Minimum-Redundancy Link-Layer Code Design for the Railroad Satellite Channel

Lam Pham-Sy*, Valentin Savin†, Nghia Pham*, and David Declercq‡

* EUTELSAT S.A., 70 rue Balard, 75015 Paris, France
† ETIS ENSEA/UCP/CNRS UMR 8051, 95014 Cergy-Pontoise Cedex, France
‡ CEA-LETI, MINATEC Campus, 17 rue des Martyrs, 38054 Grenoble, France

This paper deals with the design of link-layer codes for the DVB-S2 forward link providing service to high-speed trains. Obstacles as electrical trellises or power arches placed aside the tracks induce deep signal fading effects, resulting in frequent and nearly periodic loss bursts of data packets. We focus on the design of minimum-redundancy link-layer codes that exploit the periodicity of the deep fading events. Our approach is based on a two-layer parity-check matrix. The first layer is dedicated to the correction of erasure bursts that occur during the quasi-periodic deep fading periods. The second layer is optional, and it is dedicated to the correction of erased symbols that may occur due to occasional physical-layer failures during the line-of-sight state. The proposed design is integrated to a DVB-S2 system, and we show that it allows reliable data transmission, when the same content is broadcasted to several trains travelling on different tracks, with different speeds and in different directions.

I. Introduction

The paper focuses on the design of link-layer codes for the DVB-S2 forward link providing service to high-speed trains. Reliable data transmission to trains through satellite links, such as the Box TGV™ service operated by the French railway SNCF since 2010 (https://boxtgv.voyages-sncf.com/), is a very challenging task, especially since line of sight connection is frequently interrupted by obstacles between the satellite and the mobile receiver. Obstacles as electrical trellises or power arches placed aside the tracks induce deep signal fading effects, resulting in frequent and nearly periodic failures of the physical-layer [1][2].

Two main approaches can be applied in order to cope with physical layer failures. The first one consists of using a physical layer interleaver that disperses the effect of deep fading events among several physical layer Forward Error Correction (FEC) codewords. Since deep fading events may affect several tens of physical layer frames, such an approach would require a large memory space to store the interleaved codewords.

The second approach consists of using an erasure code at the Link-Layer (LL) of the communication system [3]. Unlike physical layer FEC codes that operate at the bit level, LL codes operate on data packets, also referred to as LL symbols, and they deal with erasure channels, i.e. a channel that either transmits the data unit correctly or erases it completely. The encoding process computes redundant LL symbols. Both source and redundant LL symbols are delivered to the physical layer, and then transmitted over the channel. At the receiver end, the physical layer failures translate into erased symbols at the LL level, which are eventually recovered after the LL decoding process.

The performance of erasure codes can be analyzed precisely, and a flurry of research papers has already addressed this issue. Low-Density Parity-Check (LDPC) codes [4] with iterative decoding [5] proved to perform very close to the channel capacity with reasonable complexity [6][7]. Moreover, “rateless” codes that are capable of generating an infinite sequence of redundant symbols were proposed in [8][9]. While this paper investigates the use of LDPC codes, the goal is to propose a simple code design that is able to effectively deal with both periodic erasure bursts and isolated erased symbols, while generating a minimum number of redundant symbols. Moreover, the same code must be able to protect the communication system, in case the same content is broadcasted to several trains travelling on different tracks, with different speeds and in different directions.

The paper is organized as follows. Section II gives a brief overview of the railroad satellite channel and defines the problem to be solved. Section III presents the proposed code design and describes its integration into a DVB-S2 system. Simulation results are presented in Section IV. Finally, Section V concludes the paper.
II. Channel model and problem definition

On an erasure channel, each transmitted symbol is either received correctly or lost (erased). When the erasures are clustered together, each cluster of erasures is referred to as a burst. If the bursts occur periodically, as shown in Figure 1, we refer to the channel as a (burst-) periodic erasure channel. This channel model is a simplification of the Gilbert-Elliott channel model [10][11].

A periodic channel can be parameterized by two variables: (i) the burst-length, \(m\), that is the number of symbols erased during one burst; (ii) the burst-distance, \(N\), that is the maximum number of transmitted symbols that can only be affected by at most one burst.

![Periodic Erasure Channel](image)

Figure 1: Periodic Erasure Channel

Beside periodic bursts, isolated erasures might occur at random with a lower probability. Hence, the overall communication channel can be modeled as a combination of a periodic erasure channel and a binary erasure channel.

This channel model is appropriate for the transmission to high-speed trains via satellite, which experiences periodically deep fades caused by obstacles placed aside the track. The railroad satellite channel will be discussed in the following section.

A. Railroad satellite channel

A thorough characterization of the statistical behavior of the Railroad Satellite Channel (RSC) at Ku-band can be found in [1], where two main scenarios have been identified. The first scenario includes long tunnels, urban areas and large train stations where no direct satellite visibility can be achieved for long time intervals. In these areas, the use of proper gap fillers guarantees the connection to the travelers [12]. The second scenario consists of relatively open areas crossed by the railway, where the satellite link should be sufficient to ensure continuous service. However, in this case the RSC suffers frequent and nearly periodic deep fading events, due to electrical trellises or power arches that are placed aside the tracks in order to provide the electric power to the trains. In the sequel, we refer to these obstacles as power arches (PAs). The second scenario is further detailed below.

The model of Railroad Satellite Channel (open areas) has been investigated in literature as a hybrid model composed of a statistical part and a deterministic part [1][3]. The statistical part takes into account only small obstacles along the railroad such as trees, bridges, small buildings, and can be modeled by using a traditional Markov-chain model. The deterministic part takes into account fading events caused by quasi-periodic obstacles in the immediate vicinity of the train, mainly consisting of the metallic structures (such as electrical trellises and post with or without brackets) that are used to supply power to the train.

In the statistical part, an appropriate model is the land mobile satellite channel (LMSC) which has two states: (i) a Line-Of-Sight (LOS) state with high received signal power, and (ii) a Non-Line-Of-Sight (NLOS) state that corresponds mainly to the shadowing caused by single trees.

The probability density function representing the signal power \(S\) in LOS state is described by a Ricean probability density function [1]:

\[
p_{\text{Rice}}(S) = c \times e^{-c(S+1)} \times I_0(2c\sqrt{S}),
\]

where \(c\) is the Rice factor defined as the direct-to-multipath signal ratio between 17 and 18 dB [3], and \(I_0\) is the modified Bessel function of order zero.

In NLOS state, the probability density function representing the signal power \(S\) can be modeled via the Suzuki/Lognormal-Rayleigh distribution of the received power \(S\) [1]:

\[
p_{\text{Suzuki}}(S) = \sum_{0}^{+\infty} \frac{1}{S_0} e^{-\frac{S}{S_0}} \times p_{\text{Lognormal}}(S_0) dS_0,
\]

\[
p_{\text{Lognormal}}(S_0) = \frac{10}{\sqrt{2\pi}\sigma \log 10 S_0} \times e^{-\frac{(\log S_0 - \mu)^2}{2\sigma^2}},
\]

where \(S_0\) is the short-term mean power due to the fading; \(\mu\) describes the average power level (in dB) and \(\sigma^2\) the variance of the power level (in dB²) due to large scale fading.

In the deterministic part, the attenuation introduced by the PAs can be described by using the Knife-Edge diffraction model. Using this model, the signal attenuation can be computed as the ratio between...
the received electro-magnetic field in presence of the PA (which is the sum of the contributions \( E_1, E_2 \), from both sides of the two-dimensional obstacle), and the received field without the obstacle \( E_0 \) [1]:

\[
A_r = \frac{E_1 + E_2}{E_0} = 1 + j \frac{1}{2} \left( \frac{G(\alpha_1)}{G(\text{max})} \int_{-\infty}^{\alpha_1} e^{-\frac{v^2}{2}} \, dv + \frac{G(\alpha_2)}{G(\text{max})} \int_{-\infty}^{\alpha_2} e^{-\frac{v^2}{2}} \, dv \right)
\]

where \( d \) is the effective width of PAs, \( h \) the height above LOS and \( G(\alpha)/G(\text{max}) \) represents the attenuation due to the two diffracted rays reach the receiver antenna with angles \( \alpha \), the gain of antenna \( G(\alpha) < G(\text{max}) \). The parameter \( v \) can be computed based on the wavelength \( (\lambda) \), the distance between the train antenna and the obstacle \((a)\), the distance between the obstacle and the satellite \((b)\), and the height of the obstacle above the LOS \((h)\):

\[
v = h \sqrt{\frac{2}{\lambda} \frac{a + b}{ab}}
\]

Although parameters \( a, b, d \) depend on each railroad systems, the attenuation due to PAs is always significant. Indeed, in the specific case of the railway environment in Italy, dedicated measurements performed at Ku-Band in Spring 2004 state that (i) the effect of the post brackets and of catenaries is in the order of 1 dB and 3 dB respectively, however, (ii) the effect of the electrical trellises results in a deep fade in approximately 8 dB attenuation [2]. Furthermore, the theoretical attenuation in the worst-case scenario computed based on the above formula is approximately 15 dB [1][3].

The deep fade duration is proportional to the effective power arch width that depends on the power arch real width, the latitude and the traveling direction of the train. Following the scenario presented in [2], we consider PAs with real width of 30 cm; latitude of 38°, and a north-to-south direction of rails (corresponding to a railway environment in Italy), resulting in an effective PA width of 87 cm.

**Example of RSC**

The realization of the railroad satellite channel with an effective PA width of 87 cm, a PA distance of 50 m, and a train speed 150 km/h is depicted in Figure 2. The RSC is characterized by Ricean fading, corresponding to Line of Sight (LOS) periods, and periodic deep fade events, where the signal is blocked by objects (power arches) in the vicinity of the receiver. During the deep fade events the instantaneous power of the received signal drops by about 15-20 dB, which causes physical-layer failures. The Deep-to-Ricean fading duration ratio, denoted by D/R, depends on the effective width of the obstacle and the distance between two consecutive obstacles. Since the physical layer fails with probability 1 during the deep fading period, the D/R value is actually the value of the Frame Error Rate (FER) floor at the physical-layer.

![Figure 2: RSC realization, obstacle effective width = 87 cm, obstacle distance = 50 m, train speed 150km/h. Periodic deep fades of about 15-20 dB is due to PAs placed aside the tracks.](image-url)

**B. Problem definition**

As mentioned above, there are three types of signal attenuations due to different obstacles in the railway environment. First, the “shadowing” obstacles result in small impairment effect of 1-3 dB that could be counteracted by a proper link margin. Second, the “bridges or tunnels” obstacles result in long term interruptions that could be counteracted by using gap fillers. Third, the “power arches” obstacles result in deep and periodic fades that depend on the geometry and the layout of the obstacles, and the orientation of the railway with respect to the position of the satellite.

This paper focuses on the periodic deep fading events due to PAs, and we consider that the RSC channel consists of two states: a Ricean fading (LOS) state and a deep-fading (obstructed) state.
Periodic deep fading events result in high FER floors at the physical layer, leading to very poor quality of services. To illustrate this, consider a railway system with train speeds between 50 to 300 km/h, an effective PA width of 87 cm, a distance between two consecutive PAs of 50 m and a DVB-S2 system with a symbol rate 27.5 Mbaud. We can compute that: (i) the duration of one baseband frame is about of 0.3 ms; (ii) the duration of PA induced fading events is between 10 ms and 62 ms. This leads to about 35 to 206 physical layer frames completely lost during one deep fading event. Moreover, deep fades will cause a FER floor of about 1.74e-2, corresponding to the Deep-to-Ricean fading duration ratio, which is also equal to the ratio between the effective width of PA and the distance between two consecutive PAs.

III. Design of minimum-redundancy link-layer codes

This section deals with the design of minimum-redundancy link-layer codes that exploit the periodicity of the deep fading events. A block diagram of the transmission chain is illustrated in Figure 3. At the transmitter side, symbols encoded by the link-layer encoder will be sent to the physical layer without any interleaver. At the receiver side, symbols decoded by the physical-layer decoder will be directly sent to the link-layer decoder.

![Block diagram of the transmission chain](image)

Figure 3: Block diagram of the transmission chain

A. Structure of the parity-check matrix

Assume that the same content is broadcasted from a sender (satellite) to multiple receivers (high-speed trains) that travel on different tracks, with different speeds and in different directions. The objective is to design LL codes, such that all receivers can recover all erasures caused by PAs, by using a minimum number of redundant symbols.

Our approach for the link-level code design is based on a two-layer parity-check matrix. The first layer is dedicated to the correction of erasure bursts that occur during deep fading periods. The second layer is optional, and it is dedicated to the correction of erased symbols that may occur due to occasional physical-layer failures during the LOS (Ricean fading) state.

Let \( m \) denote the maximum number of Link-Layer (LL) symbols that are erased during one deep fading event. Let \( N \) denote the maximum integer that is a multiple of \( m \) and such that at most one deep fading event occurs during the transmission of \( N \) symbols. Hence, \( m \) is determined according to the obstacle (effective) width and the minimum train speed, while \( N \) is determined according to the distance between two consecutive obstacles and the maximum train speed (more details are given in Section III.B).

The proposed parity-check matrix of the link-layer code is depicted in Figure 4. The first layer consists of the horizontal concatenation of \( N/m \) identity matrices of size \([m \times m]\). The second layer is designed as a binary sparse matrix (with a specific structure that will be explained shortly). The number of rows in the second layer, denoted by \( u \), should be slightly greater than the expected number of erased symbols during the LOS (Ricean fading) state. Hence the total number of rows of the parity-check matrix is \( M = m + u \). It follows that the number of source symbols is given by \( K = N - m - u \).

![Systematic two-layer parity-check matrix of LL codes](image)

Figure 4: Systematic two-layer parity-check matrix of LL codes
As explained in the next section, a specific structure is further imposed on the second layer, in order to obtain a systematic parity-check matrix and to allow encoding being performed in an efficient way.

1. Linear time encoding

Figure 4 illustrates a systematic parity-check matrix. The first $K$ left columns of this matrix correspond to $K$ source symbols. The sub-matrix corresponding to these columns in the second layer is a sparse matrix. The next $(N - K)$ columns correspond to $(N - K)$ parity symbols that we divide into three groups, denoted by $p_1, p_2, p_3$. The sub-matrix of the second layer corresponding to the $p_1$ group is the identity $[u \times u]$ matrix. The sub-matrix of the second layer corresponding to the $p_3$ group is a sub-diagonal $[u \times u]$ matrix. The sub-matrix of the second layer corresponding to the $p_2$ group is a sparse matrix.

The encoding complexity of LL codes is linear with respect to the code length. The parity symbols in the $p_1, p_2, p_3$ groups are computed in the following steps:

**Step 1:** the $(m - u)$ parity symbols in the $p_2$ group are computed based on the first $(m - u)$ rows of the first layer: each parity symbol is the XOR-sum of the source symbols participating in the corresponding row.

**Step 2:** the parity symbols of the $p_1, p_3$ groups are computed recursively as follows:

- **Sub-step 2.1:** the first parity symbol (on the left) of the $p_1$ group is computed based on the $(m + 1)$th row of the matrix, which is also the first row of the second layer, as all other symbols adjacent to this row are known. Indeed, beside known source symbols, all parity symbols of the $p_2$ group are computed in Step 1. Hence, this parity symbols is computed as the sum of these known symbols participating in the $(m + 1)$th row.

- **Sub-step 2.2:** the first parity symbol of the $p_3$ group is computed based on the $(m - u + 1)$th row of the matrix, as all other symbols adjacent to this row are known. Indeed, beside known source symbols, the first parity symbol of the $p_1$ group that is adjacent to the row was computed at Sub-step 2.1. Hence, this parity symbols is computed as the sum of these known symbols adjacent to the $(m - u + 1)$th row.

The encoding continues by going back to Sub-step 2.1 by computing the second parity symbol on the left of the $p_1$ group as the sum of known symbols adjacent to the $(m + 2)$th row of the matrix including source symbols, parity symbols of the $p_2$ group computed in Step 1, and the first parity symbol on the left of the $p_1$ group computed in Sub-step 2.2.

2. Design of the first layer

The role of the first layer is to recover erasures occurring during the deep fading periods. Let us first assume that erasures only occur during the deep fading periods. According to the definition of $m$ and $N$, at most $m$ “cyclically consecutive” erasures occur during the transmission of $N$ symbols (here, “cyclically consecutive” means that the $m$ erased symbols could possibly be distributed among the first and the last symbols of the length-$N$ codeword). Hence, any row of first layer of the parity-check matrix contains at most one erased symbol. Consequently, any erased symbol can be recovered as the sum of the other (received) symbols participating in the same row.

We now consider the case when isolated erasures may also occur during the LOS state. Let $p_{\text{LOS}}$ denote the erasure probability of symbols during the LOS state; hence, $p_{\text{LOS}}$ corresponds to the physical layer FER during the LOS period only. Assume that the LL code is defined only by the first layer of the parity-check matrix shown in Figure 4 (that is, $u = 0$). We consider the worst case, where there is a long erasure burst of $m$ consecutive symbols during the deep-fading period and erased symbols at random with probability $p_{\text{LOS}}$ during the LOS period. Hence, it can be shown that the symbol erasure probability after LL decoding is given by:

$$\varepsilon = p_{\text{LOS}} + \frac{m}{N}(1 - p_{\text{LOS}})\left[1 - \left(1 - p_{\text{LOS}}\right)^{N-2}\right] \leq 2p_{\text{LOS}}$$

From the above inequality, it follows that the high error floor due to the periodic deep fading events can be removed by using a LL code defined by a very simple parity-check matrix (corresponding to the first layer in Figure 4). Indeed, the symbol erasure probability after LL decoding is less than twice $p_{\text{LOS}}$. Since $p_{\text{LOS}}$ corresponds to the physical layer FER during the LOS period only (Rician fading period), the error floor is expected to be very low, assuming that an appropriate FEC code is applied at the physical layer.
3. Design of the second layer

The role of second layer is to cope with erasures due to occasional physical-layer failures during the LOS (Ricean fading) state. As mentioned above, these erasures occur with a very low probability, if an appropriate FEC code is applied at the physical layer. However, for our design, we consider that the expected probability of failure decoding at physical layer is about 10^-6. Consequently, the number of rows in the second layer, u, is much smaller than the code length N. Therefore, the coding rate of the matrix in the second layer, denoted by \( r_l = 1 - u/N \), is usually very high.

Because of very high coding rate, the design of the second layer based on irregular codes, possibly optimized by density evolution [6], does not give a significant efficiency. The reason is that the value of the threshold probability is within a very small interval \((0, 1 - r_l)\). Therefore, we consider that the two sparse sub-matrices in the second layer (see Figure 4) are regular, with each column containing exactly \( d = 3 \) non-zero (‘1’) entries.

4. Minimum-redundancy property

The minimum-redundancy property refers to the fact the number of redundant (parity) symbols generated by the LL code is equal or insignificantly greater than the number of erased symbols. Indeed, among the \( M = m + u \) redundant symbols generated by the LL code, \( m \) symbols are generated by the first layer, and \( u \) are generated by the second layer. The first layer is designed such as to recover any \( m \) consecutive erasures, corresponding to an erasure burst caused by a deep-fading event; hence, it satisfies the minimum-redundancy property. The second layer recovers erasures due to occasional physical-layer failures during the LOS (Ricean fading) state, and the value of \( u \) is chosen slightly greater than the expected number of erased symbols during this state. Besides, the value of \( u \) usually represents only a small portion of the \( M \) redundant symbols.

B. Integration to the DVB-S2 system

In this section, we determine the parameters \( m, N, u \) of the LL code compatible with the specifications of the DVB-S2 system [13].

1. Link-layer symbol size

Link Layer (LL) symbols are MPEG-TS packets that are directly received from or sent to the physical layer without any interleaver. Hence, the size of a LL symbol, denoted by \( S_{MPEG} \) (bits), is of 188 bytes = 1504 bits.

2. Physical layer parameters

Let \( k_{phy} \) and \( n_{phy} \) denote respectively the number of information and encoded bits of the Forward Error Correction (FEC) code used at the physical layer. Encoded bits are mapped into a constellation with \( m_{phy} \) bits per complex symbol, in order generate modulated symbols. Modulated symbols are grouped into slots and then encapsulated into a complex frame, denoted by XFECFRAME. Each slot contains \( S_{slot} = 90 \) modulated symbols, and each XFECFRAME contains \( S_{XFF} \) slots, i.e.

\[
S_{XFF} = \frac{n_{phy}}{m_{phy} \cdot S_{slot}}
\]

Finally, the Physical Layer frame (PLFRAME) is obtained by inserting a header block of 90 symbols and a pilot block of 36 symbols every 16 slots. Therefore, the size of the PLFRAME, denoted by \( S_{PL} \), is given by [13]:

\[
S_{PL} = (S_{XFF} + 1) \times S_{slot} + \left\lfloor \frac{S_{XFF} - 1}{16} \right\rfloor \times 36
\]

Let \( B_s \) (Mbaud) denote the symbol rate. Then the duration for transmitting one PLFRAME, denoted by \( t_{pl}(s) \), is given by:

\[
t_{PL} = \frac{S_{PL}}{B_s}
\]

3. Number of rows of the first layer \( m \)

Let \( t_{PA}(s) \) denote the maximum duration of one deep fading event. Hence, \( t_{PA} \) equals to the ratio of the effective width of PAs to the minimum train speed \( v_{min} \) (m/s): \( t_{PA} = \frac{d_{PA}}{v_{min}} \). Let \( l_{PA} \) denote the maximum number of PLFRAMES erased during one deep fading event, hence \( l_{PA} = \left\lfloor \frac{t_{PA}}{t_{pl}} \right\rfloor \). Therefore, the maximum number of erased LL symbols during one deep fading event is given by:

\[
m = \left\lfloor \frac{l_{PA} \times k_{phy}}{S_{MPEG}} \right\rfloor
\]
4. Code-length \( N \)

Let \( l_{LL} \) be the number of PLFRAMEs corresponding to one single LL codeword. Hence, \( l_{LL} \) is the maximum number of PLFRAMEs, such that the following two constraints are satisfied.

First, since at most one deep fading event may occur during the transmission of one LL codeword, \( l_{LL} \) must be less than or equal to the total number of PLFRAMEs transmitted during one Rician and one deep fading event, that is \( l_{LL} \leq l_{PA} + \lceil d_{\text{dist}}/(l_{PL} \times v_{\text{max}}) \rceil \), where \( d_{\text{dist}} \) (m) is the distance between two consecutive PAs, and \( v_{\text{max}} \) (m/s) is the maximum train speed.

Second, we also impose a condition on the maximum duration of a LL codeword that should not exceed a given value, denoted by \( \tau \), related to the maximum tolerated delay defined by the system. It follows that the transmission duration of one LL codeword, denoted by \( t_{LL} \) (s), is given by

\[
t_{LL} = \min(n_{PA}, (d_{\text{dist}}/(l_{PL} \times v_{\text{max}})))
\]

Consequently, the number of PLFRAMEs corresponding to one single LL codeword is given by

\[
l_{LL} = \min\left(n_{PA} + \frac{d_{\text{dist}}}{l_{PL} \times v_{\text{max}}} \right) \left\lfloor \frac{t_{LL}}{t_{PLL}} \right\rfloor
\]

which further corresponds to a number of \( n_{LL} = \left\lfloor \frac{l_{LL}}{k_{\text{phy}}} \right\rfloor \)

LL-symbols. Finally, the code length \( N \) of the LL code, which must a multiple of \( m \), is given by:

\[
N = \left\lfloor \frac{n_{LL}}{m} \right\rfloor \times m
\]

IV. Simulation results

We show that the proposed LL codes can overcome the deep fading events caused by PAs present along the railways without any interleaver at the physical layer or at the link layer. Two cases are considered: one case without any delay tolerant constraint and the other with a delay tolerant constraint.

We consider typical parameters of the railway channel, specified in Section II.A: the distance between two consecutive PAs is 50 m, and the “effective” width of PAs is 87 cm.

A. Without delay constraint

We consider typical train speeds from 60 km/h to 300 km/h. At the physical layer, we consider QPSK modulation with symbol rate 27.5 MBauds, code rate = 4/9 and code length = 16200 bits (this short code of DVB-S2 is the preferred one for Interactive Broadband service which is the main service to trains). Note that the code rate 4/9 corresponds to the “rate 1/2” LDPC code specified in the DVB-S2 standard, without concatenation with the BCH code (the rate of the LDPC code is actually equal to 4/9, and decreased to 1/2 by concatenation with the outer BCH code). We choose an expected failure probability at the physical layer \( p_{\text{LOS}} = 0.075 \).

The two-layer parity-check matrix of the designed LL code is depicted in Figure 5. The parameters of the code are with \( N = 9064 \), \( m = 824 \) and \( \mu = 618 \).

![Figure 5: Two-layer parity-check matrix of the LL code without delay constraint](image)

The performance of the proposed link-layer coding scheme is shown in Figure 6. The solid black curve represents the Link-Layer Symbol-Erasure Rate (SER) when the link-layer coding is not used. As expected, this curve presents an error floor at \( 1.74 \times 10^{-2} \). Red curves show the SER performance when the link-layer coding is used. The dashed red curve corresponds to the case when only the first layer of the parity-check matrix is used, in which case the link-level coding rate is 0.91. It can be seen that the effect of deep-fading periods is completely removed, since this curve has the same slope as the SER curve in the case when only the LOS (Ricean fading) state is present. The SER performance can be further improved by adding the second level of extra rows to the parity-check matrix, as shown by the solid red curve, in which case the corresponding link-layer coding rate is decreased to 0.84.
Figure 6: Symbol Error Rate performance of the proposed link-layer coding scheme (left figure: train speed = 60 Km/h; right figure: train speed = 300 Km/h)

We note that virtually the same SER performance is achieved for train speeds of 60 Km/h and 300 Km/h (left and right plots in Figure 6). This is due to the fact that the channel model at the physical layer is modeled as described in Section II.A and does not depend on the train speed. Therefore, different train speeds affect only the burst length and the distance between bursts. However, the parameters of the LL code have been defined such that to allow effective error recovery for any train speed between 60 Km/h and 300 Km/h.

B. With delay constraint

We consider a delay constraint $\tau = 300\text{ms}$ that is required for the quality of streaming services. For simplicity, we consider only a train speed of 60 km/h. At the physical layer we consider QPSK modulation with symbol rate 27.5 MBauds and code length = 16200 bits. We will compare two solutions: the first one uses an interleaver of depth $\tau = 300\text{ms}$ at the physical layer; the second one uses the proposed LL codes.

In the first case, the LDPC code of rate 1/3 is used at the physical layer. An interleaver of depth 300ms is used for dispersing erased symbols of long bursts. Note that the duration of a depth fading is about 53ms. Hence, all erased symbols of bursts caused by deep fading events within duration of $\tau$ will be dispersed.

In the second case, we design LL codes with delay constraint $\tau = 300\text{ms}$. At the physical layer, we consider the LDPC code of rate 4/9. We choose an expected failure probability at the physical layer during Rician fading periods $p_{LOS} = 0.075$. The two-layer parity-check matrix of the LL code has $N = 2472$, $m = 824$ and $u = 124$. The coding rate of the LL code is 0.74, which leads to an overall coding rate of 1/3 (equal to the code rate of the first case).

The performance of the proposed link-layer coding scheme and the use of an interleaver at the physical layer is shown in Figure 7. The solid black curve represents the Link-Layer SER when the interleaver is used at the physical layer. It can be seen that the effect of deep-fading periods is removed. The solid red curve represents the Link-Layer SER when the link-layer coding is used. The effect of deep-fading periods is also removed. Moreover, the LL coding solution seems to provide better performance than that of the first case for SER values below $10^{-6}$ (however, note that physical layer BCH codes are not used in our simulations).

In the first case, the drawback is the size of the memory required for the physical layer interleaver. With these above parameters, the physical layer interleaver requires about 13.3Mbits corresponding to 861 XFECFRAMES. While the use of LL codes requires only 5.9Mbits corresponding to 4120 MPEG symbols.

V. Conclusion

This paper addressed the design of link-layer codes for the railroad satellite channel, where the same content is broadcasted to several trains travelling on different tracks, with different speeds and in different directions. The proposed design is characterized by a two-layer structure: the first layer is aimed at recovering erasure bursts due to periodic deep fading events, while the second one is intended to recover randomly erased symbols during the line-of-sight period. We showed by simulation that the proposed design is able to effectively deal with both periodic bursts and random erasures.
The advantages of the proposed solution are: (i) it is implemented at the link layer, avoiding memory-expensive physical layer interleaver, (ii) it can be easily adapted to different parameters of the system, including parameters of the physical layer, parameters of the railway environment, train speed and direction, and delay constraints, (iii) it relies on the use of an LDPC code defined by a parity-check matrix with a simple structure, (iv) it requires a number of redundant symbols equal or slightly greater than the number of erased symbols, (v) linear-complexity encoding can be efficiently performed on the parity-check matrix, and finally (vi) it only requires iterative decoding and does not make use of more computationally-expensive decoding methods based on Gaussian elimination.

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References


Figure 7: Symbol Error Rate performance of the proposed link-layer coding scheme (solid red curve) vs. physical layer interleaving (solid black curve)