Mitigation of cyclic short-time noise in indoor power-line channels

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Abstract— **This paper describes two methods that can be used to mitigate part of the noise in Power Line Communications (PLC) channels. These methods were developed considering the particular characteristics of the noise in PLC channels. The first method is the increment of the symbol size for the discrete multitone transceiver (DMT) that is used for PLC, while the second is based on the use of a predictor. Both methods were evaluated using noise records obtained from real PLC channels.**

Keywords— **PLC, DMT, time-varying noise, LPTV, linear prediction**

I. INTRODUCTION

POWER line communications (PLC) are recently being developed as a medium for indoor high speed transmission. A main advantage is the ubiquity of the access point without installing a new network line, which allows the development of high speed home or small office local area networks using current infrastructure. However, the power line was not designed for broadband communications so its characteristics are not the more appropriated for this purpose: PLC channels are time and frequency variant, with high attenuation and noise.

Noise in indoor power-line communications (PLC) channels has very uncommon characteristics. Its peculiar origin –appliances with their switching power supplies together with the power distribution itself– causes it not to match any usual model: it is not Gaussian, nor stationary, nor white. Traditionally, PLC noise has been modeled as the addition of stationary and impulsive noise [1]. The stationary reflects background noise, while the impulsive noise corresponds with the switching nature of the appliances connected to the network.

However a different approach was proposed in [2], which considers that the main characteristic is the cyclo-stationarity and models the PLC channel as a Linear Periodically Time Variant (LPTV) system, in which everything is considered time-variant with a fundamental periodicity of $50/60$Hz, which is synchronized with the mains voltage.

The objective of this paper is improving the bit rate of a discrete multi-tone transceiver (DMT) based on the indoor PLC noise characteristics. Two different methods are proposed: The first method increments the DMT symbol size, which provides an improvement in the frequency selectivity. It makes discrete spectral components affect less carriers, obtaining a reduction in noise power for the others. This irregular distribution of noise power between carriers allows a global improvement in the bit rate. The second method uses a linear predictor filter in order to decrement the noise for each carrier after the DMT receiver. For a practical implementation, the coefficients for the predictor are calculated with the decided symbols instead of the transmitted ones, which are unknown. This approximation is valid if the decision error is low.

Both systems have been evaluated using long noise records obtained from real channel coming from very different scenarios, taking as main indicator an estimation of the bit rate. Both methods provided bit rate improvements, especially for noisy environment. However, in general, the gain of the first one was higher than using a predictor.

The paper is organized as follows. Section II describes the noise characteristics in PLC channels, the modulation considered for the transmission and the method used to obtain the noise records. The impact of DMT symbol size on noise is evaluated in Section III, and the predictors are introduced in Section IV. The main conclusions are drawn in Section V.

II. SYSTEM DESCRIPTION

A. PLC noise characterization

The characterization of noise in PLC channels has been performed thanks to extensive measurement campaigns in [2], [3], [4], that allowed the development of models based on them in [2], [5]. Other interesting study was developed in [1].

From these references, it can be derived a general characterization of the noise in the power-line network. First of all, the more important component is the impulsive noise, defined as an eventual short-time perturbation (with duration lower than 100μs). Indeed, three different impulsive noise categories can be found: The first one is a periodic impulsive noise, synchronous with the $50/60$Hz of the mains, typically generated by non-linear devices used in some circuits. Secondly, there is a periodic impulsive noise with higher frequency than the $50/60$Hz (between 50 and 200kHz), due to the switching power supplies, with a fundamental cyclostationarity at $50/60$Hz (see Fig. 1 for an example), that can be found for certain phases of the cycle; those pulses,

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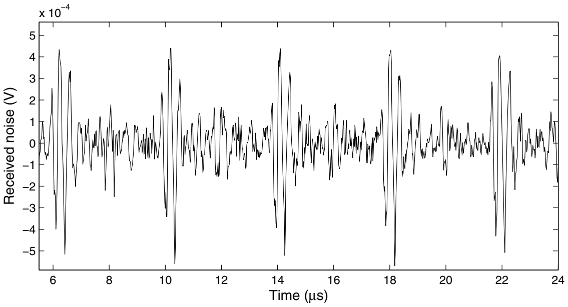

Fig. 1. Periodic impulsive noise approx. with 250kHz

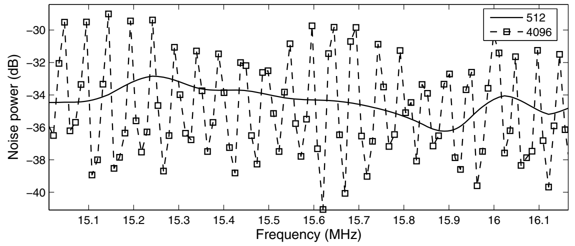

Fig. 2. Periodic components in DMT

originated by the appliances, are almost periodic during a certain interval of time, usually around hundreds of kHz, and have semi-deterministic nature. Finally, the third impulsive noise is totally asynchronous and random and is generated by the (dis)connection of elements to the mains.

Another source of noise in PLC channels are narrow-band interferences up to 30MHz coming from radio stations. Due to the extension of the mains, the power of this interference may be significant. In general, this perturbation is approximately stationary.

Finally, there is a background colored noise due to non-localized sources. It is generally considered as stationary, and has a decay with the frequency.

As depicted in [2], the main source of noise is the one produced by the devices connected to the network, i.e. the impulsive repetitive noise. Therefore the main noise source has a cyclo-stationary nature, having its spectrum a discrete number of narrow-band frequency components due to its periodicity. The methods proposed in the following sections are based on this periodicity of the noise.

B. Bit rate estimation

In order to evaluate the PLC noise effect, several measurements were taken in different locations. The locations had different noise profiles, ranging from noisy laboratories with several elements connected to the network to home environments with fewer appliances connected and, therefore, lower noise. These records were demodulated using a DMT receiver with different symbol sizes and without cyclic prefix. The cyclic prefix was removed in order to avoid its effect in the modulation efficiency [6]. In addition, as we are not evaluating the effect on the signal, but on noise, the cyclic prefix is not needed for the demodulation.

The bit rate is the indicator that is used to analyze the methods proposed in the following sections. An estimation for the bit rate can be obtained by calculating the capacity for each DMT carrier and assuming certain loss due to the limitations imposed by a real implementation. This loss can be considered by reducing the signal to noise ratio (SNR) obtained with the measurements by a factor of 9 dB.

Assuming that PLC channels are linear periodically time variant (LPTV) and noise is cyclo-stationary with a fundamental frequency of $50/60$Hz, the signal and noise power for each carrier and DMT symbol were estimated by averaging over 200 mains cycles to have better estimation accuracy.

Finally, the capacity for a DMT system can be estimated with the application of the Shannon formula for each DMT carrier and symbol in a cycle of the mains, as shown in (1).

$$C = \frac{W_T}{KL} \sum_{k=0}^{K-1} \sum_{l=0}^{L-1} \log_2 \left(1 + \frac{P_S\left(k,l\right)}{P_N\left(k,l\right)} \right) \qquad (1)$$

where W_T is the total bandwidth of the channel (25MHz in this case), K is the number of carriers, k is the carrier index, L is the number of symbols in a cycle, l represents the DMT symbol index within the cycle, and $P_S\left(k,l\right)$ and $P_N\left(k,l\right)$ are the powers of signal and noise respectively, in each carrier and symbol. The signal power was obtained by injecting a signal with a plain power spectrum density within the band and with a value of -35dBm/kHz and signal and noise powers were estimated by averaging the instantaneous values over 200 mains cycles. the sampling frequency is 50 MHz, so each period contains 10^6 samples per cycle, equivalent to between 200 and 2000 DMT symbols per cycle. Finally, very low and high frequencies (lower than 1MHz and higher than 24 MHz) were filtered in order to avoid the effect of the band borders.

III. INCREASE OF DMT SYMBOL SIZE

A. Description

One of the main parameters that can be modified in a DMT system is the symbol size. If the number of samples in a DMT symbol is bigger, the frequency resolution is increased. On the other hand, it makes the time resolution to be reduced. In previous analysis [7], the symbol size is obtained considering the channel response characteristics; in this paper, the symbol size shall be determined considering PLC noise.

As explained in Section II, an important component in PLC noise is periodic impulsive noise, which means that its spectrum is composed of discrete frequency components due to its periodicity. Therefore, an increase in the frequency resolution, will make less DMT carriers to be affected by noise (an example can be seen in Fig. 2). This irregular distribution of noise power between carriers is expected to allow a global improvement in the bit rate, due to the characteristics of DMT modulation.

Analysis of the bit rate was performed over long noise records with different symbol sizes in order to obtain their relationship. The symbol sizes that were used for the tests can

TABLE I
DMT SYMBOL SIZES USED FOR ITS EFFECT ON BIT RATE

Symbol sizes			
512	1024	2048	4192

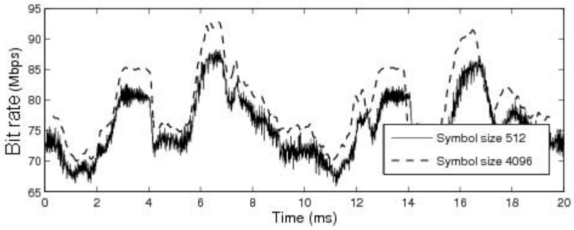

Fig. 3. Temporal evolution of bit rate for one channel

be found in Table I. They have been chosen in powers of two because it is a typical request for calculating the FFT in real implementations.

B. Results

In general, the analysis result is that the bit rate is increased with the symbol size; an example can be found in Fig. 3, which shows the evolution of the bit rate for symbol sizes 512 and 4096 along one $50/60$Hz cycle. Fig. 4, shows the summary for several noise records, with all the symbol sizes in Table I. Fig. 4 shows the gain of using any symbol size compared to 512 samples, in order to have a relative measurement, because the absolute values have a huge variation depending on the location. It is important to highlight that the gain obtained due to the increase of symbol size against the cyclic prefix [6] in not included in the figures, since no cyclic prefix was used for current analysis.

As it can be seen in Fig. 4, the gain ranges from 0% to 25%, with an average of approx. 7% between symbol sizes 512 and 4192. It can be noticed how the gain deeply depends on the channel, because it is affected by the periodic characteristics in the noise, which are determined by the location.

To sum up, using high DMT symbol sizes impact on a high bit rate because noise interferes less carriers. It is a simple way to obtain better performance without implementing new functionalities or special processing to the DMT receiver.

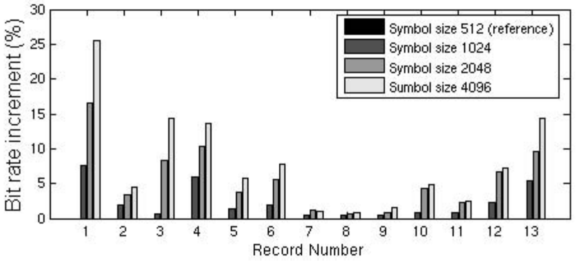

Fig. 4. Bit rate for different symbol sizes and channels. The cyclic prefix effect is not included.

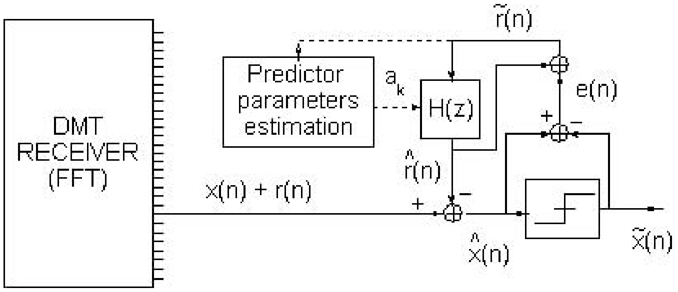

Fig. 5. Predictor diagram for one DMT carrier

IV. PREDICTOR

A. Description

The periodic impulsive noise , $u\left(n\right)$, observed at the input of DMT demodulator, is asynchronous with the DMT symbol period. Let be n_0 the delay that experiments the periodic noise between two consecutive DMT symbols, and $\Gamma_k\left(l\right)$ the noise at the k carrier and symbol index l, then:

$$\Gamma_k\left(l\right) = \text{FFT}\left\{u\left(n\right)\right\} \tag{2}$$

$$\Gamma_k\left(l+1\right) = \text{FFT}\left\{u\left(n-n_0\right)\right\} = \Gamma_k\left(l\right)e^{-j2\pi k n_0} \tag{3}$$

so the impulsive periodic noise generates a complex exponential signal at each output of the DMT demodulator, with a normalized frequency of kn_0. From (3) it can be concluded that a component of the demodulated noise follow a periodic pattern that can be easily removed (reduced in the practice) with a linear filter. The order of this filter shall depend on the periodic components that compose the noise.

The Fig. 5 shows a diagram for the predictor for one of the DMT carriers; the complete system will be a bank of predictors, one for each carrier. In Fig. 5, $x\left(n\right)$ represents the signal symbol for one DMT carrier, $r\left(n\right)$ is the noise associated, $H\left(z\right)$ is the linear predictor filter, $\hat{x}\left(n\right)$ is the estimated symbol after applying the predictor, and finally $e\left(n\right)$ is the residual predictor error. The expected behavior is that noise in the estimated symbol, $\hat{x}\left(n\right)$, is lower than in the plain received symbol $\left(x\left(n\right)+r\left(n\right)\right)$. Consequently, the error rate in the decisor should be improved by the predictor.

The requirement for this system to work properly is that the decision error rate to be small enough. It is needed to consider that $e\left(n\right)$ only represents a residual error in the prediction process, and not a decision error. In general, the conditions in (4) and (5)

$$E\left[\left(x\left(n\right)-\tilde{x}\left(n\right)\right)^2\right] \rightarrow 0 \tag{4}$$

$$E\left[\left(r\left(n\right)-\tilde{r}\left(n\right)\right)^2\right] \rightarrow 0, \tag{5}$$

which can be translated to a requirement of relatively high signal to noise ratio (SNR), are required. If this condition is not fulfilled, the predictor may not only give no gain to the system, but even affect it negatively.

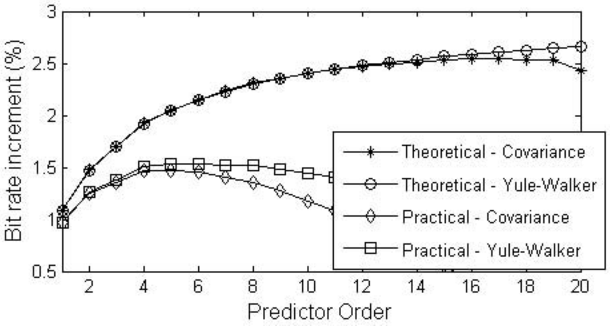

Fig. 6. Average bit rate increment for different orders

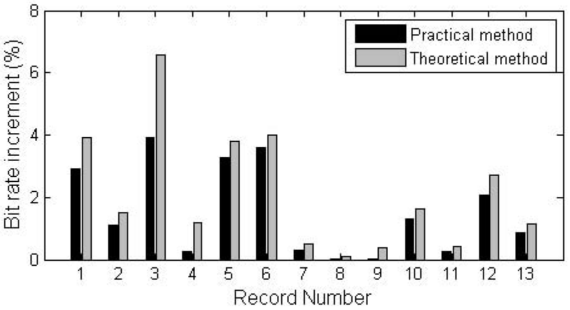

Fig. 7. Bit rate increment using the predictor

TABLE II

CHARACTERISTICS TO OBTAIN THE LINEAR PREDICTOR COEFFICIENTS

Method	Order
Yule-Walker	6

B. Linear Prediction Filter

The general form for the predictor filter follows the one in (6)

$$H(z) = 1 - a_2 z^{-1} - a_3 z^{-2} - \ldots - a_{p+1} z^{-p}, \qquad (6)$$

where $a_2, a_3, \ldots, a_{p+1}$, are the coefficients for the the filter of p-order, which are time dependent since the noise is not stationary. In order to obtain these coefficients, different methods can be applied. First of all, there are many methods for the extraction of the coefficients from a signal; in this paper the Yule-Walker and the covariance methods are evaluated. Another important point is decide the signal period that will be used to obtain the coefficients; in this paper two possibilities are proposed, one of them more theoretical and another more practical.

Both proposals are based on the cyclo-stationary nature of the noise in the PLC system. The assumption is that the coefficients for certain $50/60$Hz cycle phase do not vary from cycle to cycle. The difference is that the theoretical method consider all the available noise record to derive the coefficients. However, in the practical one, the coefficients for one $50/60$Hz cycle are calculated based only in the parametrization of the previous cycle. Therefore, bigger gains are expected from the theoretical method, though it cannot be implemented for a realistic system. The gain for other real system implementation will be enclosed by the values obtained with the two proposals in this paper.

Regarding the model order, it was obtained by calculating the average increment in the bit rate for different noise records and using predictor orders ranging from 1 to 20. The average value for all the records can be found in Fig. 6. From this result, it can be derived that a good election would be the Yule-Walker method with order $p = 6$ (as shown in Table II).

C. Results

The bit rate is going to be evaluated for the theoretical and practical methods depicted in the previous section and using the parameters in Table II. The symbol size considered for this analysis was 1024 samples and several noise record were considered for the analysis. Fig. 7 represents the result for some of the records, showing gains with ranges from 0% to 6.6% for the theoretical method, and from 0% to $3.9\%$with the practical one, with an average of 2.1% and 1.5% respectively. From this results, we can state that the average gain for a system based on predictors would be between 1% and 3% approximately.

As with the other method, the variation of the system characteristics between different localizations is clear. As exposed in the introduction, it is a key characteristic of PLC channels that make difficult to apply a generalist method regardless the localization.

Finally, it can be spotted that the improvement of using a predictor is clearly lower than the previous method (increasing the DMT symbol size). However, the additional gain provided by the predictor may be enough to include it into a real system.

V. CONCLUSION

To sum up, two method for mitigating the noise effect on PLC channels have been developed, using long records coming from several PLC channel measurements for their evaluation.

As a first conclusion, the gain for different records can be evaluated. It can be seen that, in general terms (with some exceptions), both methods provides better gains for the same records. The main reason is that both methods are based on the periodicity of the received noise, which makes the records with stronger periodic component obtain more gain in both cases, e.g. records captured in localizations with many appliances connected to the network, like laboratories or office environments. The records with lower gains correspond with home environments where the noise is substantially lower than in the first case.

Secondly, one method can be compared against the other, with the main conclusion that the gain obtained with the increment of the symbol size is higher if compared to the predictors. This is because the DMT modulation have an extremely good behavior for frequency-localized noise when increasing the symbol size.

Additionally, both methods could be complementary and be applied together, giving even better gain together than independently. It is expected that higher symbol sizes provide higher gains for the predictor, because the noise is then confined in less carriers allowing the predictor to obtain the same or bigger gains with a lower order.

Therefore, both methods provides an improvement in the bit rate, so they should be applied whenever the increase of complexity can be afforded in the PLC system. The application would consists in incrementing the DMT symbol size as much as possible (in function of the channel response and the available computing power) and afterward, the use of the predictor can be used to obtain an extra increase on bit rate.

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