A Time Variant Model for Indoor Power-Line Channels

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Abstract.- The subject of this paper is the utilisation of the low voltage distribution lines inside the consumer premises for high bit-rate digital communications. Specifically, a model useful to simulate the behaviour of this kind of communication channels is presented. The model contemplates the topology of the power grid and the characteristics of the wires and loads connected to them, so that both the channel response and the noise received can be obtained. It is possible to study also the dynamic evolution of the channel, because the model incorporates statistics of time variation of loads.

Key words.- Power line communications, wide band, channel modelling, channel response, noise, measurements, statistics, time variation.

1. Introduction

Nowadays, power-line communications have become the focus of remarkable investigations trying to improve previous applications restricted to low data rates. However, the existence of international regulations [1], which limits the available spectrum for these purposes, reduces the possibilities of practical systems by now, although this situation is supposed to change in the near future. It is necessary to mention that power lines, (designed to deliver electrical energy, not to transmit information) represent a quite hostile medium for communication signals, and its characteristics depend drastically on the specific location selected. In particular, these channels exhibit important variations with frequency, link distance and time. These aspects have been investigated both in the distribution grid outside customer premises [2], and indoors [3,4].

A software model, based on the consideration of the low voltage power grid inside buildings as a network of multiple connected transmission lines, has been developed. It is quite versatile for designing the topology of the lines to study, so that good approximation to real conditions can be obtained. Noisy loads, with impedance and noise level frequency variants (whose values can also change whether they are in active state or not), can be connected to any socket in the model, likewise transmitter and receiver. In this manner, the channel response at high frequencies and total noise at receiver can be calculated.

The channel model is described in next section, where the representation of the network topology and loads is explored as well as the dynamics of the system. Some results obtained from simulations are presented in section three, and finally some conclusions can be found in the fourth section.

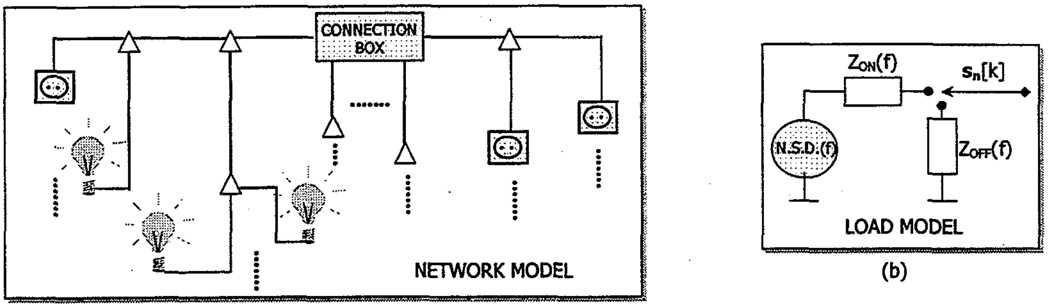
2. Channel Model Description

Opposite to preceding work in the field of power-line channel modelling [5,6], where parametric methods have been used to estimate the channel transfer function, here a more physical approach is studied. This paper presents an improved model respect to [4], including almost total flexibility in the network topology layout, noise sources, and time variation.

2.1. Network model

The considered model is based on the assumption that electric wires are a set of multiple transmission lines, interconnected to produce a tree-like network (see Fig.1.a). The transmitter and receiver are going to be coupled to the power grid, between neutral and line conductors, through corresponding frequency variant impedance. In the transmitter part, this impedance is obtained from measurements of the output load of typical signal sources plus a coupling circuit [4], while in the receiver part, the input loads of the coupling unit and signal analysers were measured.

The network has been programmed as a data structure, which contains many nodes of different classes: a root node, that represents the connection box (the interface with the outside mains), intermediate nodes that represent junctions, and terminal nodes, the last two with an associated section of line. Each of these nodes is described by its type of wire, length, its ascendant and descendant nodes, and, if it is a terminal node, by its impedance and change probabilities. The transmission lines parameters are taken from characteristics (diameters, materials...) of common electrical cables used in real installations, and their length and relative position should be estimated from layouts.



(a)

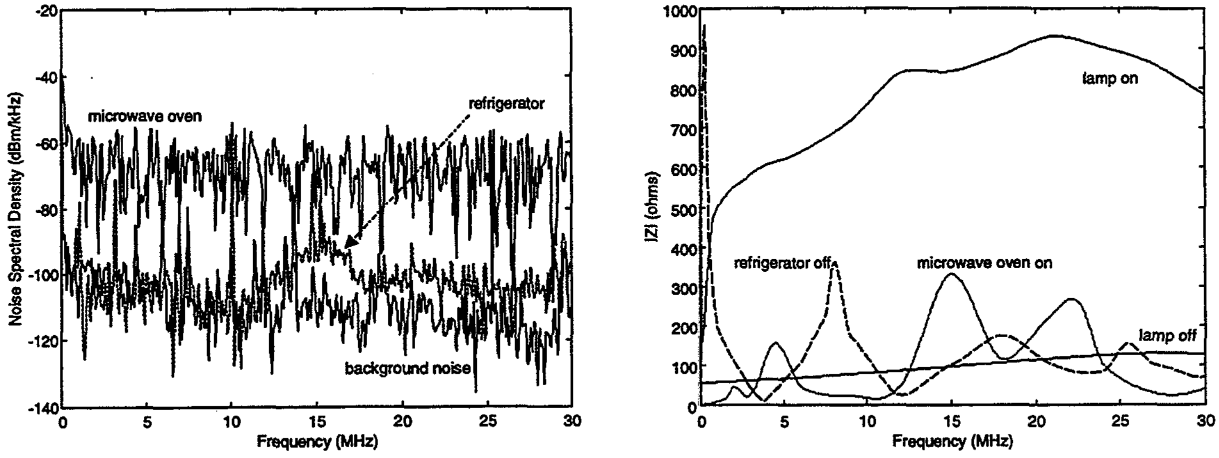
(b)

Figure 1. Simplified model of network topology, and load model.

The sockets, terminal nodes, are assumed access points where either transmitter or receiver equipment or loads can be located. The connected loads (fig. 1.b) can be selected from a set of possible values of complex impedance dependent on frequency and the status of the load. These have been recorded from measurements of typical electrical appliances (e.g. lamps, TVs, PCs, etc.) at home (fig. 2.b), with a network analyser and an auxiliary circuit (similar to the so-called LISNs) that allows to energise the device on working state. So the arborescent nature of real power lines is approximated in a faithful way. And once the signal path has been set, the branches of the tree have to be collapsed, moving the impedance through the lines, in order to attain the channel transfer function.

2.2. Noise model

It is well known that the model of Additive White Gaussian Noise (AWGN) is not adequate for power-line channels [2,3,4], so a different proposal is presented in this work. Noise sources can be associated to every load (Fig.1.b), whose power spectral densities (NSD) have been measured as well, with help of a set-up similar to the one used for the characterisation of the loads. A high number of appliances have been analysed, among which, for instance, the noisiest ones are the microwave oven or the light dimmer. The washing machine produces a medium level of noise, while the less noisy devices, in that broadband scenario, seem to be incandescent lamps or even TVs and PCs.



(a)

(b)

Figure 2. Measurements of load characteristics at home: **a)** Noise power spectral density, and **b)** Impedance values against frequency for several examples.

In Fig. 2, the NSD of some of them is shown, and they are in good correspondence to other studies [7]. Some samples of impedance values, associated to the sources, are plotted as well. It is observed that loads characteristics are quite diverse. They range from few Ω, under the mean characteristic impedance of the lines (about 200Ω) that determines the mismatch level at the discontinuities, up to kΩ. Their influence on the final received noise or channel transfer function is going to depend considerably on how close to the signal path they are.

Either of the measured loads can be introduced in the simulated network in any socket, and afterwards its contribution to the final channel will be calculated following the path towards the receiver (Fig.4.a). In addition, a background noise, obtained by measuring the power grid when no appliances where actives in the proximity, is added to create the noise model. Apart from that, a model that contemplates narrow-band interference could be aggregated for completeness. Although, somehow these contributions have been taken into account in an indirect way, because some ingress of radio interference was present during the measurement procedure of the noise sources, and they are not avoided even despite the averaging (that is why some spikes appear in the NSDs). Because nature of this narrow-band interference is mainly radiation, our model for this channel based on conduced currents would not be appropriate, so a statistical technique would be needed, like the one explained in [8]. This issue will be fulfilled soon, when more information about this kind of interference was available, especially measurements.

2.3. Time variation

Clearly, the channel conditions change through the course of the day, when appliances are switched on and off. However, those variations are going to be quite infrequent respect to the bit rate used in the communication channel. So the channel evolution can be seen as successive transitions of stationary states, corresponding to a certain channel transfer function and equivalent noise. These events are contemplated in the model by changing the impedance and noise values of the loads plugged in the sockets in a statistical way. A simple strategy is to study the state changes using discrete-time sequences generated from discrete sources with memory. For this purpose Markov models seem to be quite suitable (fig. 3.a). In general, only two states would be necessary (active or not), but for some "small" appliances like mixers, hair-dryers, vacuum cleaners, etc., a three-state model would be needed (unplugged, plugged but not working -because impedance changes-, and active). The transition probabilities can be estimated from assumptions based on common behaviour at homes, which are going to depend drastically on the period of the day under study.

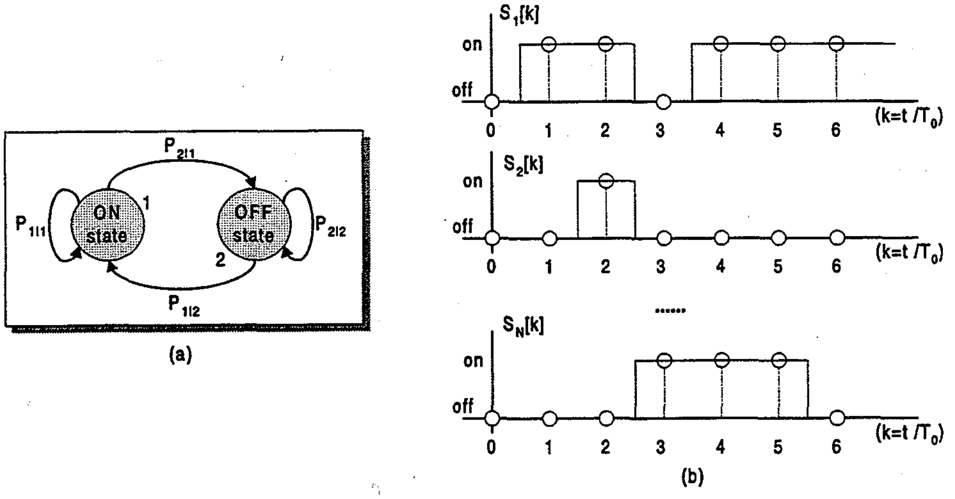
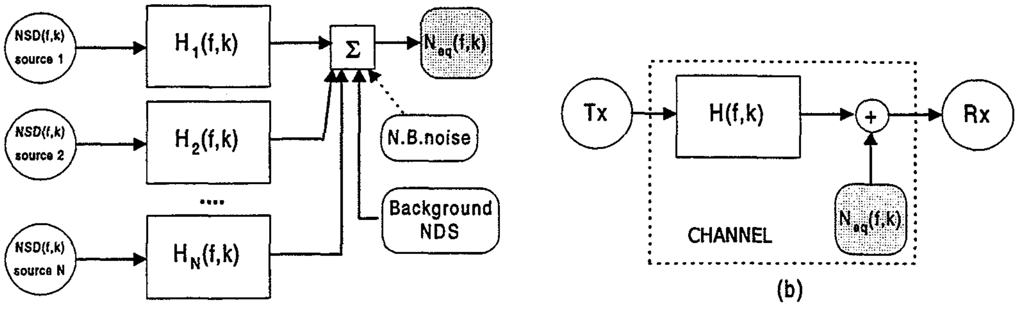


Figure 3: Time variation modelling, **a)** state diagram of the noise sources; **b)** examples of states variation of several noise sources.

2.4. Complete Model

Once the topology 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 and for the different noise sources are calculated, and added to obtain the complete channel model as depicted in fig. 4. In this approach, the superposition principle is being assumed, because the channel is supposed linear with respect to the signal and noise sources.



(a) (b)

Figure 4. The complete time-variant model, **a)** noise generation model; **b)** equivalent channel model.

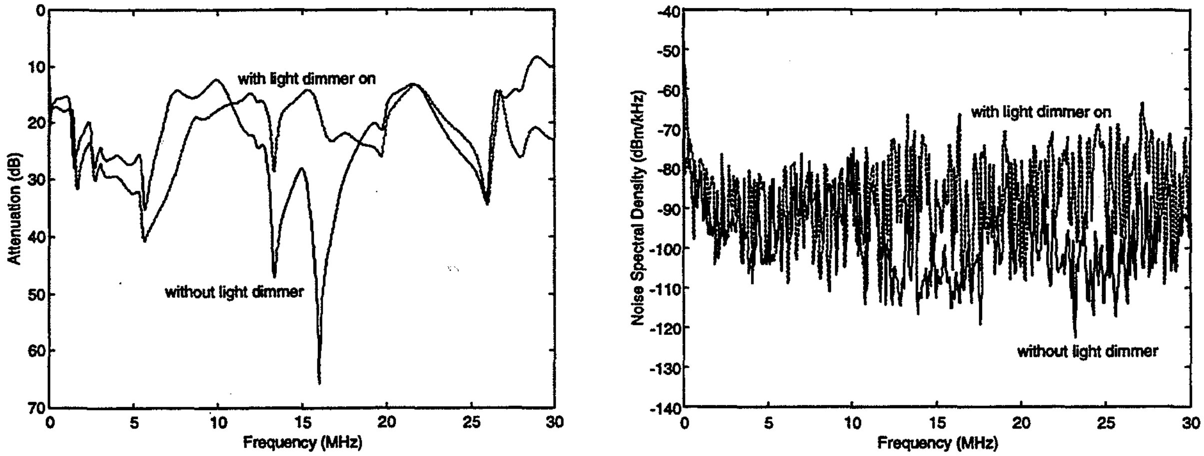
As discussed in the previous section, the channel is going to be time variant, considering a discrete time (k), which resolution directly determines the computer time needed to obtain simulation results. However, a very short time slot (less than some minutes) may not produce more accurate results, due to the slow variation of physical changes in real power-line environment. Once the channel response and equivalent noises have been calculated, they can be registered and used to get simpler filter models, appropriate e.g. for channel emulation.

3. Channel Model Results

The objective of the presented channel model is to provide a way to study the behaviour of typical power lines for different indoor configurations. For this method, you can estimate the input parameters for the simulator, basically network topology, from some physical knowledge of the layout of the building, wires installed or kind of existing loads.

To illustrate that, the plot in fig 5 displays the amplitude of the channel frequency response obtained by simulation of the power line of an apartment of about $80m^2$, where the path between transmitter and receiver should not exceed 35-40m in most cases. The power grid contains four different electrical circuits, modelled with more than 50 nodes, or line sections interconnected, also 10 loads among all in the network were considered dynamic in the analysed period.

Relative changes in network topology have a strong influence on the channel response. For instance, it is remarkable the effect produced by the connection of a load (a light dimmer) some metres apart from receiver. It smoothes the frequency response (a medium value of impedance is put where there was an open circuit, with a high reflection coefficient that causes 'notches'), but enhances the noise level. In addition, the frequency band between 15 and 18MHz could be useful or not depending on the load connection status. It is also very important the location of transmitter and receiver even in the same house, because differences of more than 30dB of attenuation in some frequency bands are not strange [4].



(a) (b)

Figure 5. Some examples of simulation results: **a)** Effect of connection of a light dimmer near receiver in the channel attenuation, and **b)** Effect in noise power spectral density.

Time variation of another possible link among those simulated in this network, is evaluated during two hours of "real time" in a period of the day with much human activity, e.g. evening hours. Resolution time has been adjusted to 5 minutes, and transition probabilities for state diagrams of the loads have been conceived with this assumption (e.g. it is less likely for a microwave oven to remain in working state after this time, than to change to off-state). In fig 6, it is shown the evolution of the amplitude frequency response of the channel response between 7 and 15MHz. In this case, variations of 15dB are observed for certain frequencies, which must be produced by load changes, while others notches remains at the same frequency, may be due to some socket with nothing plugged in.

Clearly, the results obtained by the model must not be expected to match perfectly with the ones that could have the real network, because there are several approximations made in the modelling procedure. Some of them are: uncertainty in the wires layout, adoption of transmission lines model, possible errors in the load characteristics and noise measured, discrete-time variation considerations or load changes probability estimation. Actually this mismatch between real channel responses and the simulated ones have been verified by means of some measurements (see [4,9]). However, these 'validation tests' have revealed that model results are in good correlation with measured channels, at least in terms of mean attenuation in the whole band, its grade of variation, or averaged noise received, and hence channel capacity (which may be the more important parameter). Main discrepancies appeared in the exact frequencies of 'notches' and spikes. Therefore, it can be concluded that this tool can supply realistic power-line channels.

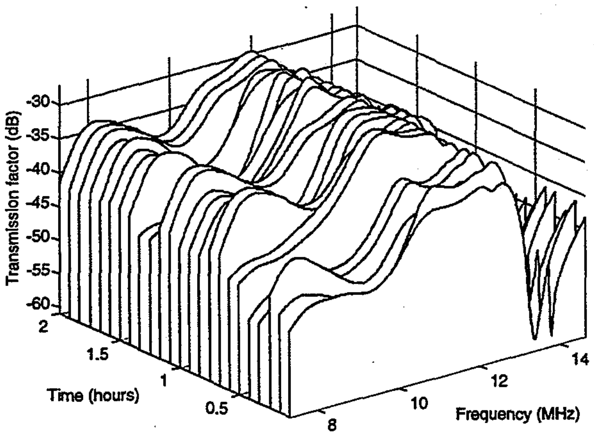


Figure 6. Simulated channel evolution over a period of two hours, for a selected frequency band.

4. Conclusions

A quite complete model, and adjusted to the nature of indoor power-line channels, has been proposed. It can provide feasible channel responses in an easy way, and it is scalable and adaptable to many kinds of structures of electrical networks, without the necessity of going there and carrying out measurements for each one. This model allows to study the evolution of the channel performance during the day, so that later analysis can be made of e.g. worst conditions of disturbances, average capacity, or minimum throughput attainable. All that information can be used to evaluate the usefulness of adequate transmission techniques or receiver structures and algorithms that could adapt to the channel conditions and changes.

Results so far show that reliable transmission would be feasible at high bit rates [10], what would permit the use of the indoor power lines as a good medium for new emerging services, like home LANs, common access to external telecommunication networks, advanced home automation applications, etc.

Remaining tasks in the time-variation modelling would be to develop a model of events that outperforms current assumption of discrete-time changes. Also to study further the transitions between stationary states, when some impulse noise is presumed to appear, though these unfavourable situations can be solved with error control techniques.

5. References

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