Cancelling Wideband Impulsive Noise by Processing the Masked Tones in Power Line Communications

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***Abstract*—It has been demonstrated that Power Line Communications (PLC) can interfere with some radio services. In order to avoid it, PLC standards specify not to transmit at the same frequencies where these radio services operate. These frequencies are called the masked tones. As they carry no transmitted power, the masked tones can be used to detect and cancel impulsive noise (IN), which most of times is wideband and leaks out into the whole PLC band. This research work presents a new procedure to identify and eliminate IN from PLC receivers, being able to recover the original signal samples which have been impaired by the IN pulses.**

***Index Terms*-- Electromagnetic interference, frequency domain analysis, impulsive noise, OFDM, Power Line Communications.**

I. INTRODUCTION

We call impulsive noise (IN) pulses of high amplitude that unexpectedly appear in a communication channel. The term Power Line Communications (PLC) comprises a number of technologies, equipment, applications and services that provide users with communication means over existing power lines, i.e. cables transmitting electricity. Several standards have been released [1]-[2] and most of them use modulation techniques derived from Orthogonal Frequency Division Multiplexing (OFDM).

IN presently is the subject of research due to its harmful influence on PLC. IN in power lines is classified in three types [3]-[6]:

- Type 1. Periodic IN asynchronous to the mains frequency, which is mostly caused by switched-mode power supplies.
- Type 2. Periodic IN synchronous to the mains frequency, which is mainly caused by switching actions of rectifier diodes found in many electrical appliances.
- Type 3. Asynchronous IN, which is caused by switching transients in the power network.

The Power Spectral Density (PSD) of the second and especially the third type of IN can be many orders of magnitude higher than the background noise.

IN is a wideband phenomenon, in radio channels it can be found in frequencies up to 7 GHz [7]; in PLC it has also been demonstrated that IN covers a bandwidth beyond that of a typical communication channel, this is especially true for the third type of IN, the asynchronous one [5]. In reference [6] IN is measured at frequencies up to 20 MHz obtaining high PSD within the whole band. In reference [8] IN from several household appliances is registered and the PSDs obtained show varied frequency distribution shapes but always with appreciable power in all the frequency components. More household appliances are tested in frequencies up to 60 MHz in [9], with similar results.

A novel method to cancel IN by processing the signal components received in the idle (masked) carriers specified in standards like [1] is presented in this paper. The organization of the paper is as follows: Section II explains the role of the idle carriers in detail. Section III describes existing methods to detect and to eliminate IN based on threshold techniques. Section IV is the explanation of the cancelling method that we present. Section V explains how to set a detecting threshold. Section VI shows a simulation model for our method and the results obtained from it, and Section VII presents the conclusion to this research.

II. THE IDLE CARRIERS IN THE PLC STANDARDS

Electric power wires act as low efficiency radiating and receiving antennas. As their efficiency is low, received interferences from radio emitters should not be too high in most cases; radiating power from a single PLC device should not be too high either, however, the added effect of thousands of PLC systems working at one time need to be considered [10]. Radio regulation authorities have restricted the use of PLC at specific frequencies in order to avoid electromagnetic interference (EMI) with radio services, especially medium frequency (MF) radio broadcasting and radio amateur services. PLC standards have to take into account these EMI restrictions by masking (turning off) transmission on those spectrum carriers at the frequencies indicated by the rules, which are not necessarily the same for the different regions worldwide [11].

The IEEE 1901 standard [1] takes into account these restrictions with a tone mask template which specifies which carriers can be used. There are two types, broadcast and extended tone masks. The broadcast tone mask is the default configuration but PLC stations in the network can agree to use an extended tone mask (carriers in addition to the carriers used by broadcast tone mask) if the conditions allow it. Therefore, the idle (masked) carriers contain no significant power, only Gaussian noise and some radio interference is expected to be found in them, however when an IN pulse arrives at an OFDM receiver it introduces power into all of the carriers within the symbol, due to its wideband property. The IN power introduced into the idle carriers is very high compared to their background noise, and that constitutes the core of our cancelling system: Using the information within the idle carriers in order to cancel IN. Fig. 1 shows the PLC spectrum with the IEEE 1901 broadcast tone mask for North America mixed with an example of a typical IN distribution in the frequency domain.

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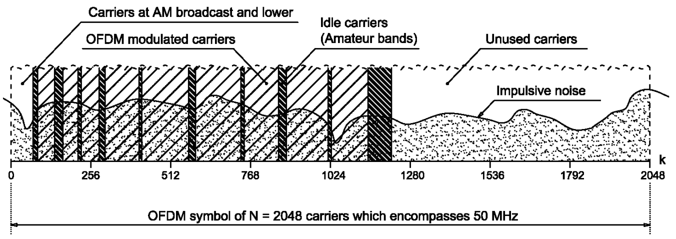

Fig. 1. The IEEE 1901 broadcast tone mask for North America mixed with a typical impulsive noise distribution in the frequency domain

III. The Threshold Detection and Blanking Method for OFDM Systems

When taking measures against IN is desired, the first step is to identify those samples affected by it. Recalling that IN consists of high amplitude pulses, the most intuitive detecting procedure is to set a threshold in order to spot those samples exceeding it as being suspicious to be IN.

Having determined the locations of the samples which are suspicious to be affected by IN, we can proceed to eliminate or mitigate them by using a variety of methods. Among them, threshold detection and blanking (TD&B) deserves special mention for its simplicity; it consists of zeroing all the samples exceeding the threshold. Fig. 2 shows this procedure whose performance is researched in [12]. The TD&B method has been subject of several patents which are very similar to each other [13]-[14]. There is a similar method which consists of clipping instead of zeroing (blanking) the exceeding samples [15], research comparing clipping and zeroing can be seen in [16]. The TD&B method is easy and quick, and constitutes a good benchmark for us to take into account in order to compare performance with the cancelling method which is presented in this paper.

Although there are some methods against IN specially designed for PLC, most of them have been developed for OFDM systems in the radiocommunication area. The majority of methods are supported on threshold detection techniques, as [17]-[21] which first identify the IN pulses by means of a threshold and then use the information contained in the OFDM pilot carriers to cancel them, at the expense of strong signal processing.

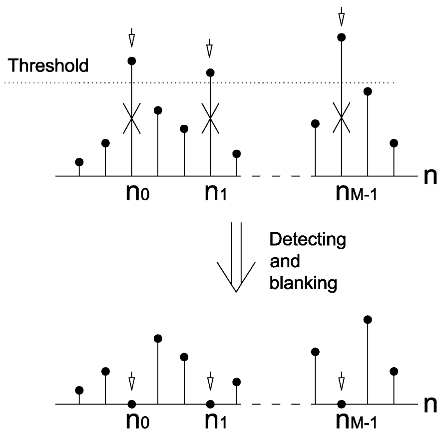

Fig. 2. The classical threshold detection and blanking method

IV. Cancelling Impulsive Noise by Using the Information Contained in the Idle Carriers

Probably, the best known method against IN is TD&B. Although it is quite efficient taking into account its simplicity, it has two major drawbacks:

- Many high amplitude OFDM samples exceeding the threshold would be converted to zero, which is very harmful for the desired signal.
- Even though blanking the IN samples effectively prevents their high power ruin the whole symbol, the original OFDM samples cannot be recovered.

The powerful method that we present overcomes these two drawbacks: First, it is able to detect when a high amplitude sample belongs to the OFDM signal, and second, it is able to cancel the IN pulses leaving the OFDM sample contribution unscathed. This second characteristic states the difference between blanking and cancelling.

The block diagram of the method which is presented in this paper can be seen in Fig. 3, where input signal s[n] is the raw OFDM symbol in the time domain. The method has four stages:

- First, it is needed to detect where the IN candidate samples are. This is accomplished at the blocks “Calculate threshold” and “Detect exceeding samples”, using the procedure of spotting the pulses locations where the samples exceed a specific threshold in the time domain.
- Second, it is needed to extract the idle carriers which correspond to the carriers where no information has been transmitted. The blocks for this stage are “FFT” and “Extract idle carriers”. These idle carriers are the ones that can be seen in Fig. 1 as heavily striped bands in the OFDM symbol.
- Third, with the location of the samples allegedly impaired by IN and with the complex values of the idle carriers, the block “Calculate cancelling sequence” outputs an estimation of the complex values corresponding to the IN pulses allegedly located. This block is smart enough to know if the candidate samples are IN or not, and to discriminate the IN contribution from that of the desired signal.
- Fourth, the estimated complex values of the IN pulses d[n] are subtracted from the original sequence s[n], obtaining the clean sequence c[n].

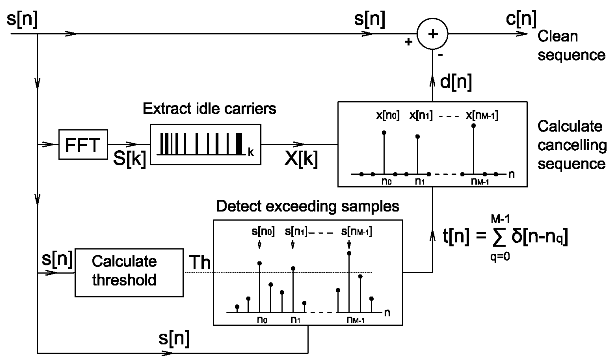

Fig. 3. Block diagram of the cancelling method which is presented

In the first stage, the output for block "Detect exceeding samples" is:

$$t[n] = \sum_{q=0}^{M-1} \delta[n - n_q] \tag{1}$$

being M the number of samples exceeding the threshold.

In the second stage, the output for block "Extract idle carriers" is :

$$X[k] = \sum_{p=0}^{P-1} X[k_p] \cdot \delta[k - k_p] \tag{2}$$

P being the number of idle carriers considered. Indexes k_p of these idle carriers are given in the corresponding PLC standard, therefore the block just observes the complex values $X[k_p]$ of these idle carriers.

For the third and fourth stages, block "Calculate cancelling sequence" makes use of the P spectral components $X[k_p]$ to estimate the IN sequence:

$$d[n] = \sum_{q=0}^{M-1} x[n_q] \cdot \delta[n - n_q] \tag{3}$$

Estimation d[n] is accurate if and only if M≤P, this means that the method is good enough to cancel up to P IN pulses. This limit is not a drawback in practice; for example, the IEEE 1901 tone mask of Fig. 1 specifies P=237 idle carriers over a total of N=2048; in the event of M>237 pulses within an OFDM symbol, the exceeding M–237 samples could be blanked following the usual method of Fig. 2. In addition it must be taken into account that by definition IN consists of few pulses of high amplitude, therefore 237 pulses are something more than plain IN. Computation has to be considered too, the more IN pulses detected the more calculations need be made; therefore, the practical limit on the maximum number of pulses to be cancelled will be determined by technology factors. The number P=237 carriers is not necessarily a constant. From time to time some of the idle carriers might come up with appreciable power from radio interference; the cancelling system should monitor the idle carriers in order to withdraw the interfered ones from the list of carriers for assessment.

This cancelling method offers the following advantages:

- It is not necessary any hardware modification in the receiver chip to implement this method, it is fully firmware.
- The method is applied at the beginning of reception with the raw OFDM symbol in the time domain, before channel equalization and before synchronization.
- The cancelling stage is independent of the rest of blocks of the PLC receiver. It only needs the N OFDM samples as the input and returns the N samples clean of IN as the output. Therefore it has no feedback path with the decoded bits or other receiving stages, which simplifies the design, isolates it from other tasks at the receiver and avoids instability.
- The method is computationally adaptable, that is, the computational load can be adjusted to meet processor capability.

V. Setting a Threshold

Several authors have already demonstrated that OFDM signals tend to have Gaussian properties in the time domain when the number of subcarriers N is high [22]-[23]. According to it, our threshold calculation procedure considers that an OFDM signal is a Gaussian process of mean zero and standard deviation σ_{OFDM}. Statistically, Gaussian amplitude in an IQ receiver follows a Rayleigh distribution function of parameter σ_{OFDM}, and its density function is:

$$f(x) = \frac{x}{\sigma_{OFDM}^2} e^{-\frac{x^2}{2\cdot\sigma_{OFDM}^2}} \tag{4}$$

In this section we will find a procedure to set the detecting threshold in a way similar to statistical hypothesis testing. The null hypothesis H_0 stands for a sample being "not guilty", that is to say not being IN. On the other hand the alternative hypothesis H_1 stands for a sample being "guilty", that is to say being IN. In these tests, rejecting the null hypothesis is equivalent to assuming that IN has been detected in the sample. For any amplitude threshold TH there is an associated certainty value P that a sample exceeding TH is an IN pulse.

If no IN is present, OFDM Gaussian amplitude is the only signal that can exceed the threshold and wrongly trigger the IN detection method. TH has to be set high enough so that it is exceeded by Gaussian amplitude with a very low probability. Let us define the random variable x that follows a Rayleigh distribution with parameter σ_{OFDM}, such that:

$$p(x \le TH) = P \tag{5}$$

We will decide that we are receiving IN if x>TH. In words, if x exceeds TH, then it is not Gaussian with probability greater than P. Therefore, if the sample amplitude exceeds TH then the sample is an IN pulse with probability greater than P. For instance, P=0.999 means that it can be assured that the sample exceeding TH is impulsive with at least 99.9% of probability. Fig. 4 shows the Rayleigh probability density function with the threshold TH set at P=0.99.

There is no optimal value for P, the higher P is, the more certainty there will be that samples over the threshold are due to IN, nevertheless there will be low amplitude IN peaks that would not be detected; on the other hand the lower P is, the lower the probability of small IN not being detected. However, more frequently OFDM Gaussian amplitude will exceed the detection threshold and will wrongly be considered as IN; for example P=0.9 means that, on average, one out of ten times the channel will be wrongly considered to be corrupted by IN;

with p=0.99 this will happen to one sample out of one hundred times, etc.

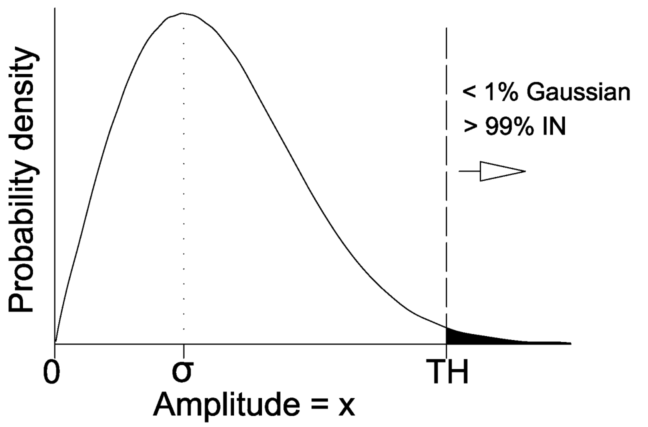

Fig. 4. Rayleigh probability density function with the amplitude threshold TH set at P=0.99.

Setting the threshold with this method is straightforward because in an IQ receiver the parameter σ_{OFDM} can be calculated from the estimated root mean square (rms) value of the signal samples in the following way.

$$\sigma_{\mathrm{OFDM}} = \frac{rms}{\sqrt{2}} = \sqrt{\frac{1}{2N}\sum_{n=0}^{N-1}|s_n|^2} \tag{6}$$

s_n being the signal samples and N the number of samples within a processing frame. Once σ_{OFDM} has been obtained and keeping (5) in mind, the threshold TH can be tabulated from a precalculated set of values as in Table I, for example.

TABLE I
RAYLEIGH THRESHOLD LEVELS FOR DIFFERENT CHOICES OF P

P = 0.99 (99 %)	TH = 3.03· σ_{OFDM}
P = 0.999 (99.9 %)	TH = 3.72· σ_{OFDM}
P = 0.9999 (99.99 %)	TH = 4.29· σ_{OFDM}
P = 0.99999 (99.999 %)	TH = 4.80· σ_{OFDM}

VI. SIMULATION RESULTS

Following, we present a simulation model with the aim of comparing our new cancelling method with the classic TD&B. It simulates a simplified PLC transmission disrupted by IN. The result obtained from the simulation is the bit error rate (BER).

The model consists of a simplified 64-QAM OFDM transmission according to Fig. 1, with N=2048 carriers, of which only 917 are effectively modulated with random information, 237 are idle carriers containing Gaussian noise of 20 dB attenuated power relative to that of the signal, and the rest are padded with zeros. The OFDM symbols are not windowed, have no error control techniques and no guard interval.

After modulation, the model adds IN which is generated in the form of four different sequences, with one, two, four and eight samples per OFDM symbol generated on average. As an example, Fig. 5 shows the whole sequence corresponding to one sample per OFDM symbol. The IN sequences have been generated according to the algorithm expounded in [24]. This algorithm can be considered a variant of the Bernouilli-Gaussian model [25], but with pulse amplitudes generated by a log-normal instead Rayleigh probability distribution function.

Average IN pulse power is 20 dB over the OFDM mean power. The cancelling method and the blanking method are tested for certainty thresholds of 99.00%, 99.90%, and 99.99%, these percentages are probability that the samples exceeding the threshold do not belong to the OFDM signal.

Finally, the signal modulated carriers are recovered and the 64-QAM symbols demapped to calculate the BER. It is important to take into account that in this model BER calculation involves no error control techniques.

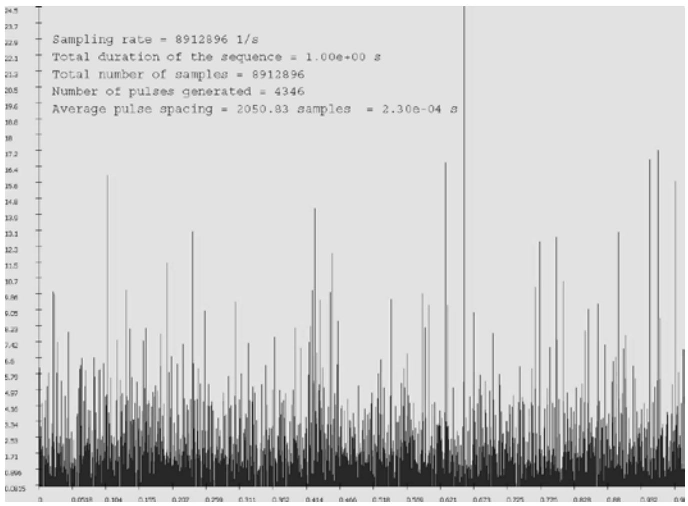

Fig. 5. Example of impulsive noise sequence, generated for the simulation.

Fig. 6 shows the bit error ratio (BER) performance. We see two separated groups of lines corresponding to the two methods used: Our cancelling method and the blanking method. The abscissa axis has four evaluation points, corresponding to the four different IN sequences with one, two, four and eight pulses generated per OFDM symbol. In the dotted line it is represented the lower limit on the assessable BER because the number of bits used for the simulation is $2.39{\cdot}10^7$; any point on this line implies that the BER found is zero.

The results make the high dependence of the blanking method on the threshold value apparent. For example with a threshold of 99% 1 out of 100 samples are blanked even if none of them contains IN, hence the extreme BER near 0.1; only the 99.99% threshold yields fair BER; on the other hand the cancelling method is clearly less threshold dependent. We can see that our new cancelling method outperforms the classic blanking method in two orders of magnitude at least.

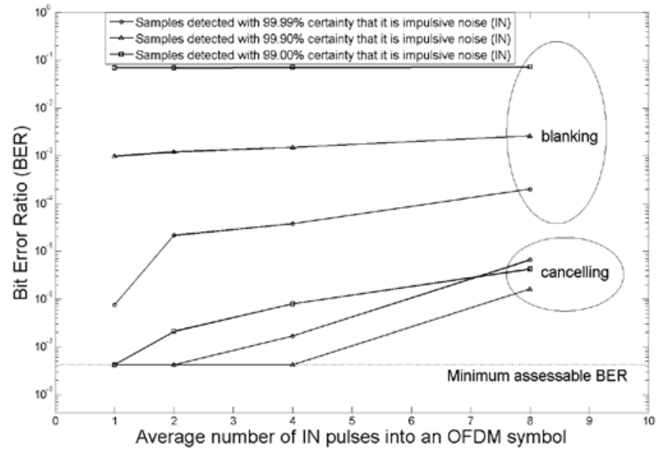

Fig. 6. Simulation results of the cancelling method compared to the classical threshold detecting and blanking method

The results from the simulation demonstrate the advantage of cancelling versus blanking. The relative effectiveness of the classic blanking procedure stems from the fact that losing few samples in an OFDM signal does not damage it too much, but this is not that true when the blanked OFDM samples are by chance of high amplitude. Besides, many IN pulses within an OFDM symbol constitute a serious impairment if we blank them, because the loss of many OFDM samples can be very significant. The cancelling method overcomes these problems.

VII. Conclusion

A novel IN cancelling method for PLC has been presented, consisting of setting a threshold to detect IN pulses and then cancelling them by using the information received in the idle (masked) carriers within the OFDM symbol. Cancelling IN means that the IN is eliminated leaving the original OFDM signal unscathed. A simulating model bas been run in order to compare the method performance versus the classic blanking procedure which consists of setting to zero those samples allegedly containing IN; the cancelling method outperforms the blanking method in two orders of magnitude at least.

VIII. References

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IX. Biographies

Pablo Torío received the Ingeniero de Telecomunicacion degree from the Universidad de Vigo, Spain, in 1995 and the Doctor Ingeniero de Telecomunicación (Ph.D.) degree from the Universidad de Vigo, Spain, in 2005.He began his professional activities at SASIB RAILWAY (currently ALSTOM) as a Signalling and Communications Engineer, in Madrid. In 1997 he worked for TYPSA as a Project Engineer. In 1998 he joined the Departamento de Tecnoloxías das Comunicacións, Universidad de Vigo, as a researcher. Currently he is Director del Departamento de Tecnologia del IES Teis, Vigo, Spain, teaching Tecnología Industrial and Electrotecnia. His research interests include studies on radioelectric noise, digital radio and television, LTE, radio electronics and satellite communication.

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