capacities presented in Fig. 8 and Fig. 9.

Fig. 10 shows the variation with time of the instantaneous capacity of a PLC channel. The capacity is mainly influenced by the noise.

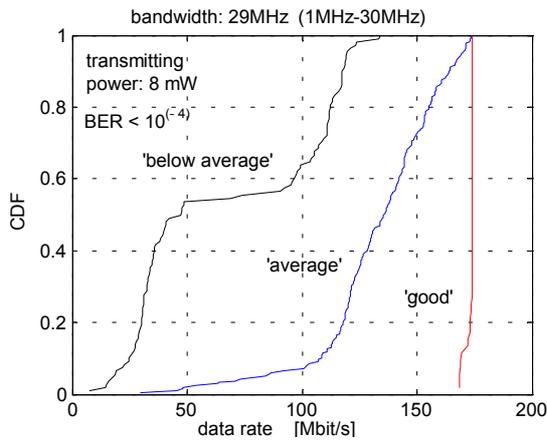


Fig. 11. CDF plots of attainable data rates (adaptive modulation)

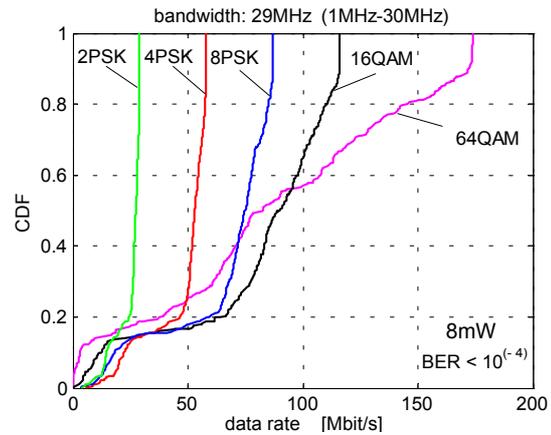


Fig. 12. CDF plots of attainable data rates

IV. ATTAINABLE DATA RATES

In this section for different modulations data rates are presented that can be achieved at a bit error probability below 10^{-4} . The transmitting power still is 0.4 V^2 or 8 mW at 50Ω , the bandwidth 29 MHz; constant power density of $1.38 \cdot 10^{-8} \text{ V}^2/\text{Hz}$ is assumed. The following symbol alphabets are considered: 2-PSK, 4-PSK, 8-PSK, 16-QAM and 64-QAM. For each sub-channel the signal-to-noise ratio and then the bit error probability is calculated [6]. If it is below 10^{-4} the data rate is increased according to the considered symbol alphabet.

Fig. 11 shows the attainable data rates for the three categories of PLC channels under the assumption that in every sub-channel that symbol alphabet is used which leads to the maximal data rate with a bit error probability below 10^{-4} (adaptive modulation; transmitter needs channel knowledge). This leads to data rates between 168 and 174 Mbit/s for the category 'good'; and even more than 45 % of the 'below average' PLC channels achieve a data rate of more than 50 Mbit/s, only 3% less than 15 Mbit/s.

In Fig. 12 a comparison of the data rates for different symbol alphabets is presented. The same alphabet is applied in every sub-channel (transmitter needs no channel knowledge). No classification in categories is used; 430 PLC channels are considered. One result is that 64-QAM only for about 44 % of the channels leads to a higher data rate than 16-QAM (at a bit error probability below 10^{-4}). Using 4-QAM for 72 % of the channels a data rate between 50 and 58 Mbit/s is reached.

V. CONCLUSIONS

It is obvious that the application of broadband PLC will be a useful completion of future communication systems

because the channel capacity of PLC channels is promising. This is shown by our measurements for PLC channels typically found in an appartement or in an office. PLC can enhance the capacity of wireless networks cost-effectively even using very low transmitting power to meet the European standards. Perhaps PLC is not as suitable for outdoor networking (to bridge the "last mile") as for indoor networking. Because the power line is a shared medium and for outdoor PLC the capacity is lower: only lower frequencies can be used for the longer distances in the outdoor application. This is a result of the low pass characteristic of power line. While the typical distances in an apartment permit high capacities.

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