Modelling and Evaluation of Indoor Power-Line Transmission Medium

Francisco Javier Cañete, José Antonio Cortés, Luis Díez, José Tomás Entrambasaguas

1. Abstract

The aim of this article is to outline the possibilities of indoor power lines when used to support local area networks at homes or small offices. For this purpose, the channel characteristics are described and a channel model is presented. This model is related to the physical nature of common indoor power lines, so that its parameters can be defined in a straightforward way. Based on it, performance of communication systems that use discrete multitone modulation, which appears to be the most suitable technique for these channels, is evaluated. Finally, a discussion about medium access control strategies is included.

KEYWORDS: power line, broadband digital communications, home LANs, channel modelling and measurements, time variant channels, DMT, MAC.

2. Introduction

Nowadays, technology in homes is demanding new communication solutions. It is not strange to find more than one personal computer claiming for interconnection and resource sharing. This necessity involves multimedia data interchange (video and audio distribution, multiplayer gaming, and other general purpose applications data), the use of communal peripherals (printers, scanners…), and obviously, access to the Internet. In the future “smart home”, there are also other services related to automation systems that require connecting several devices (sensors, controllers, etc.). The power-line network can easily offer enough bandwidth to support all these integrated services without the installation of additional wires.

The utilization of the power grid for communication purposes is not a new idea. In fact, utility companies have been using the medium and high voltage distribution lines for operation and maintenance, metering and load management since long ago. Recently, the fall of PTTs (Postal, Telegraph and Telephone) monopolies in Europe has opened new possibilities for them: to offer access to wide area telecommunication networks through the low voltage distribution lines, so to compete with other “last mile” technologies like DSL (Digital Subscriber Line), wireless local loop, or telephone lines.

However, the focus of the presented work is not on outdoors applications like the one mentioned above, but on indoors ones. In this group, some systems have been developed according to international standards restricted to narrow band, like Cebus (Consumer Electronic Bus), EHS (European Home Systems) and X10. Further research has been made to extend the data rate, and there are new commercial standards, like HomePlug, and products that offer more than 10Mbps. Most of these systems make use of sophisticated transmission techniques (with high spectral efficiency and adaptive modulation formats, robust coding, etc.) to face the difficulties of a medium not designed in principle to manage high frequency signals. Actually, international regulations for these latter systems still have to be upgraded (which seems to be an imminent task), because the current ones in Europe severely limit the available band for communication purposes (about 150kHz [1]), or the power spectral density (PSD) for any conducted signal [2]. In North America, this latter restriction is less stringent, which has allowed the launch of power line modems.

This study of indoor power-line communications is organised in three main parts, covering the description of the physical nature of the medium, the modelling of the channel and the analysis of adequate transmission techniques.

3. Description of the medium

The fact that indoor power lines were not conceived for communication purposes makes their characteristics certainly peculiar. The channel is time and frequency variant, and exhibits remarkable disparity between locations, according to its network topology, the type of wires and connected loads. Even in a specific site, different characteristics can be found depending on the selected transmission path or the momentary status of connection of the electrical appliances. In the following, the nature of the power grid when used to transmit signals in the frequency band up to 30MHz (a usual limit for conducted emissions) is explored in more detail.

3.1. Physical structure

In power-line transmissions, the link is commonly established connecting the transmitter and receiver subsystems to the power grid, using the line and neutral conductors. The layout of the wiring is usually not known precisely, but generally, there are several circuits extending from the main connection to the external lines, as depicted in fig.1. Hence, the network has a tree-like structure, which may be seen as the connection of multiple transmission lines ending in a certain complex impedance value, according to the particular device plugged in the socket.

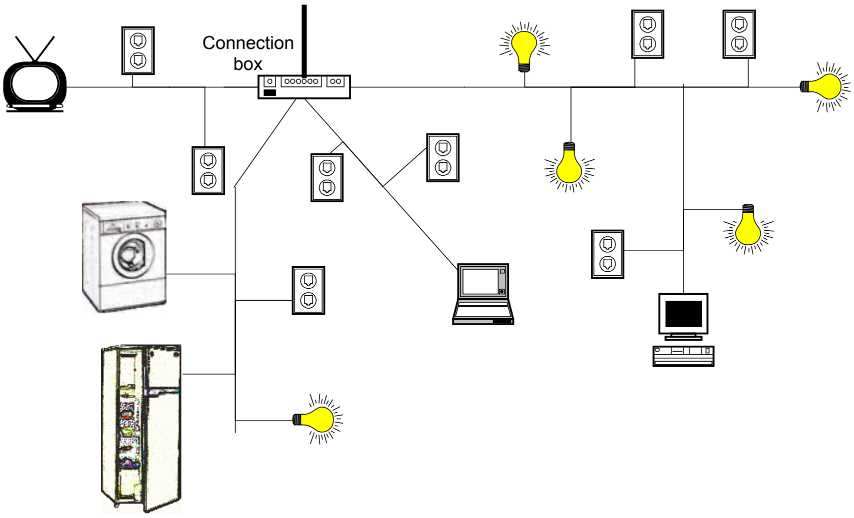

Figure 1: Simplified diagram of typical layout of an indoor power network.

The number of elements in the network and their characteristics (for instance branch length, relative position, sort of wire, type of load, etc.) will determine the frequency behaviour of the channel. In any case, the attenuation is usually very high, even when the involved distance is short, due to the high number of “branches” in the network and the absence of impedance matching. The impedance value presented by the appliances is quite diverse, with absolute value ranging from few ohms up to kΩ’s. The mismatch level, or reflection coefficient, at the discontinuities depends on this value and the characteristic impedance of the power line, typically about 200Ω.

In general, isolation between power lines of neighbouring homes is not guaranteed by the usual electric devices (switches, meters, etc.). Thus, additional circuits are needed to prevent conducted interference. However, there may be also interference coupled by radiation, which makes more difficult this task.

3.2. Channel response

The structure of electrical circuits has remarkable influence on the channel response, causing linear distortion of amplitude and phase. Multipath propagation phenomena appear due to the reflections that a signal suffers in every branch, empty socket or load encountered along the direct path from transmitter to receiver. The resultant impulse response of the channel consists in several delayed echoes of the main impulse, what means a frequency response with deep “notches” of high attenuation [3,4]. The shape of these responses bears resemblance to the habitual ones in other multipath channels like those of mobile radio. More than the link distance, the relevant factors for the variation of the attenuation with frequency are the number of branches and their relative situation, lengths and loads. All these properties can be observed in fig.2, where some channel responses are plotted. There are no frequency bands better than others a priori. It can be said that the probability of encountering a high level of attenuation is similar for the entire spectrum under study.

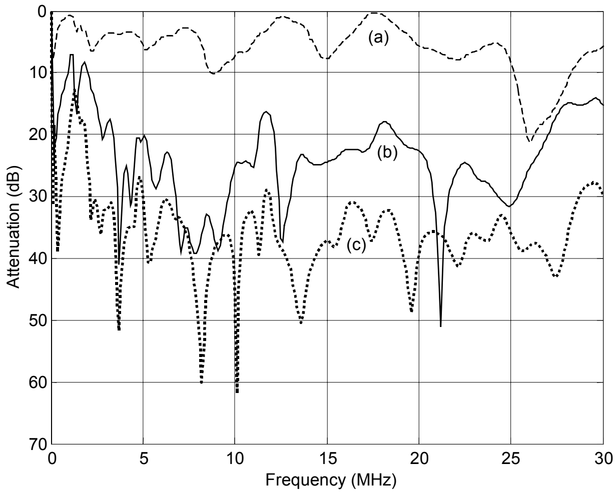

Figure 2: Amplitude response for three measured channels in an apartment: a) through the same electrical circuit, b) with more transmission distance, c) through different circuits.

3.3. Disturbances

The existent noise in power line communication is far from being the typical AWGN (Additive White Gaussian Noise) [5]. It is strongly coloured, and is caused mainly by the appliances plugged in near to the receiver. It has multiple impulsive components that can be classified in: periodical noise synchronous with the mains frequency (due to devices with rectifiers), periodical noise non-synchronous with the mains (due mainly to switched power supplies), and non-periodical impulsive noise (due to connection and disconnection of noisy loads or any other sporadic event). The remaining part, of unknown origin, may be considered as a background noise that has a spectrum decreasing with frequency.

There is also narrow band interference from external sources of radio waves that are captured by the wires. In this sense, it must be mentioned that, despite the frequency range used by the system, power wires are extremely prone to receive signals in bands above 30MHz (commercial FM for instance). Hence, special care must be taken in the specification of receiver filters in order to prevent disturbance caused by unwanted higher frequency signals.

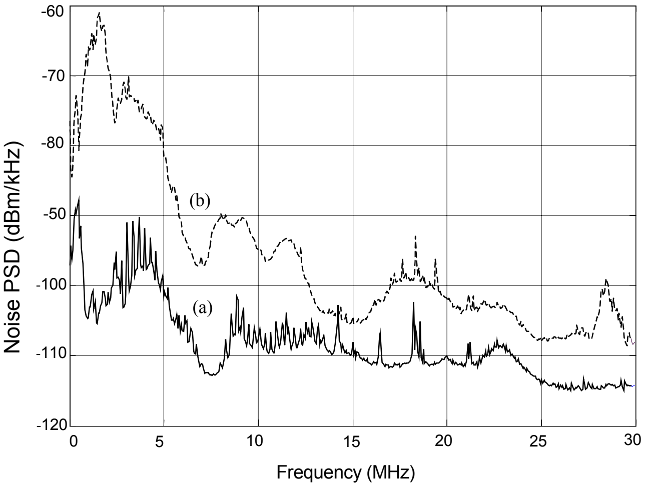

Figure 3: Measurements of indoors background Noise PSD: a) in an apartment, b) in a university laboratory.

The noise power spectral density (PSD) measured in certain locations can be observed in fig.3. The enhancement in low frequencies is clearer in the laboratory (mainly equipped with personal computers, so it can also represent offices), where there was more activity. The noise generated by most common appliances has been registered [4] and the results exhibit significant differences. There are devices with low noise level like standard lamps, heaters, small electronic apparatus (radios, alarm clocks…) and others with emission levels many dB over the background noise, like light dimmers and microwave ovens. All of them have been analysed to obtain a database to be used in the channel model described later.

3.4. Time variation of channel parameters

In the analysis of the time variation of power line channels, two main phenomena should be considered. The first is the long-term variation caused by the connection and disconnection of the devices or loads. This implies a change in the channel response, usually frequency selective (i.e., not in the entire band), and more remarkable the nearer to the receiver the load is. Correspondingly, when the load generates a high level of disturbance, its changes of status produce significant variations in the received noise level. However, the rate of these changes is usually rather lower than the bit rate of the system, so the channel can be assumed stationary between them.

The second aspect is a short-time channel variation synchronous to the mains frequency. This effect is related to the characteristics of the loads. Although some of them exhibit a non-linear behaviour, the fact that the large signal component of the actual signal is periodical (230V and 50Hz in Europe), allows one to consider the channel as linear but periodically time variant.

For certain frequency bands (and depending on the power line under study), the fluctuations observed in the channel transfer function from one instant of the mains cycle to another exceed 5dB. Besides this time dependency in the channel response, a cyclostationary term appears in the received noise, although their level of variation is usually below the one produced by loads connection changes. Anyhow, fluctuations of more than 20dB have been registered in offices environments, making it clear that they must be taken into account when designing an efficient transmission system.

4. A channel model proposal

The traditional way to develop a model for communication channels is to make an extensive campaign of measurements in different configurations, from which analytical or statistical parameters are extracted [6,7]. In the case of power lines, the possible arrangements for actual channels are so large that this approach may not be justified, since it would be difficult to adapt the mathematical parameters for a channel of different nature. Thus, an alternative solution is proposed: to adopt a model related to the physical parameters of indoor power lines and derive from it the final channel characteristics. The model is applicable to any network configuration with just approximate knowledge of their size, number of electrical circuits or sort of cables.

4.1. Network topology

The physical model is based on the consideration of the low voltage power grid inside buildings, as a network of multiple sections of transmission lines interconnected and terminated in loads of diverse nature. Its structure has been designed to be quite versatile to adapt to the topology of the networks under study, and to allow a complete mobility of the transmitter and receiver, as well as the existing loads, among the different sockets.

The basic transmission line that has been contemplated is a two parallel wires structure, whose parameters have been estimated from typical electrical cables data sheets used in real installations. The length and relative position of the different sections will define the network layout, usually arborescent, which is configured having in mind the arrangement of real ones. This layout can be modified by selecting its parameters for any possible installation, changing sort of wires, lengths, connections, etc. It is interesting to select them randomly in a range of values, defined from general characteristics of indoor power lines (of apartments, detached houses, small offices…). In this way, the model can be used for the statistical analysis of their behaviour.

4.2. Loads

The sockets, or terminal nodes, are considered the access points to the channel where transmitter or receiver equipment or loads can be located. Every device connected to the power grid represents a load to the network, whose model includes besides impedance values, noise sources associated to them (like Thèvenin-equivalent generators). These frequency and time variant values have been obtained directly from measurements of typical electrical loads. Some of them have constant impedance values as long as their connection status does not change, but others exist that present a cyclic variation of their value according to the mains frequency. Regarding the generated noise, an analogous behaviour is observed: the former group of devices introduce a stationary noise, but the latter group generates noise with cyclostationary and impulsive components.

Moreover, the load model implies a form of long-term variation in the channel, in the sense that is quite slow in relation to the communication signal bit rate. Clearly, the channel conditions change through the course of the day, when appliances are switched on and off, which represents a state transition, and therefore a new channel. In general, only two states would be necessary to describe each device influence: active or not. Transitions between states are considered events that occur as random sequences, and transition rates for each load are estimated according to common behaviour at homes (based on human activity periods during the day) [4].

4.3. Equivalent channel

After the physical structure of the power-line network has been modelled, the transmitter and receiver locations are selected in order to define the link. Then the channel responses for the signal path [H(f,t)] and for the path seen by the different noise sources [H_{Nj}(f,t)] are calculated, which constitutes the base of the mathematical model, as depicted in fig. 4.

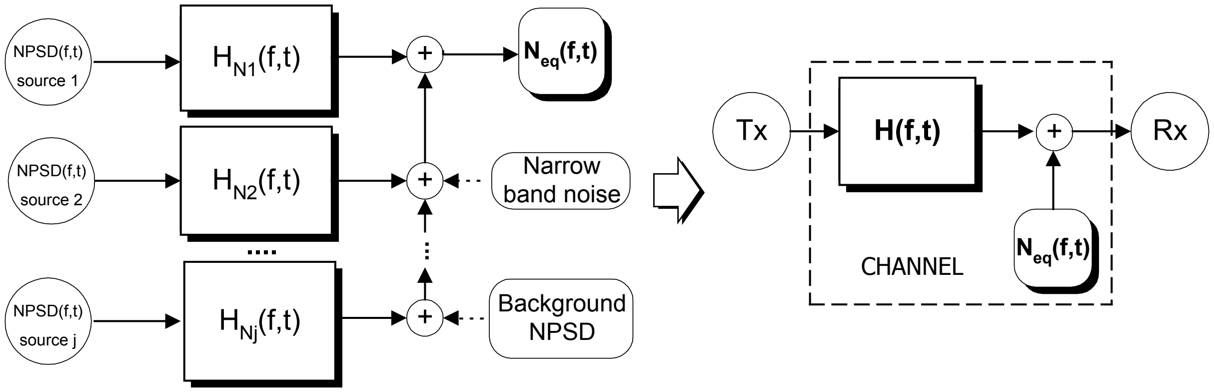

Fig. 4: Complete time-variant channel model.

The channel has been supposed to have a linear response (because available measurements indicate that non-linear effects, apart from the ones that cause periodicity, are negligible). With this assumption, the superposition principle can be applied to the noise sources (measured in terms of noise power spectral density NPSD(f,t)) to obtain the total equivalent noise at the receiver [$N_{eq}(f,t)$].

Other noise components, whose nature can not be related to the loads in the network, are quantified from the carried out measurements, and are directly summed: narrow band interference and background noise. Given that narrow-band interference origin is mainly radiation, our channel model based on conducted signals would not be appropriate. Hence, this parametric approach is adopted.

The channel time variation can be modelled by means of two superimposed effects: the one motivated by the load transitions, i.e., time evolution of the channel is an ensemble of successive random channels, and the second, which is a periodical variation (synchronous to the mains frequency) during these stationary states. Both time variation components are applicable to the channel response and the received noise, and are weighted randomly but in proportion to the measurement results over real indoor power lines. As an example of the channel evolution in a home power-line, samples of the amplitude response obtained along a period of 48 hours of simulated time are shown in fig. 5. Differences larger that 15 dB are observed for several frequency bands.

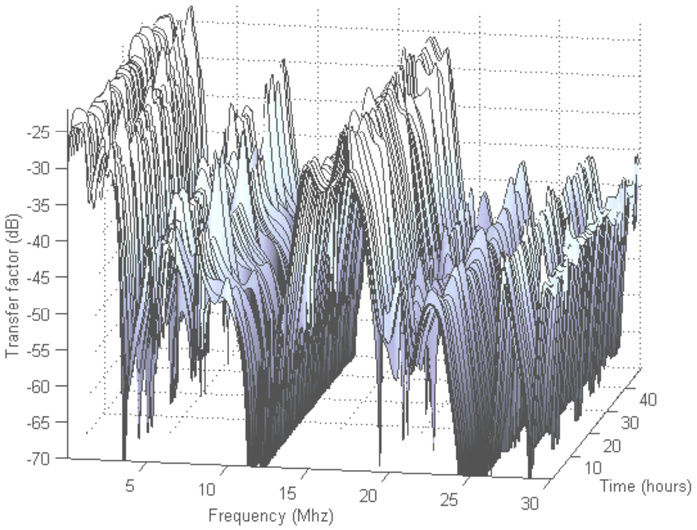

Figure 5: Time evolution of a residential channel.

The final objective of the model is not to exactly match a particular channel configuration (which would not be very reasonable due to the great sensitivity of channels respect to its physical conditions even in the same power network), but to serve as a generator of feasible channel models. However, and in order to guarantee its validity, the model has been tested by contrasting its results with the actual measurements for a certain home power-line [4].

5. Transmission techniques for power lines

To cope with the aforementioned impairments several transmission schemes have been explored. Due to the severe intersymbol interference (ISI) caused by the strong dependence of the attenuation with frequency, single-carrier modulations are not appropriate for broadband communications over power-line channels. In addition, because of the short symbol times needed to attain high bit rates, they become extremely vulnerable to impulsive noise.

Spread spectrum modulations and CDMA (Code Division Multiple Access), their natural multiple access technique, have aroused considerable interest in the last years. The low PSD of the transmitted signal, required to comply with the EMC regulations, and their greater immunity to multipath fading and ISI, compared to single-carrier systems, makes them adequate candidates for power-line communications. On the other hand, they do not take advantage of the spectral shaping of the power-line channel, in which signal-to-noise ratio (SNR) differences among bands may be up to 40dB. However, the most serious drawback of these schemes arises in a multiuser environment, where the desired signal received from a distant user may be completely hidden by the interference caused by a close transmitter, which may be tens of dB stronger.

Multicarrier modulations seem to be the best transmission schemes for broadband power-line communications. Accordingly, nearly all modem manufacturers in this area have selected any of their two very common forms: DMT (Discrete MultiTone) and OFDM (Orthogonal Frequency Division Multiplexing). The basic principle is to divide the available spectrum into subbands or subchannels. Those subbands with EMC problems or deep notches are left unused. Therefore, even when the spectral resources are sparse they can be fully exploited. An additional consequence of the division into parallel subchannels is that the symbol length becomes longer. Hence, their sensitivity to impulsive noise and ISI is reduced. On the other hand, the decoding delay increases (although it still remains acceptable for most applications) and, as the resulting signal is the sum of a large number of independent components, it exhibits a large peak-to-average ratio (PAR). Nevertheless, there are several methods that successfully control this effect.

5.1. Discrete MultiTone modulation

In DMT modulation, the incoming data flow is divided into several streams, each of them used to modulate different carriers that are transmitted simultaneously [8]. The number of bits assigned to each carrier is selected according to its SNR. Moreover, the bit distribution may be changed with time to minimise the effects of the channel variations on the performance. DMT employs rectangular pulse shapes and carrier frequencies that are multiple of the symbol rate. This reports two important benefits. Firstly, the spectra of the modulated carriers overlap but are orthogonal and, secondly, the modulation and demodulation processes can be efficiently implemented by means of the Fast Fourier Transform (FFT) and IFFT.

However, when the signal passes through a dispersive channel, ISI and intercarrier interference (ICI) appear. These effects can be avoided by inserting a cyclic prefix (CP) between each DMT symbol. The CP is a sort of guard time, removed at the receiver, that consists of the repetition of the last part of the following DMT symbol. As long as the CP remains longer than the memory of the channel it will absorb the transient at the beginning of each symbol. Equalization is then easily performed by a one-tap filter per carrier that compensates for the attenuation of the channel.

Unfortunately, the actual impulse response of power-line channels is of significant duration. This means that very long CP’s would be needed and, since it conveys no information, performance may be seriously affected. To handle this situation, not exclusive to power-line channels, time domain channel shortening techniques have been adopted in systems like ADSL [9]. The time domain equalizer (TEQ) is a FIR filter inserted before the demodulator block (even before the CP discarding). The aim is to constrain the impulse response of the cascade connection of the TEQ and the channel to a length shorter than the cyclic prefix. In practice is not possible to achieve this objective and some residual energy will remain out of CP after the equalization process.

5.2. DMT parameters for power lines

One of the main aspects in the design of the DMT transmission scheme is selection of the number of carriers and the cyclic prefix length, whose values play an essential role in the bit rate achieved by the system. Their optimum values depend on the channel characteristics. Increasing the number of tones reduces distortion but may lead to an impractical implementation complexity and excessive delay. The cyclic prefix has a twofold impact on the bit rate. On one hand, expanding its length reduces DMT symbol rate and the amount of energy available for the detection process. On the other hand, it decreases ISI and ICI, allowing a higher number of bits per tone.

In order to determine the most adequate values for these parameters, the channel model described in section 4 has been used to generate a large number of indoor residential channels in the frequency range up to 30MHz. The influence of the number of carriers and cyclic prefix length (without using a TEQ) in the bit rate has been assessed for all of them. Representative curves are depicted in fig.6.

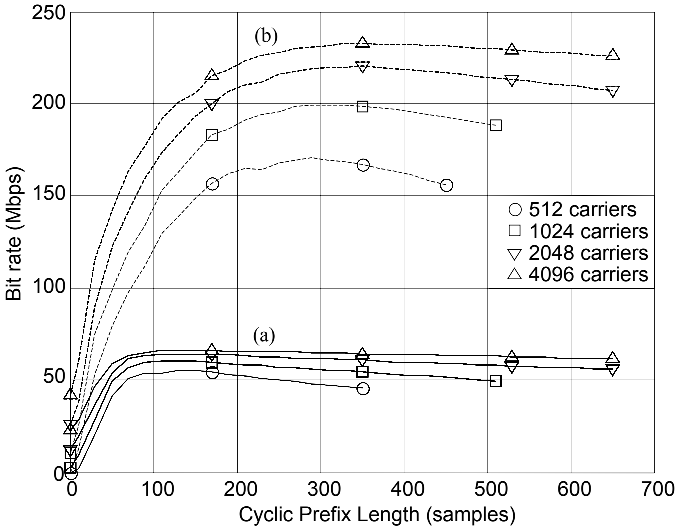

Figure 6. Bit rate versus cyclic prefix length for several number of carriers (at a sampling frequency of 60MHz): a) high noise scenario, b) low noise scenario.

As expected, the most appropriate length of the cyclic prefix is different for each particular channel. Specifically, the optimum value, which is in the range of 130 to 350 samples (at a sampling frequency of 60MHz), depends on the length of the channel impulse response and on the SNR profile. Increasing the CP improves the bit rate only if the power of the remaining ISI and ICI stays much greater than that of the noise introduced by the channel. Once the contribution of the latter term dominates, lengthening the CP is counterproductive because the DMT symbol rate and the available energy are reduced without profit. However, from fig.6 it can be inferred that around 200 samples would be an adequate trade-off for most channels. Obviously, there will be noise limited channels with poorer performance (and shorter optimum CP lengths) than the one in fig.6 (a), but selecting those CP values would degrade the performance of the rest of channels (which are the majority) to an inadmissible extent.

Regarding the number of carriers, it can be noticed that significant gains can be obtained when going from 512 to 1024 tones. From this point on, bit rate gains tend to reduce and the increment in the implementation complexity may not be worthwhile.

In an attempt to shorten the preceding CP's, the use of a TEQ has been investigated. It can be concluded that the TEQ is not a good option for power-line channels, since greater improvements in the performance can be obtained with reduced computational complexity alternatives like doubling the number of carriers.

5.3. Medium access control techniques

Before using the mains in a multiuser environment, the duplexing scheme and the medium access control (MAC) strategy must be selected. Concerning the first aspect, TDD (Time Division Duplex) is the most convenient option. The main reason is the considerable ICI that a transmitter causes on its own receiver when using the FDD (Frequency Division Duplex) method in power-line scenarios.

In relation to MAC techniques, the straightest approach would be to use a random access algorithm, similar to the CSMA/CA used in the IEEE 802.11 wireless LAN standard. This scheme is very simple but, since it does not take into consideration link characteristics, it may result in a quite unfair sharing of the medium. In order to provide each user with a bit rate according to its necessities, a dynamic TDMA strategy that makes use of reservation procedures can be employed. The basic idea is to divide time up into uniform slots. During a particular slot, whose duration is several times the DMT symbol period, only one user occupies the available bandwidth. There exist special intervals in which users exchange information about their profiles (e.g., performance of their channels, requested bit rate and priority) and, based on a preestablished algorithm, agreed on the slot distribution.

Since unused carriers in a certain link (because of their low SNR) may experience acceptable SNR in other links, the preceding scheme is actually wasting capacity. Hence, a straightforward extension would be to allow a "secondary" user to utilise the remaining carriers. The price to be paid is the increment in the signalling among users and the multiple access interference (MAI) that, in the form of ICI, the "secondary" user may cause on the "primary" one.

The above strategy is just an intermediate step towards a more general one in which the available bandwidth is shared among all the users. This is the so-called DMT-FDMA and, theoretically, it achieves the highest performance. However, it has very serious practical problems. Firstly, even in the case of synchronised transmissions, link characteristics may be severely degraded by the MAI caused by other users. Secondly, the optimum carrier allocation scheme is a non-linear optimisation problem [10] with thousands of unknowns. Moreover, even when suboptimal linear programming approaches are applied, the MAI between users obliges use of iterative procedures. In addition, since per-carrier information must be exchanged in each iteration, the amount of signalling is considerably higher than in DMT-TDMA. Therefore, although theoretically suboptimal, DMT-TDMA approaches seem to be the most feasible option.

6. Conclusions

The real possibilities of indoor power lines as a LAN alternative will depend on multiple factors, like the final cost of the modems or its possibilities to reach the market. Nevertheless, the comparison of its performance with other LAN strategies gives a promising indicator. In this sense, although existing power-line products achieve tens of Mbps, studies carried out with DMT modulation conclude that there is still room for improvement. Specifically, it seems that the ability of systems to exploit the short-term variations of the frequency response and cyclostationary noise component may play a notable role in their final performance. Besides this, significant enhancement can be obtained by using adequate transmission and MAC schemes that take into consideration the needs of the users and the characteristics of their links.

7. Acknowledgements

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9. Biographies

Francisco Javier Cañete Corripio received the M.S. degree in telecommunication engineering in 1996 from the University of Málaga. In 1997, he joined its Communication Engineering Department, where he is currently working toward the Ph.D. degree. From 2000 to 2001, he also collaborated in the Nokia System Competence Team in Málaga. His research interests include digital and mobile communications and channel modelling mainly focused on high-speed transmission through power lines.

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José Tomás Entrambasaguas Muñoz received the M.S. and Ph.D. degrees, in 1975 and 1990, respectively, both from the Polytechnic University of Madrid, Spain; where he worked from 1975 to 1978. In 1978 he joined Fujitsu-España R&D center, working in packet switching, transmission systems, and local area networks. In 1993, he joined the University of Málaga at the Communication Engineering Department, where his current interests include digital signal processing, digital communication and methodologies for efficient development of complex communications systems.