Distortion evaluation of DMT signals on indoor broadband power-line channels

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Abstract

Indoor power-line channels are frequency and time selective. At this moment, the distortion suffered by DMT signals when traversing these channels must be accomplished by means of computationally intensive simulations, since no consensus on a statistical channel model has been reached yet. This work proposes a simpler method to compute this distortion.

Index Terms

Discrete Multitone (DMT), Intercarrier Interference (ICI), linear periodically time-varying (LPTV) system.

I. Introduction

IN the absence of long-term changes, indoor power-line channels response can be modeled as a linear periodically time-varying (LPTV) filter [1]. When a DMT signal traverses such kind of channel, it experiences a twofold distortion: intersymbol interference (ISI) and intercarrier interference (ICI) caused by the frequency selectivity and ICI due to the time variation [2]. Nowadays still there is no general agreement on a statistical channel model. Hence, the system performance is evaluated by means of time-consuming simulations employing a linear time-varying (LTV) filter [3]. This work proposes an alternative method in which distortion caused by the frequency-selectivity is obtained by means of simulations employing a linear and time-invariant (LTI) filter, and the ICI due to the time variation is estimated using a novel analytical expression derived in the paper.

II. Channel model

This work is exclusively concerned with the distortion caused by the channel response in DMT signals. Hence, no noise is considered in the analysis, and the channel is modeled as an LPTV system. To validate the proposed method, the response of an actual indoor power-line channel in the frequency band from 1 MHz up to 20 MHz is employed. It has been selected because of its significant time variations, which can be clearly noticed in Fig. 1, where the time evolution of the amplitude response along the mains cycle at two frequencies is shown. As seen, there are frequency bands with more than 6 dB of amplitude variation. Table I gives the values of its delay spread and Doppler spread, computed as described in [4] and [1], respectively.

Average delay spread (μs)	0.24
RMS value of the delay spread (%)	0.81
Average Doppler spread (Hz)	234.54

TABLE I: Delay spread and Doppler spread values of the selected channel

III. Distortion estimation

Denoting by $x[n]$ a DMT signal with N carriers and cp samples of cyclic prefix, and by $h[n,m]$ the channel response at time n to an impulse applied at time $n-m$, the channel output to the input signal $x[n]$ can be expressed as [3]

$$y[n] = \sum_{m=0}^{L_h-1} h[n,m]x[n-m], \tag{1}$$

where L_h is the length of the impulse response.

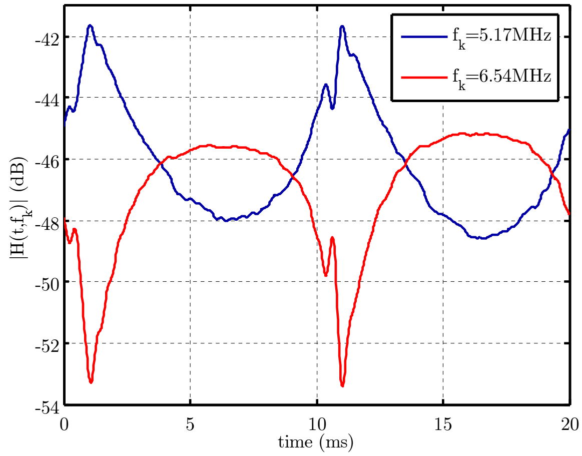

Fig. 1: Time evolution of the amplitude response along the mains cycle at two frequencies.

As it will be corroborated in section IV, the time variation of the channel can be approximated as linear along each DMT symbol for reasonable symbol lengths. Hence, the impulse response during the useful part of the ℓ-th symbol can be expressed as

$$h[n+\ell L+cp,m]=h_\ell[m]+\frac{(n-N+\frac{1}{2})}{2N}\Delta h_\ell[m], \qquad 0\le n\le 2N-1, \tag{2}$$

where $L=2N+cp$, $h_\ell[m]$ designates the impulse response at the middle of the useful part of the ℓ-th symbol and $\Delta h_\ell[m]$ denotes the difference of the impulse response value from the beginning to the end of the symbol.

A power-line DMT system in which transmissions are synchronized with the mains voltage is considered. Assuming that P complete DMT symbols can be fitted into each mains period, the symbol index, ℓ, can be expressed as $\ell=p+rP$, where $0\le p\le P-1$ and $-\infty<r<\infty$. Then, due to the periodic behavior of the channel, it holds that $h_{p+rP}[m]=h_p[m]$ and $\Delta h_{p+rP}[m]=\Delta h_p[m]$. Let us denote by $H_p[k]$ and $\Delta H_p[k]$ the DFT of $h_p[m]$ and $\Delta h_p[m]$, respectively.

In order to derive an analytical expression for the ICI due to the channel time variation, the cyclic prefix is fixed to $cp\ge L_h-1$. This ensures that there is no distortion due to the frequency selectivity. Setting the frequency equalizer (FEQ) in carrier k to $H_p^{-1}[k]$, the signal to distortion ratio (SDR) caused by the channel time variation (TV) in the k-th carrier of the p-th symbol transmitted in each mains cycle as

$$SDR_{TV}(p,k)=\frac{E\left[|X_{p,k}|^2\right]}{E\left[|X_{p,k}-Y_{p,k}H_p^{-1}[k]|^2\right]}=\frac{16N^2\,|H_p[k]|^2}{\displaystyle\sum_{\substack{i=-(N-1)\\ i\neq k}}^{N}\frac{|\Delta H_p[i]|^2}{sin^2\left(\frac{\pi}{2N}(i-k)\right)}}. \tag{3}$$

The computation of the distortion caused by the frequency selectivity can be easily accomplished by taking into account that it is mainly determined by the channel delay spread. Since the latter is almost time-invariant, as shown in [4], it is reasonable to expect the same behavior for the distortion. Hence, it can be computed by means of simple simulations using an LTI filter. The impulse response of this filter can be obtained by taking the average impulse response exhibited by the channel along the mains cycle.

Finally, assuming that the distortion terms due to the frequency selectivity, $SDR_{FS}(k)$, and to the time variation, $SDR_{TV}(p,k)$ are independent, and that the latter is almost unaffected by the cyclic prefix length, the overall SDR for a given cp value can be estimated according to

$$SDR(p,k)=\left[SDR_{FS}(k)^{-1}+SDR_{TV}(p,k)^{-1}\right]^{-1}. \tag{4}$$

IV. Method validation

Results obtained with the proposed methodology are now compared to those given by LPTV simulations. The sampling frequency is set to 50 MHz. The LPTV filtering is performed using the *direct form A* structure described in [3]. The filter bank consists of 976 filters obtained by sampling the channel response presented in section II at regularly distributed intervals within the mains cycle.

In a first instance, the validity of (3) to compute the ICI caused by the channel time variation is assessed. To avoid the distortion due to the frequency selectivity, the cyclic prefix is fixed to the extremely high value of $cp = 1022$ samples (20.44 μs at 50MHz). Fig. 2 shows the time and frequency-averaged SDR values versus the base-two logarithm of the number of carriers: curve (a) has been obtained using (3) and curve (b) from LPTV simulations. As seen, even for a number of carriers as high as $N = 2^{15}$, the difference between (a) and (b) is smaller than 3dB.

In order to corroborate the time-invariant behavior or the distortion due to the frequency selectivity, the ICI due to the channel time variation must be made comparatively negligible. To this aim, the cyclic prefix has been fixed to $cp = 150$ samples (3 μs at 50MHz). SDR values resulting from simulations with the LPTV channel are depicted in curve (c). Curve (d) depicts the frequency-averaged values of the SDR when an LTI simulation employing the average impulse response of the LPTV channel is accomplished. As seen, for $N = 2^9$, where distortion due to the channel frequency-selectivity is the limiting term, the differences between (c) and (d) are smaller than 2dB.

Finally, let us assume that we want to compute the overall SDR for $cp = 150$. The suitability of expression (4) for this purpose can be observed by noticing that the differences between the time and frequency-averaged SDR values given by (4), shown in curve (e), and the ones obtained by means of the LPTV simulations, displayed in curve (c), are smaller than 2dB for $N < 2^{15}$.

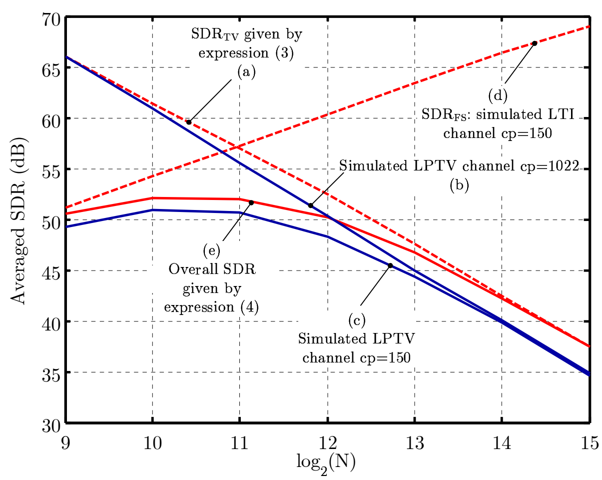

Fig. 2: Averaged SDR in the selected channel.

V. Conclusion

This paper has presented a new methodology for estimating the distortion caused by the frequency and time-selectivity of indoor broadband power line channels in DMT signals. The method has been validated using an actual indoor power-line channel with significant channel response variations.

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