Indoor Power-Line Communications: Channel Modelling and Measurements

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Abstract.- The subject of this paper is to analyse the low voltage distribution lines inside the consumer premises, in order to attain a channel model useful to simulate its behaviour for high bit-rate digital communications. Measurements have also been performed both in the laboratory and in residential buildings, and results are presented and discussed. Finally, some estimations of the channel capacity have been carried out.

Key words.- Power line communication, high bit rate, channel modelling, impulse response, frequency response, noise, measurements, channel capacity, OFDM, DMT.

1. Introduction

So far low voltage power-line communication systems have been mainly concerned for low data rate transmission (e.g. standards like CEBus). In fact, there are regulations that restrict severely the frequency range, in both Europe (EN 50065 [1]) and other parts of the world. Two kinds of applications are being developed in this field: 'last mile' services, or access to large telecommunication networks; and indoor services, like the installation of Local Area Networks (LAN) at offices or homes. Due to limits of the channel capacity, an extended frequency band should be released for transmission at higher rates.

Power lines were designed, obviously, to deliver electrical energy and not to transmit communication signals, and it makes the conditions in the channel quite adverse. The channel parameters (i.e. amplitude and phase responses, input and output impedances, or noise sources) depend on the particular location characteristics under study: complex and often unknown topology (with many branches), kind of wires involved, heterogeneous loads, etc. These parameters also exhibit variations with frequency, position and time (as electrical appliances are switched on/off). However, changes are presumed to be much slower than the data rate, so the assumption of time-invariance during several symbols is justified.

In the preceding literature on the topic, the hostile nature of this communication medium has been studied [2]. Recently, attention has been turned to the high frequency range [3][4], highlighting different sources of disturbances (broad band, like impulse noise, background noise, or the one produced by switching devices; and narrow band: radio interferences, noise synchronous to the power frequency...), and signal degradation (from impedance mismatch and discontinuities, branch cables...). All these difficulties can lead to model this channel in a 'black-box' approach, extracting a few system parameters from extensive measurement results [5]. However, in this work, a method to obtain channel frequency response from the physical characteristics of the network (cables layout, loads connected, transmission distance, etc) is presented. This procedure, despite its complexity and once its adequacy had been accomplished, would permit to produce channel models automatically without the necessity of measuring. Although, in order to adjust the model performance, measurements of channels responses, existing noise, and load impedances, have to be carried out.

2. Channel model

As mentioned above, in this paper a procedure to obtain the channel response from the power network characteristics and topology, is proposed. It is based on considering power lines as a structure of transmission lines, with multiple branched lines, which may be loaded or not, representing the different sockets placed in the rooms. For information transmission purposes the link is usually established connecting the transmitter and receiver subsystems between the line and neutral conductors of the power grid. Data from manufacturers of typical cables used in indoor power wiring (with several sections for the different electrical circuits employed) have been adopted to find the secondary parameters (R, L, C, G per unit length) of the elementary transmission line considered: two parallel wires. The loads have been modelled as complex impedance vectors in frequency (values estimated from measurements: TV's, PC's, lamps... input impedance from the mains plug at frequencies up to 30MHz). In case that no device were plugged, an open circuit is assumed.

It is necessary to use a coupling circuit to prevent the communication equipment from damage when connecting it to the electrical wiring to launch or receive the information signal. In the model, the effect of the introduction of this adaptation interface has to be added to the transmitter output impedance and receiver input impedance, to reflect the mismatch losses.

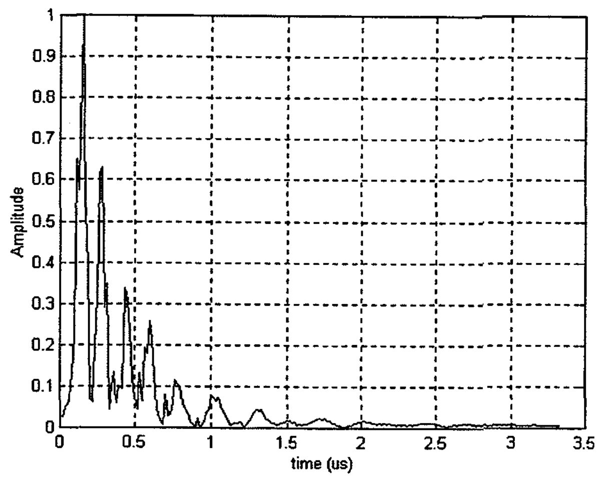

Figure 1: Impulse response of modelled channel (normalised).

From real electrical schemes of several residences, approximate models for channel simulations have been created. In Fig. 1, impulse response for a model designed from an apartment power network is shown (two sockets of the same electrical circuit in different rooms have been selected to form the link, and the distance could be 15-20m approximately). Echoes appeared, due to the multiple reflections experimented by the signal as it travels through the network (because of wave propagation phenomena produced by impedance mismatch and branches). The corresponding amplitude frequency response is presented in Fig. 2, where notches at certain frequencies are observed, in which phase exhibits nonlinearity (see Fig. 3). Between them, there are bands with nearly flat response that could be combined for reliable transmission. Although there is a high attenuation level (present even in short-distance links). In general, the more branched and loaded the network, the longer the impulse response.

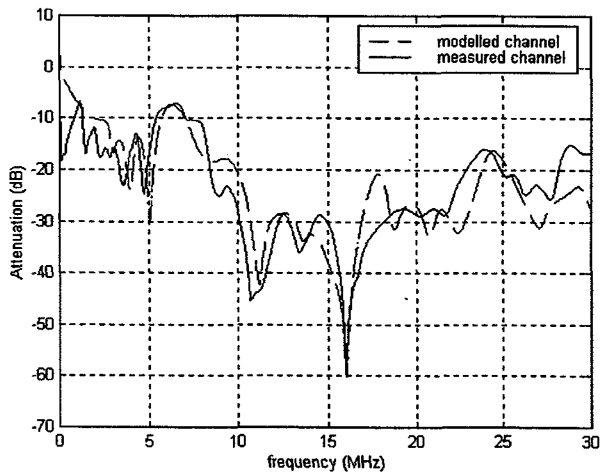

Figure 2: Example of channel amplitude responses obtained from the model and measurements.

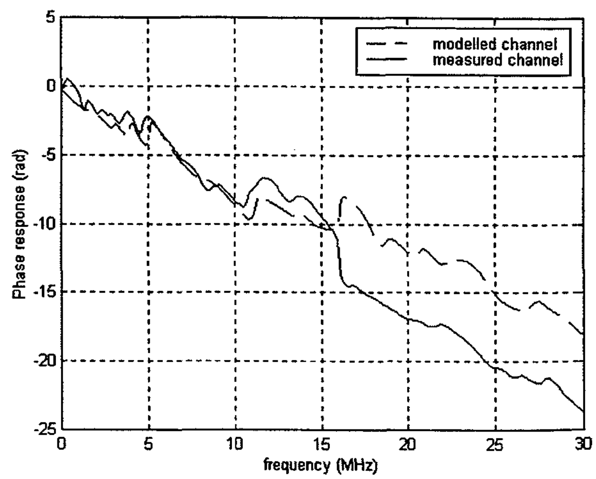

Figure 3: Example of channel phase responses obtained from the model and measurements.

The procedure validity is studied contrasting its results with actual measurements, as seen in Fig. 2-3 (measured impulse response has not been displayed in Fig. 1 to make clearer the plot, as it is similar to the modelled one). It is not sensible to expect a perfect fit, since the model has been constructed without an exact knowledge of the real layout. But certainly, the drafts bear rather resemblance. Anyway, the purpose of the model is not to match with a certain channel configuration; it is to serve as a generator of feasible channel models, useful to prove diverse transmission techniques.

3. Channel measurements

In order to verify the simulations results and to get information about the medium, measurements of noise and channel transfer functions have been performed for different indoor power line channels, under various conditions and loads. A network analyser plus two coupling circuits (essentially high-pass filters and transformers) in the transmitter and receiver side respectively, have been employed to make the measurements. The access points to the electrical wiring (distant sockets) were reached with the help of coaxial cables, whose influence (and that of the coupling units) was contemplated in the measure procedure. The frequency range has been extended up to 30MHz.

The channel response depends on the electrical path that signal follows, and especially on the location of the branched lines. It is common to find shorter links with higher attenuation level than longer ones. For example when transmitter and receiver are not on the same electrical circuit, because the main signal path includes the distribution box, where all the circuits are connected in parallel, and important impedance mismatch (causing reflections) and power distribution (and dissipation) among them occurs. According to the model results, the transfer functions measured display some nulls in the amplitude responses at certain frequencies. In Fig. 4 the attenuation of the frequency response for three measured channels in a residential building are plotted. The first exhibit low, but not uniform, attenuation, despite the link was established over the same electrical circuit and the distance was short (no more than 5-6m.). The second line correspond to another configuration over the same circuit but with more distance (about 15-20m.), the attenuation registered is, evidently, higher, and more frequency variant. Finally, a result for a little shorter distance, but between different circuits is drafted, presenting a worse behaviour. On the right, the plot shows the measurement results for three arrangements of plugged devices in the laboratory, but keeping the transmitter and receiver fixed. It is clear the significant influence in channel amplitude response both of location and, as observed in this figure, of loads (the transmission distance in this case was approx. 15-20m).

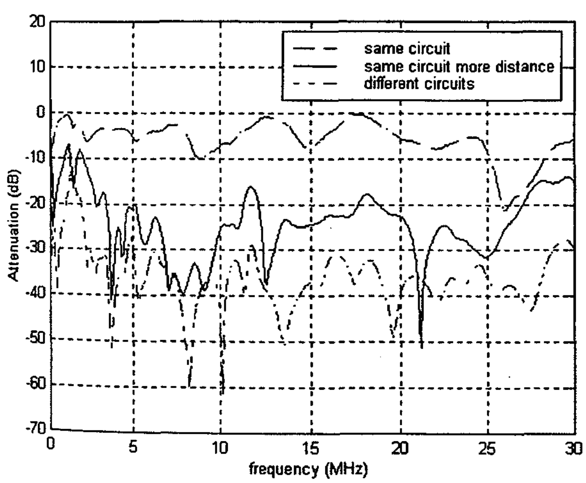

Figure 4: Amplitude response for three different channels measured in an apartment. Transmitter and receiver were located in different electrical circuits and positions.

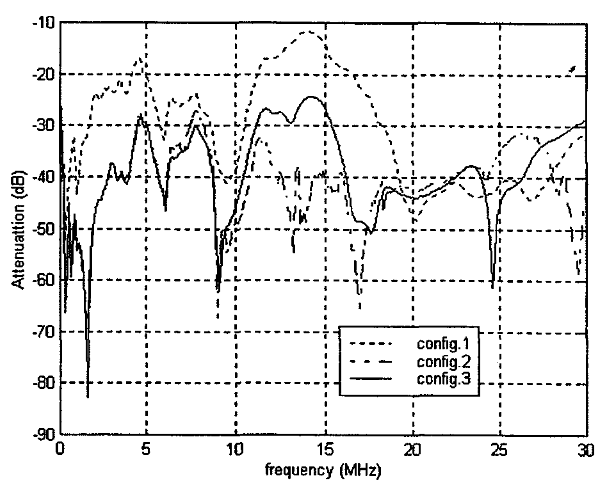

Figure 5: Amplitude response for a power line channel measured in the laboratory with different configurations of load.

Noise power spectra have also been measured in different environments. The plots usually (but not always) show a descending spectral power density as frequency increases. These facts suggest that the system should avoid both the low frequency band, and the amplitude notches. In Fig. 6 an example of the recorded data in the laboratory is depicted, whereas in the next figure, the results obtained from an apartment in the same socket but in a repose state (config. 1), and a noisy active state (config. 2) are presented. In Fig. 7 config. 1 no remarkable appliances were connected to the power network (except the fridge, some incandescent lights...), and this is why the noise level is quite low. Although some narrow band disturbances are observed, possibly caused by radio interferences (e.g. peaks appeared when activating a cordless telephone). On the contrary in config. 2, additional devices were plugged in he vicinity (a microwave oven the most important), and the registered noise is drastically increased.

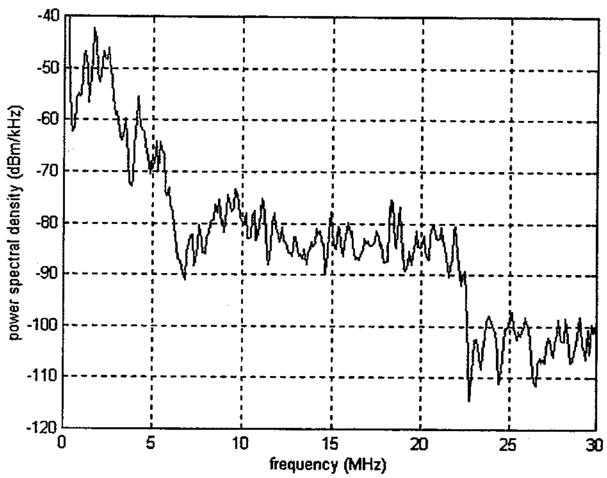

Figure 6: Noise measured in the laboratory

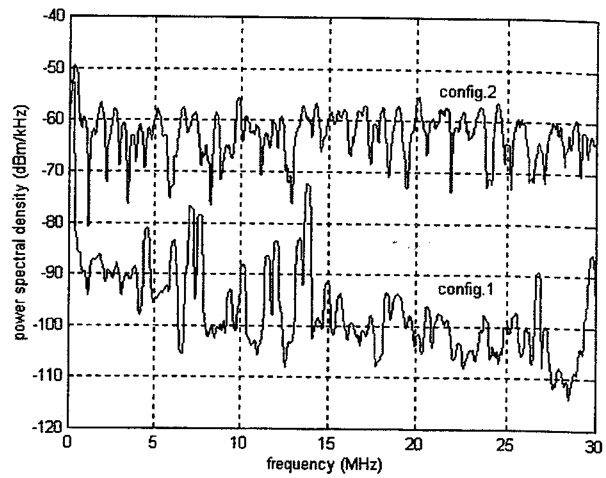

Figure 7: Noise measured in an apartment in the same situation, but in config.2 additional electrical appliances were turn on.

4. Channel capacity analysis

Channel capacity is the upper bound in digital transmission, hence models and measurements results are used to estimate the spectral efficiency (b/s/Hz) attainable. The signal launched into the power network by the transmitter is supposed to have a flat power spectral density of –20dBm/kHz (a not excessive value, but higher than allowed by current regulations [6]). Three scenarios have been chosen to illustrate power line communications capability; data in all cases are extracted from measurements.

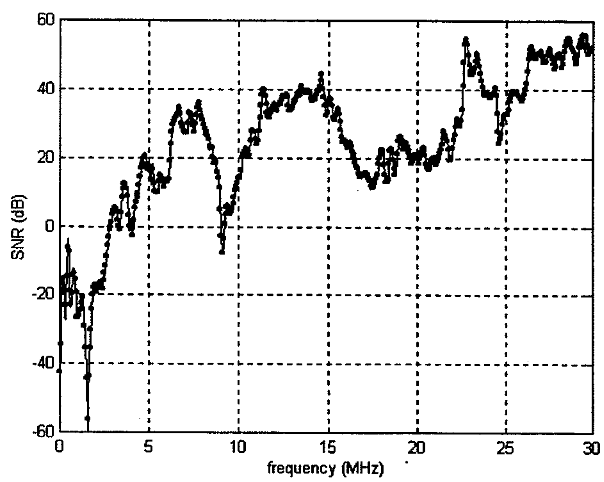

Figure 8: Channel signal to noise ratio for a laboratory measurement.

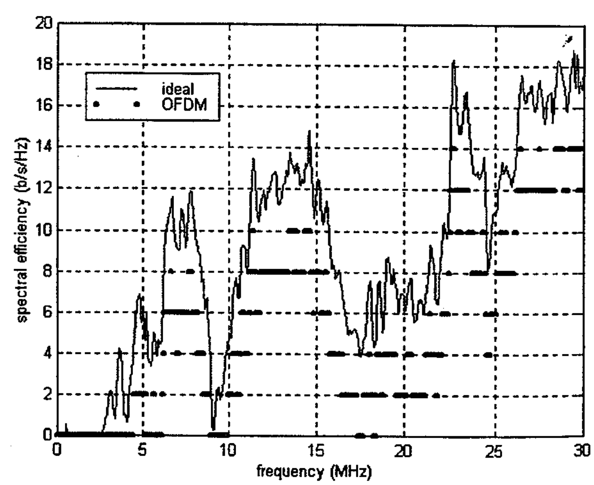

Figure 9: Respective channel capacity estimation.

The Shannon theorem has been applied to calculate the maximum ideal capacity, along with a more practical approach, which is to use an Orthogonal Frequency Division Multiplexing (OFDM) scheme for transmission, also known as Discrete Multitone (DMT). OFDM is a good technique over spectrally shaped channels [7]. It is based on partitioning the data rate before digitally modulating (in general with QAM) several carriers in narrow subbands (in which the channel characteristics can be considered uniform), which are then multiplexed to create an OFDM symbol. A convenient number for the studied bandwidth is 512 subchannels. In order to avoid intersymbol interference, a cyclic prefix (whose length depends on the channel impulse response duration) should be added, what reduces the overall capacity. An error probability of 10^{-6} has been assumed for the calculations, and the channel impulse response duration has been estimated to contain 99% of the total energy.

First results are depicted for the channel at the laboratory (the 3rd configuration in Fig. 5, and noise in Fig. 6). The signal to noise ratio measured is presented in Fig. 8, and the corresponding channel capacity in Fig. 9. The decay of noise with increasing frequencies suggests a higher bit load in this part of the band. Moreover, for efficient transmission, the frequency notches have to be removed. The averaged spectral efficiency with this procedure is 2.2 b/s/Hz (with Shannon limit is 4.4b/s/Hz), resulting in a total capacity of more than 60Mb/s.

From apartment measurements the channel capacity is analysed for the same configuration (Fig. 2), but with two different noise environments: best case (with noise of config. 1 in Fig. 7) and worst case (with noise of config. 2 in Fig. 7). Both of them involved a transmission distance of about 15-20m. In the first channel conditions, no appliances were connected to the power line, and that implies more favourable conditions for signal transmission as observed in Fig. 10. Hence a higher spectral efficiency is registered (Fig. 11) and there are no empty bands. The averaged value is 6.2 b/s/Hz using OFDM (9.1 b/s/Hz in the ideal case), which means a total capacity of almost 200Mb/s. In contrast, the second channel studied has to face strong disturbances produced by several loads, and this is why the signal to noise ratio measured is much lower, Fig. 12, (becoming negative for some frequencies). Consequently, the channel capacity is hardly 45Mb/s (or 1.5 b/s/Hz, and Shannon limit equals to 3.5 b/s/Hz).

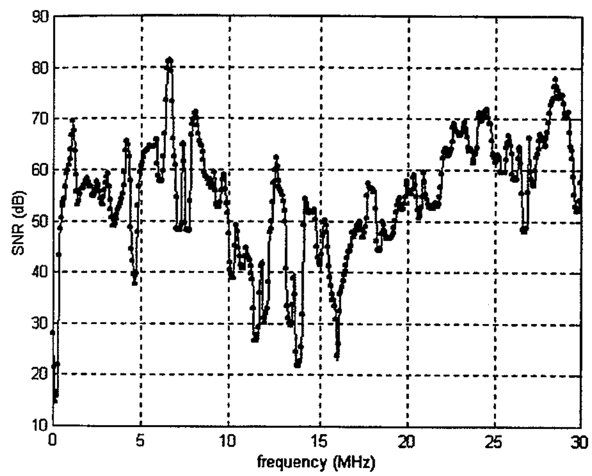

Figure 10: Channel signal to noise ratio for an apartment measurement. Best conditions of load

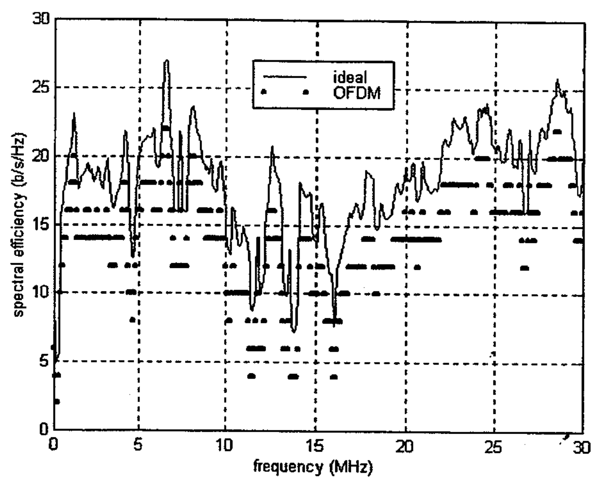

Figure 11: Respective channel capacity estimation.

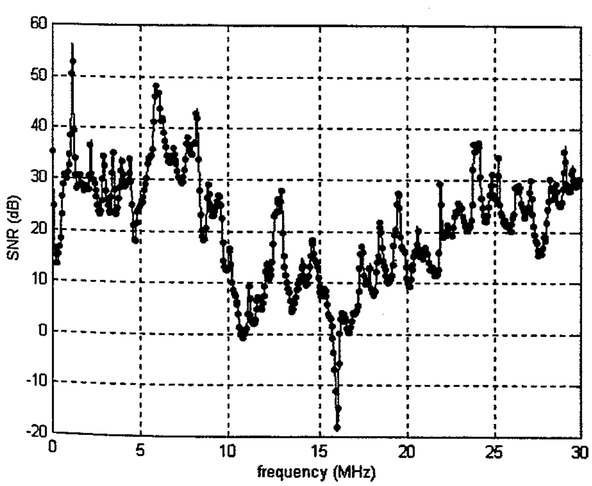

Figure 12: Channel signal to noise ratio for an apartment measurement. Worst conditions of load.

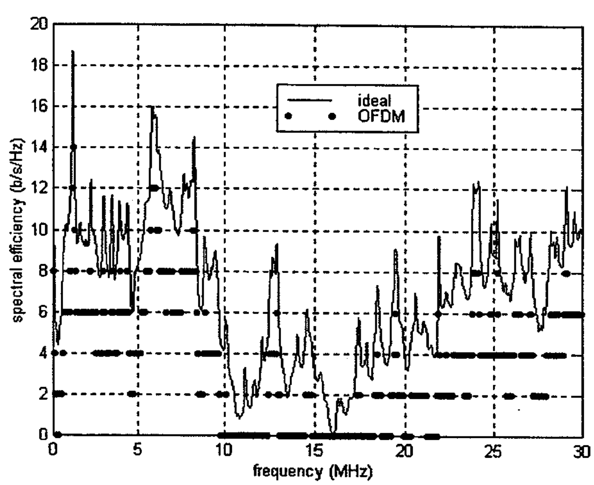

Figure 13: Respective channel capacity estimation.

These results confirm the good opportunity that power lines represents for broadband communications. Anyway, the distances contemplated in the analysis are not too long, so it could be expected to find lower channel capacities when using larger power grids.

5. Conclusions and further work

In this work, a method to achieve impulse responses for indoor power line channels has been proposed. The explained procedure allows obtaining communication system parameters directly from the physical characteristics in typical electrical wiring inside residential buildings. It has been used to model some real channels and verified with measurements. The results show remarkable characteristics of these channels: spectrally shaped responses with high attenuation level even in short distances, great dependence on the environment, time variation and important noise. The channel response simulations are being completed with noise models, estimating the source features from measurements of several electrical appliances (impedance and emission level). In spite of the chaotic appearance and strong disturbances in the channel, the signal to noise ratio in some portions of the spectrum up to 30MHz would be enough to provide reliable high bit rate communication.

In the channel capacity analysis here presented, theoretical approaches and more practical ones (adoption of discrete multitone with QAM) have been considered, demonstrating that transmission at tens of Mb/s could be feasible. However, this capacity may change seriously with time, due to the connection and disconnection of the loads and noise sources (electrical devices mainly), what leads to think about the application of an adaptive transmission technique, for example variable rate OFDM [7].

6. References

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