On the Mitigation of Impulsive Noise in Power-Line Communications With LT Codes

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***Abstract*—In this paper, we present a concatenated coding scheme that mitigates the effect of impulsive noise in orthogonal frequency-division multiplexing-based power-line communications (PLC) systems. What we propose is a novel technique that uses Luby transform (LT) codes as the outer scheme along with irregular low-density parity check (LDPC) codes as the inner code applied on the physical layer. The scheme fully exploits the features of LT codes and mitigates the impulsive noise effect even under high impulse level conditions. By introducing a small percentage of additional packets at the LT transmitter, the packets that are mostly affected by impulsive noise on the PLC channel are treated as erasures at the LT decoding procedure, thus resulting in a reduced error rate. In this innovative scheme, the receiver can identify the packets to be marked as erased even without channel state information, just by taking into account the properties of the inner LDPC code. Furthermore, we propose a method according to which the redundancy introduced by LT codes can be kept at low levels.**

***Index Terms*—Impulsive noise, low-density parity check (LDPC) codes, Luby transform (LT) codes, power-line communications (PLC) channel, raptor codes.**

I. Introduction

COMMUNICATIONS through power lines has recently gained a lot of scientific interest. Their main advantage is that there is no need for extra cabling infrastructure, which reduces costs and time of deployment. On the other hand, the main drawback is that the power-line network was originally not designed for supporting data transmission. As a result, the telecommunication signal undergoes severe degradation caused by frequency-selective fading and impulsive noise.

Since the power-line communications (PLC) channel is a hostile environment for the telecommunication signal, encoding is considered to be fundamental for data protection. A popular and effective coding technique for PLC channels is turbo coding [1], [2]. LDPC codes have been also studied for the PLC channel [3], [4]. They were first introduced by Gallager [5] and are described by their parity check matrix [6], while their performance is enhanced when it comes to irregular LDPC codes and when the soft-decision decoding algorithm, namely the sum-product decoding algorithm, is used [7].

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Recently, a new class of codes, named Fountain codes, has gained a lot of interest. LT codes, a category of Fountain codes, have been introduced by Luby [8]. Soon after, Raptor codes, which are a concatenation of LT codes and another outer coding scheme, became a topic for investigation [9], [10]. These codes are effective on erasure channels. The main concept is that data are processed in terms of packet sequences. The redundancy is introduced in terms of packets, whereas the packet sequence size at the decoder's point is defined by the original information packet sequence size [11]. The performance of LT and Raptor codes has been studied on the PLC channel for the physical and the application layer in [12] and [13], respectively. The growing interest in Fountain codes has motivated this work for further investigation.

In this paper, LT and Raptor codes are studied on the power-line channel. For the implementation of Raptor codes, irregular LDPC codes are chosen along with LT codes. In order to improve system performance, we propose to invert the sequence of the two coding schemes considered in Raptor codes. The idea is to interpose between the LT encoder and the LT decoder in an LDPC-protected PLC system, where some packets will be marked as erased, so that LT codes can function under the conditions of a binary erasure symmetric channel (BESC). Since the impulsive noise in the PLC channel occurs in bursts, some packets are highly affected by it, while others are not. With the proposed technique, the packets that entail a great number of errors are marked as erased, thus allowing the LT decoder to treat them as erasures. It is the LT decoder nature that allows us not to consider some packets for data recovery at the decoding process. On the other hand, LDPC codes' properties enable us to identify the erased packets at the receiver, which completes the picture. By implementing the proposed technique, not only is the performance enhanced, but also the system complexity remains at similar levels. Finally, we propose a modification that can lead to a reduction of redundancy in the encoding process. The contribution of this paper is summarized as follows.

- We consider OFDM transmission on a PLC channel affected by multipath fading and impulsive noise.
- We propose using a concatenation of LDPC and LT codes, with the latter being the outer scheme, contrary to Raptor codes, in order to improve the system performance.
- We propose implementing an innovative erasure decoding technique to mitigate the effect of impulsive noise.
- We present a technique to maintain the redundancy introduced by coding at acceptable levels.
- We report several performance results for various impulsive noise conditions.

The rest of this paper is organized as follows. Section II describes the system model, while in Section III, the coding schemes are analyzed. In Section IV, the performance of LT and Raptor codes on the PLC channel is shown. In Section V, the proposed method is analyzed and the simulation results are reported. Finally, the conclusions are drawn in Section VI.

II. System Model

A. OFDM and Coding Techniques

The system realization is performed by using the popular OFDM transmission technique, mainly due to the robustness it offers in multipath fading environments. The LT and LDPC codes are considered along with binary phase-shift keying (BPSK) modulation. More details about the OFDM characteristics and codes properties appear in the following sections.

B. PLC Channel and Noise Model

To evaluate performance, we will consider the statistically representative channel model described in [14]. A given channel frequency response is obtained by

$$G_{CH}(f) = A\sum_{i=1}^{N_P} g_i e^{-\left(a_0+a_1 f^K\right)d_i} e^{-j2\pi f(d_i/v_P)}, 0 \leq f \leq B. \tag{1}$$

It is assumed that a finite number N_P of multipath components is taken into account [15]. The number of paths and their lengths are drawn from a Poisson arrival process with pathrate per-unit length equal to $\Lambda = 0.2$ and maximum path length $d_{\max} = 800$ m. The parameters are defined as $K = 1$, $a_0 = 0.3 \cdot 10^{-2}$, $a_1 = 4 \cdot 10^{-10}$, $v_P = 2 \cdot 10^8$, and the path gains g_i are uniformly distributed in [-1, 1]. More details can be found in [14]. The band 0–37.5 MHz is used for channel generation, while the subchannels in the 2–28 MHz band are used for information transfer. The most important application scenario is home networking and multimedia signal transmission.

The noise comprises background and impulsive noise [16]. The background noise is modelled as white Gaussian. On the other hand, the impulsive noise is assumed to occur in bursts. It is characterized by the impulse duration, its amplitude statistics, and the interarrival time between subsequent impulses. We assume the latter parameter to be exponentially distributed with mean λ[17]. The impulse duration t_d follows a uniform distribution. Finally, the amplitude is assumed to be Gaussian with zero mean and variance σ_i^2. The ratio between the background noise and the impulsive noise is defined as $\Gamma = \sigma_w^2/\sigma_i^2$. The parameters used in this paper will be defined in detail in Section V-B.

III. Coding Techniques

A. Characteristics of LT Codes- Encoding Procedure

LT codes belong to the category of Fountain codes. They are very effective when applied on erasure channels. Their main concept is that redundancy is introduced in terms of packets and data is processed in sequences of packets. Therefore, for a given number K of packets for transmission, a sequence of R packets is produced. Each of them is produced out of a certain number of source packets after performing the *xor* operation among its equivalent data bits. The number of source packets that take part in this procedure is the so-called degree. For the entire encoded packets sequence, a generator matrix is defined. The generator matrix is set to be fixed for multiple transmissions and can be produced by a deterministic random-number generator. In (2), an example of a simple generator matrix $\boldsymbol{G}$ is shown for $K = 4$, $R = 5$.

$$\mathbf{G} = \underbrace{\left.\begin{bmatrix} 1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 \end{bmatrix}\right\} K.}_{R} \tag{2}$$

The positions of the aces identify which source packets are utilized. Another characteristic of these codes is that the value of R can be flexible, but larger than a value N for successful decoding. So, the encoding procedure can be described as follows.

- For each encoded packet, a different degree d_j is chosen from a particular distribution.
- The d_j source packets are randomly picked.
- The xor operation is performed among their equivalent bits.
- An iteration round of the encoding process is completed.

Assuming that source packets are called $z_i, i = 1, \ldots, K$ and encoded ones are called $c_j, j = 1, \ldots, R$, each encoded packet is related to the source data blocks according to

$$c_j = \sum_{i=1}^{K} z_i \cdot G_{ij} \tag{3}$$

where G_{ij} is the element in the ith row and jth column of the generator matrix and the summation implies modulo two operations. An ace in the ith row and jth column of the matrix means that the ith source packet has participated in the production of the jth encoded one [11].

B. Decoding of LT Codes

The decoding procedure can be realized through an iterative message passing algorithm and it shares similarities with graph codes decoding. Assuming that the encoded packets connected to the ith source packet are denoted with $A(i)$, the decoding can be summarized in the following steps:

a) Determine a received packet c_j whose degree during the encoding process equals $d_j = 1$.
b) Set $z_j = c_j$. This source packet is now determined.
c) Use the xor operation between z_i that was determined at the previous step and the set of c_j' that are connected to it, with $j' \epsilon A(i) \backslash j$

$$c_{j'} \oplus z_j.$$

d) Remove all connections entailing z_i.
e) Repeat step a) until all source packets are determined.

Attention should be paid at step a. If a packet with $d_j = 1$ is not found, the decoding process records a failure and data recovery is not further possible [11]. For the realization of the decoding, the knowledge of the generator matrix is of vital importance. For this purpose, it is assumed that a generator, which is identical as the one used by the transmitter and synchronized to it, can be applied for the matrix reproduction.

C. Role of the Degree Distribution in LT Codes

As it has been aforementioned, the decoder's proper function is closely related to the existence of degree one received/encoded packets. Therefore, the degree distribution plays an important role in the LT codes. Degree distribution design should ensure the presence of low and high degree packets for the correct decoder operation and the connection of each source packet to at least one encoded packet.

The LT encoded packets degree is described by the soliton distribution. Ideally, at each iteration round of the decoder, the degrees are decreased so as a new packet with degree one comes out. These conditions are achieved by the ideal soliton distribution [11], [18], having a probability mass function

$$P_d(a) = \frac{1}{K}, \qquad \text{for } a = 1$$
$$P_d(a) = \frac{1}{a \cdot (a-1)}, \qquad \text{for } a = 2, 3, \ldots, K. \tag{4}$$

This distribution is not so much effective as K increases, leading to a possible decoding failure. Therefore, an improved version, the so-called robust soliton distribution, comes to cope up with this defect. The new probability mass function is

$$p_{d'}(a) = \frac{p_d(a) + p_g(a)}{Z} \tag{5}$$

$$Z = \sum_{u=1}^{K} [p_d(a) + p_g(a)]. \tag{6}$$

The auxiliary term $p_g(a)$ is defined as

$$p_x(a) = \begin{cases} \frac{Q}{(K \cdot d)}, & a = 1, 2, \ldots, (\frac{K}{Q}) - 1 \\ Q \cdot \frac{\ln(\frac{Q}{\delta})}{K}, & a = \frac{K}{Q} \\ 0, & a > \frac{K}{Q} \end{cases} . \tag{7}$$

The parameter Q stands for the total number of degree-one packets and is given by

$$Q = \lfloor c \cdot \ln(\frac{K}{\delta}) \cdot \sqrt{k} \rfloor. \tag{8}$$

The parameter Q as well as K/Q are rounded to the nearest integer, while δ indicates a bound on the probability that the decoding experiences a failure after the reception of a specific number of packets. The parameter c is a constant and can be characterized as a "free parameter" usually chosen to be minor than one [11]. The number of packets required for the decoder to function properly with a probability of $(1 - \delta)$ is $N = K \cdot Z$. If the number of received packets R is defined as $R \geq N$, then the success decoding probability is below $1 - \delta$[11], [18].

The desired probability of decoding failure determines the redundancy introduced to the system in terms of additional packets sent by the transmitter. For instance, $\delta = 0.02$ means a maximum decoding failure of 2%. Fig. 1(a) shows the redundancy (red) introduced in terms of a fraction of the number of encoded packets to the number of source packets $(red = R/K)$, assuming that $R = N$, for a fixed value of $K(K = 650)$ and by varying the parameters c and δ. The minor fluctuations appearing on the graph derive from the way to compute redundancy via the soliton distribution.

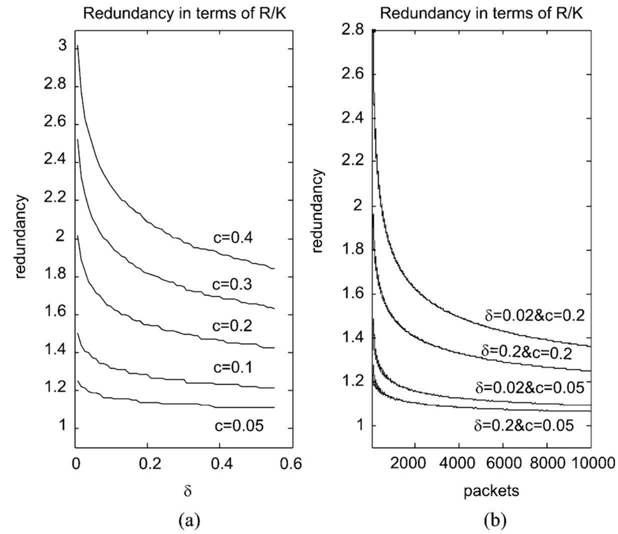


Fig. 1. Redundancy $(red = R/K)$ introduced by LT and Raptor codes for (a) different values of c and δ, with $K = 650$ and (b) for different values of K with fixed c and δ.

The redundancy defined as $red = R/K$ is also a function of the initial source packet sequence size. As the number of source packets is increased, the redundancy of the coding scheme that uses the soliton distribution is reduced. Fig. 1(b) shows the resulting ratio R/K versus K.

D. Raptor Codes

Raptor codes are an extension of the LT codes described above. They are a concatenation of LT codes and a powerful outer coding scheme, used to compensate for errors that LT codes cannot cope with. A sophisticated distribution, like the robust soliton distribution can be avoided, since the outer coding scheme makes up for a potential inefficiency. LDPC codes are chosen in this paper to form raptor codes.

E. LDPC Codes

LDPC codes belong to a subgroup of Linear Block Codes. These codes are characterized by their parity check matrix, $\boldsymbol{H}$, which is a sparse matrix. In case $\boldsymbol{v}$ is a codeword, the following relation holds true:

$$\boldsymbol{H} \cdot \boldsymbol{v}^T = 0. \tag{9}$$

A code rate of k/n results in a parity check matrix with size $(n - k) \times n$. An important aspect of LDPC codes is that their parity check matrix can be described via a bipartite graph, facilitating the decoding procedure.

The class of LDPC codes used in this paper is the quasicyclic (QC) LDPC codes. It is characterized by a parity check matrix consisting of square blocks, which facilitates the encoding procedure [19]. These blocks could either be circulant permutation matrices based on the identity matrix or matrices with all-zero components. All nonzero permutation matrices $\boldsymbol{P}^i$ of size $q \times q$ are derived from the identity matrix (I), after shifting its columns to the right by i times $(0 \leq i \leq q)$. It is crucial that the parameter q is set to a prime number and that the inequality $q \geq m \geq j$ is not violated; otherwise, the coding technique will not operate properly. The parameters m and j are related to the parity check matrix design as well as the resulting code rate r

$$r = \frac{1-j}{m}. \tag{10}$$

The decoding is performed via an iterative algorithm, also known as a sum-product decoding algorithm [7].

IV. LT and Raptor Codes Applied on the PLC Channel

In this section, the performance of LT and Raptor codes is examined on the PLC channel in terms of impulsive noise and coding characteristics as follows. The encoded packet size is set to 1552 data bits for both LT and Raptor codes. This is due to the aforementioned limitation $q \geq m \geq j$ of QC–LDPC codes, according to which, the encoded packet size cannot take a random value. Including a cyclic prefix of 248 points, the OFDM symbol size results in 1800 points.

Regarding the impulsive noise, it is considered to occur in bursts. In accordance with Section II-B, we set $\Gamma = 0.1$, meaning that the impulsive noise variance exceeds the background noise 10 times. The mean λ of the interarrival time is set to $\lambda = 0.015$, while the impulse duration t_d is uniformly distributed with 10 $\mu\text{sec} < t_d < 1$ ms. As a result, an average 5% of the total packets are affected.

As explained in the previous section, LT and consequently Raptor codes have the characteristic of adding additional packets to the initial source packets sequence. This is actually the main difference from the usual error correcting codes, meaning that redundancy is not introduced in terms of parity bits in the codeword. The LT and Raptor codes performance is examined under the two different distributions explained before, the ideal soliton distribution and the robust soliton distribution. In Raptor codes, a $1/2$ LDPC code rate is utilized.

We set the parameters defining the soliton distribution as $c = 0.2$, in order to obtain good results without increasing too much redundancy [11] and $\delta = 0.02$, thus ensuring that the decoding will run to completion with a probability of at least 98%. As a result, by adjusting the initial sequence of packets to $K = 650$, the number of packets needed by the decoder is $N = 1228$. So we can set $R = N$ as the number of encoded packets. It should be noted at this point that the redundancy concerning the LT codes can be highly decreased; however, at the cost of the decoder reliability, as explained earlier.

Fig. 2 shows the performance of LT and Raptor codes in the presence of impulsive noise on the power-line channel. The impulsive noise is considered to be 10 and 20 dB stronger than the background noise level in Figs. 2(a) and (b), respectively. The results show that Raptor codes provide a gain for high E_b/N_0 values. On the other hand, LT codes cannot cope up with the conditions of the power-line channel since, due to their structure and decoding algorithm, a single error spreads through the decoding procedure and generates multiple final errors. Raptor codes introduce a significant improvement, which is anticipated, since the LDPC outer codes are a powerful coding scheme. It is also noticeable that the two distributions have a small effect on the performance. For a fair comparison, we show the E_b/N_0 instead of signal-to-noise ratio (SNR) versus bit-error rate (BER) in order to include the effect of different code rates.

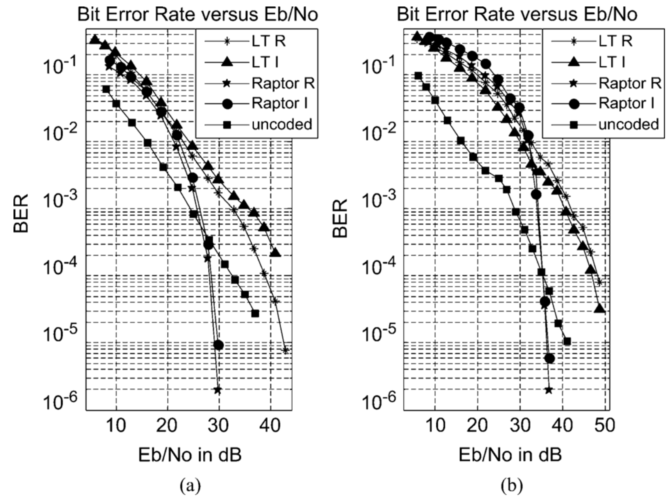


Fig. 2. BER versus E_b/N_0 for LT and Raptor codes (LDPC and LT codes) with the ideal (LT I, Raptor I) and the robust soliton distribution (LT R, Raptor R), noise. (a) 10 dB stronger than N_0. (b) 20 dB stronger than N_0.

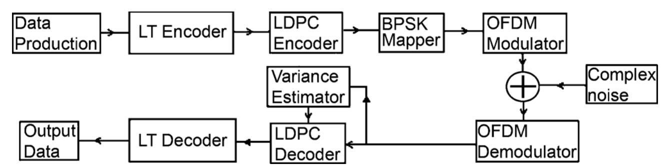


Fig. 3. System block diagram.

Fig. 2 shows that this scheme does not work well on the PLC channel, which motivates further research around the subject. The goal is to exploit the characteristics of LT codes to reduce the effect of PLC impulsive noise.

V. Mitigating Impulsive Noise—Proposed Combined Coding Technique

A. LT Codes as the Outer Coding Scheme—Exploiting the Properties of LT and LDPC Codes

According to Section IV, one might jump into the conclusion that LT codes are not suitable for the PLC channel, introducing impulsive noise. However, what we propose in the following is an alternative concatenated coding scheme, applied for the first time—to the best of our knowledge—for the mitigation of PLC impulsive noise. The concept is to interpose between the LT-encoder and the LT-decoder a low noise channel, by replacing the PLC channel by an LDPC protected PLC system. Our goal is to create the conditions of a BESC, where the usage of LT codes can be effective. This could improve the system performance for moderate-to-high values of E_b/N_0, where the background noise is kept at low levels. Fig. 3 shows the block diagram of the proposed scheme applied on the PLC channel.

The main concept is derived by the fact that the power-line impulsive noise occurs in bursts, which results in affecting a successive number of packets, whereas others remain unaffected. The key point is that the LT decoder can properly function when the number of received packets exceeds a particular value. Once this value is reached, any additional packets may be excluded from the data recovery process, by treating them as erasures. Our idea is to mark as erased the packets that entail the greatest number of errors -which are effectively those affected by impulsive noise. Afterwards, these are allowed not to be considered in the LT decoding procedure, resulting in reproducing the original data with the maximum accuracy. To achieve the success of this technique, a small percentage of additional packets are sent by the transmitter. To be more precise, we set $R > N$ as the number of packets sent by the LT transmitter and, in particular, $L = R - N$, where L is the number of packets to be treated as erasures at the decoder. The parameter L is kept constant and is actually chosen based on the assumption of the impulsive noise rate. In particular, L is set to be equal to the average impulsive noise rate, which is the number of packets that are, on average, hit by impulsive noise.

Nevertheless, distinguishing the erased packets is another problem that we need to overcome. To tackle with this matter and identify the packets to be marked as erased, we take advantage of the characteristics of the inner LDPC coding scheme. The LDPC decoder uses an iterative algorithm to process the data. At the end of each iteration round, the syndrome $\boldsymbol{s}$ is computed

$$\mathbf{s} = \mathbf{H} \cdot \hat{\mathbf{v}}^T \tag{11}$$

where $\hat{\mathbf{v}}$ stands for the estimated codeword $\hat{\mathbf{v}} = [\hat{v}_1\ \hat{v}_2\ \dots\ \hat{v}_n]$, $\boldsymbol{s}$ is in matrix form $\hat{\mathrm{s}} = [\hat{s}_1\ \hat{s}_2\ \dots\ \hat{s}_n]$, and $\boldsymbol{H}$ stands for the parity check matrix, as defined in the encoding process

$$\mathbf{H} = \begin{bmatrix} h_{1l} & \dots & h_{1n} \\ \vdots & & \vdots \\ h_(n-k)1 & \dots & h_(n-k)n \end{bmatrix}.$$

It is noted here that $\boldsymbol{s}$ represents the error pattern that occurred during the transmission. It contains zero components for all parity check equations that are satisfied and nonzero components for the ones that are not satisfied. We take into account a metric defined as

$$S = \sum_{i=1}^{n-k} s_i \tag{12}$$

which can also be written as $S = \sum_{i=l}^{n-k} \sum_{j=1}^{n} h_{ij} \cdot \hat{v}_j^T$, with the second summation implying modulo 2 additions. By considering the vector $\hat{\boldsymbol{e}} = [\hat{e}_1\ \hat{e}_2\ \dots\ \hat{e}_n]$ to be the error vector introduced during transmission and by taking into account that every codeword has a zero syndrome vector, it is easily derived that

$$S = \sum_{i=l}^{n-k} \sum_{j=1}^{n} h_{ij} \cdot e_j. \tag{13}$$

As expected, the value $\sum_{j=1}^{n} e_j$ is increased as the errors introduced to our data become more frequent. We assume two error vectors occurring under two different channel conditions. In the first situation, very few errors are introduced, whereas on the second, many errors are introduced. We obtain $\sum_{j=1}^{n} e_j = a \rightarrow 0$ and $\sum_{j=1}^{n} e_j = b \rightarrow n$, respectively, which further gives us S_a and S_b. For metric S_a, it results in $S_{a(\max)} \rightarrow 0$ (very few errors introduced), whereas for metric S_b, it is $S_{b(\max)} \rightarrow (n-k)$ (too many errors introduced). For a large value of n, the average value of S_b becomes $S_{b(av)} \approx (n-k)/2 > a$. So we obtain

$$S_{b(av)} > S_{a(\max)} \geq S_{a(av)}. \tag{14}$$

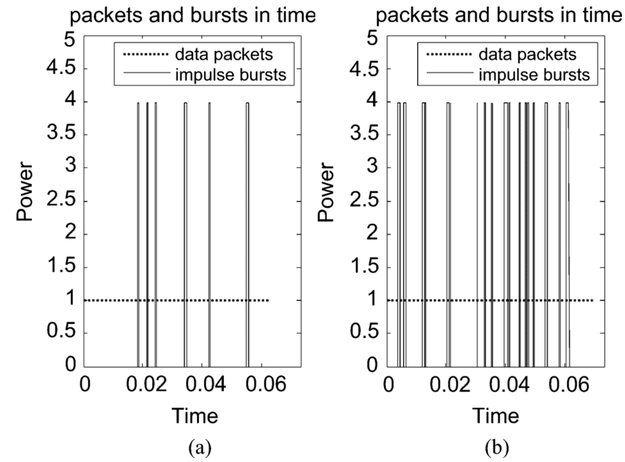


Fig. 4. Packet transmission and impulse bursts in time with (a) $p = 5\%$ and (b) $p = 15\%$ of packets affected by impulsive noise, respectively.

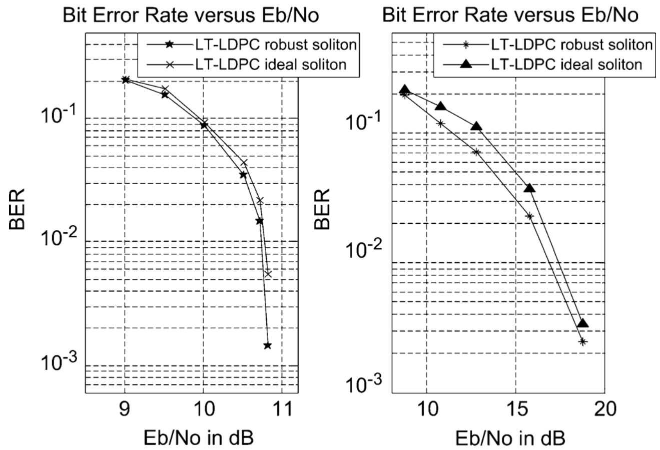
Although it is not proved that the minimum syndrome weight corresponds necessarily to the minimum weight error vector, the two variables appear to have a linear dependence [20]. As a result, the metric S, which is easily produced at every iteration round in the LDPC decoding process, can be considered as a reflecting metric of the received codeword error weight. What we propose is to use this metric to distinguish which packets shall be treated as erasures at the decoding process. The L packets entailing the highest syndrome level are considered to contain the greatest number of errors. They are marked as erased and are not taken into account at the data recovery process at the LT decoder.

B. Simulation Results

In this section, the results obtained with the proposed technique are illustrated. Both the ideal and the robust soliton distribution are used for the generation of the LT packets. Furthermore, the LDPC encoded word length is set at 1552 b with a code rate of $1/2$, resulting with BPSK modulation in an OFDM symbol including the cyclic prefix of length 1800. The LT encoded packet has a length of 776 b, while $K = 650$ source packets are considered.

Regarding the impulsive noise, the same parameters are considered as explained in Section IV, that is, $\lambda = 0.015$, 10 μs $< t_d < 1$ ms, and $\Gamma = 0.1$. Thus, we obtain that, on average, 5% of the transmitted packets are affected by impulsive noise. Fig. 4(a) shows in time domain the transmission of data packets along with the impulse bursts occurring during the transmission. Since $\Gamma = 0.1$, the impulse level exceeds the background noise 10 times. In Fig. 4(a), the SNR is set to 4 dB. The total number of sent packets results in 1300, with an OFDM packet duration at 4.8 μs.

By altering the bursts interarrival time parameter λ, while keeping the rest of the parameters unchanged, the intensity of impulses changes. Particularly, by decreasing λ to $\lambda = 0.003$, the bursts occurrence becomes more frequent, resulting in 15% of the transmitted packets to be influenced. To balance the negative effect, more additional packets need to be sent by the transmitter. Fig. 4(b) shows in time domain the impulse noise occurrence along with data transmission, with an OFDM packet duration at 4.8 μs, $SNR = 4$ dB, $S = 0$ dB (signal power) and a number of sent packets equal to 1444.



(a) (b)

Fig. 5. BER versus E_b/N_0 for concatenated LT and LDPC codes, with LT as the outer scheme (a) with and (b) without the method of treating packets as erasures at the decoding procedure.

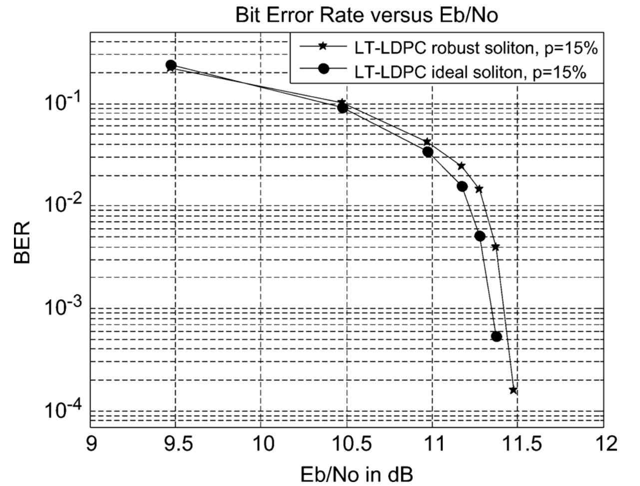


Fig. 6. BER versus E_b/N_0 for concatenated LT and LDPC codes, with LT as the outer scheme with the proposed method, and with $p = 15\%$ of transmitted packets affected by impulsive noise.

Fig. 5(a) demonstrates the performance of the proposed scheme in terms of BER, with $p = 5\%$ of packets affected by impulsive noise. It is reminded at this point that Fig. 2(a) shows the performance of LT and Raptor codes, as well as the uncoded scenario under the same channel and noise conditions. Comparing Figs. 5(a) and 2(a), it can be concluded that the performance obtained from the proposed scheme has been significantly enhanced with respect to LT and Raptor codes, even for low E_b/N_0 values. It is noticeable that the curves in this figure follow a very sharp decline after a certain E_b/N_0 value. It is also noteworthy that the proposed method is successful with respect to the recovery of original data for $E_b/N_0 \geq 10.9$ dB and with a BER below $9.91 \cdot 10^{-7}$. In addition, the two distributions perform in a similar manner. Even if the nonsophisticated distribution is used, the alteration to the system performance is in the order of 1 or 2 dB. For reasons of completeness, we also show in Fig. 5(b) the performance when the proposed coding scheme is introduced; however, without the technique of treating packets as erasures at the decoder. It is obvious that when the proposed technique is not introduced, the performance deteriorates, since the potentials of LT codes are not exploited.

Further on, we test the performance of the proposed technique under the conditions of more intense impulsive noise. Fig. 6 shows the performance of the scheme when more intense impulsive noise ($p = 15\%$) is present. The conclusions are similar for this case, as well. It is remarkable that the proposed technique introduces a very sharp decline to the BER curve, while it is successful for $E_b/N_0 \geq 11.6$ dB and a BER in the order of $6.6 \cdot 10^{-7}$. It is clear from Fig. 6 that the scheme is effective even under conditions of severe impulsive noise. Consequently, it could lead to a successful data recovery when the signal is transmitted through a highly impulsive channel. It is also noteworthy that the effectiveness of the proposed method does not strongly depend on the impulse noise power.

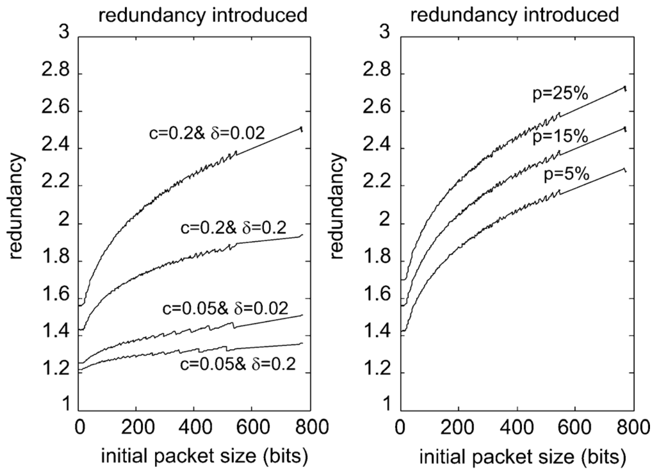
C. On the Improvement of the Proposed Coding Scheme

A problem involved with the proposed coding technique and, in general, with LT codes is the redundancy introduced. As was explained before, the decoder needs a certain number of packets in order to produce the transmitted sequence of source packets error-free. In a different case, the decoder fails to function properly. The redundancy is expressed in terms of the final number of packets transmitted as opposed to the number of source packets produced. However, by decreasing the number of packets in the source sequence, the redundancy of the code scheme that uses the soliton distribution is raised.

In the previous section, an encoded LDPC word of 1552 bits was used, whereas the LT encoded packet entailed 776 bits. A first thought would be to increase the number of source packets produced, in order to obtain a final sequence of transmitted packets leading to a smaller redundancy. Nevertheless, this would mean that the decoder would "wait" for the entire sequence of packets to be received before initiating the decoding procedure, thus increasing the latency.

Our idea is to reduce the redundancy without increasing the latency. Therefore, we propose enlarging the initial set of LT packets and, on the other hand, reducing the original packet length. Enlarging the LT source packet sequence leads to a decreased redundancy, as explained earlier. Reducing the original packet length means that the total number of data bits sent by the transmitter could remain unaffected. A nonaltered or even decreased number of bits needed at the receiver's point before initializing the decoding procedure results in a nonaltered or decreased latency. Thus, we propose using a smaller LT packet size, whereas multiple LT packets are combined to form one LDPC packet. This ensures that the OFDM method parameters remain the same for comparison with the results obtained for a longer LT packet.

In Fig. 7, we give an overall picture of the redundancy introduced by LT encoding as a function of the LT source packet size. The computations are performed with a lower boundary of packet size at 10 bits. The metric presented in Fig. 7 is also a function of the number of LT packets used to form the LDPC encoded word considering a cyclic prefix of around 20% and an OFDM symbol size from 1024 to 2048 points. Assuming that the desired BER is on the order of 10^{-6}, the variables K and N of the LT encoder are calculated. We consider the number of packets affected by impulsive noise as $L = R \cdot p$, with p as the percentage of these packets. Consequently, the redundancy is



(a) (b)

Fig. 7. Redundancy introduced to the proposed concatenated coding scheme by LT encoding in terms of the LT packet size. (a) For different values of c and δ. (b) For a different percentage of packets affected by impulsive noise.

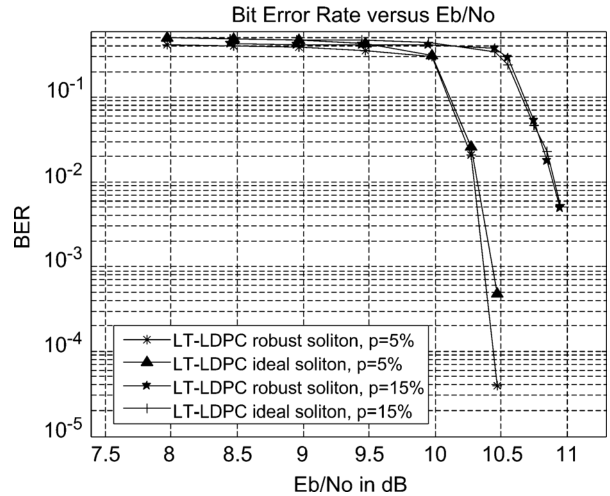


Fig. 8. BER versus E_b/N_0 for concatenated LT and LDPC codes, with LT as the outer scheme with the proposed method. $p = 5\%$ and $p = 15\%$ of transmitted packets affected by impulsive noise, LT packet size: 79 b.

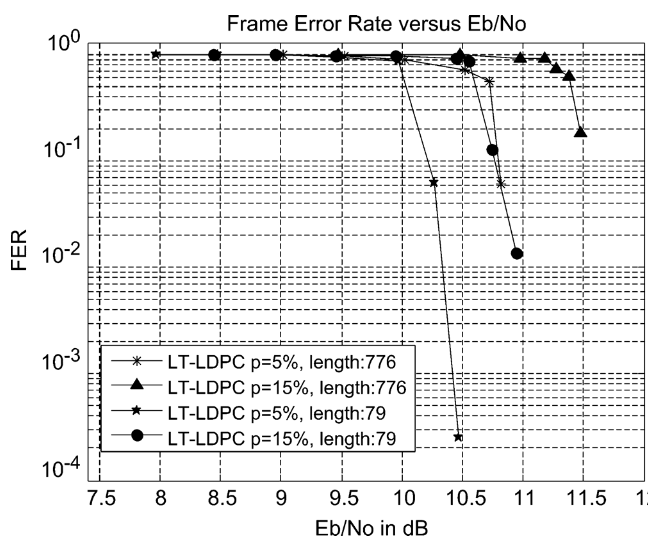


Fig. 9. FER versus E_b/N_0 for concatenated LT and LDPC codes, with LT as the outer scheme with the proposed method. $p = 5\%$ and $p = 15\%$ of packets affected by impulsive noise.

computed as the ratio of transmitted packets to the initial source packets, that is, R/K. In Fig. 7(a), the redundancy is computed for $p = 15\%$, whereas different values of c and δ are used. In Fig. 7(b), we set $c = 0.2$ and $\delta = 0.02$ along with different values of p. The resulting curves do not appear to be smooth, since the OFDM symbol size is not the same for every LT packet size. This is derived from the variable LDPC codeword length, due to the limitation imposing that the parity check matrix construction should not violate the rules explained before. To examine the performance of the new proposed technique, we again implement the idea of treating the packets, which are affected by impulsive noise, as erasures at the LT decoder. We take into account the cases of less and more severe impulsive noise, considering $p = 5\%$ or $p = 15\%$ of the transmitted packets to be affected by impulsive noise. To test this coding scenario, we use an LT packet size of 79 bits, whereas 10 LT encoded packets form one word entering the LDPC encoder. The resulting LDPC encoded word becomes size 1580 with a code rate of $1/2$, while the entire OFDM symbol remains at 1800 points with a cyclic prefix of 220 points. The alteration in the LDPC codeword size occurs because of the parity check matrix construction rules. With this modification, we set $K = 4004$, $N = 5970$ at the LT encoder, leading to a total number of 597 LDPC packets transmitted. Consequently, the redundancy is reduced, whereas the latency is not increased. On the contrary, this method contributes to latency reduction, since the adequate number of packets for the decoding process initialization is smaller than in the case for a longer LT packet.

The final number of OFDM packets transmitted by the system is 629 and 702 for each impulsive noise scenario, respectively. Fig. 8 illustrates the system performance for these two scenarios. It is noticeable that the benefit of implementing the technique of treating the packets affected by impulsive noise as erasures at the receiver can be experienced along with a reduced LT encoder redundancy. It is also clear that the altered scheme also experiences very good performance especially above a certain E_b/N_0 value. The conclusions are similar to the case of longer source packets. A remarkable enhancement is experienced for $E_b/N_0 \geq 10.5$ and 11 dB for $p = 5\%$ and $p = 15\%$, respectively, where the method is successful, with a BER on the order of $1.58 \cdot 10^{-6}$. Likewise for the previous case, the two different distributions at the LT encoder make little differentiation on the performance.

Altering the packet size has also an effect on the resulting frame error rate (FER). Fig. 9 depicts this effect and it shows the FER versus E_b/N_0. As is clear from the graph, with a longer packet, the FER is higher.

D. Tolerance on the Impulsive Noise

In this section, we examine the tolerance of the proposed scheme to various impulse noise intensities. Therefore, we design the proposed coding scheme to compensate for a 10% of packets being affected by impulsive noise and we set $K = 650$, $N = 1228$, $R = 1365$. Fig. 10 illustrates the system performance for a packet length of 776 and 79 b, respectively. We fix the E_b/N_0 and plot the BER for different values of p (percentage of packets affected by impulse noise).

Fig. 10 shows that for a sufficient level of E_b/N_0, like the middle E_b/N_0 value of the ones examined, the proposed

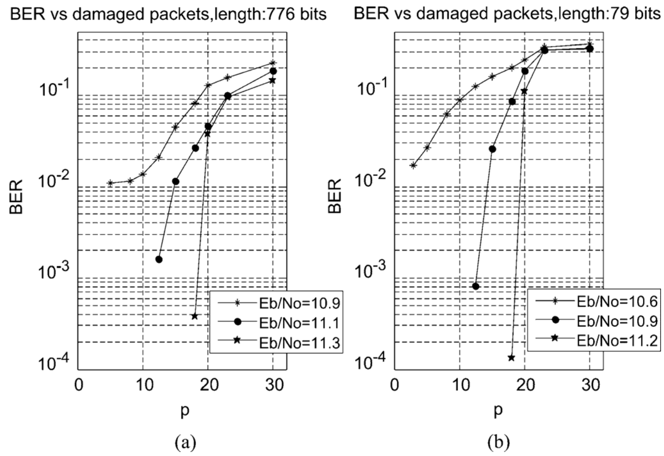


Fig. 10. BER versus the percentage p of damaged packets for fixed values of E_b/N_0. (a) Packet length: 776 bits. (b) Packet length: 79 bits.

scheme operates very well when $p < 10\%$, since it is designed to cope up with a level of 10% packets expected to be hit by impulsive noise. After this boundary value of p, the performance deteriorates; however, there is a tolerance of 5% extra packets hit by impulse noise for which a $BER < 10^{-2}$ can still be achieved. As the E_b/N_0 value increases, the performance is improved and the system becomes more tolerant to impulsive noise. A BER lower than 10^{-3} can be achieved with p up to 18%, which is noticeable in both considered packet lengths.

VI. Conclusion

In this paper, an innovative method has been proposed to mitigate the effect of the impulsive noise introduced by the PLC channel. The utilization of concatenated LT and LDPC codes, with LT being used as the outer coding technique has been proposed. According to the proposed technique, an LDPC protected channel is interposed between the LT encoder and the LT decoder. The novelty lies behind the fact that the packets being mostly affected by the impulsive noise are identified as erased and are thus not considered in the data recovery at the LT decoding procedure, leading to enhanced performance. LDPC codes used as the inner scheme contribute toward this direction. The syndrome produced by the LDPC decoder is used as a metric to inform the LT decoder about which packets are marked as erased. In addition, we also consider a reduced redundancy scheme that still exhibits high performance. The redundancy as a function of the LT source packet size is also studied. Finally, the robustness of the scheme as a function of the impulsive noise rate is investigated. The results show that high robustness is achieved for various levels of impulsive noise.

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