A Novel Physical Layer Split FEC Scheme for Long Time Interleaving with Fast Zapping Support

David Gómez-Barquero, Pedro F. Gómez, David Gozálvez, Bessem Sayadi, Laurent Roullet

***Abstract*—This paper describes a novel forward error correction (FEC) and time interleaving scheme, known as BB-iFEC (Base Band – inter-burst FEC), aimed to provide long time interleaving with fast zapping support. BB-iFEC is a split FEC scheme with an outer FEC and an outer time interleaver concatenated to the inner FEC and inner time interleaver. It is based on the link layer FEC scheme of the hybrid satellite-terrestrial mobile broadcasting standard DVB-SH (Satellite to Handhelds), known as MPE-iFEC (Multi Protocol Encapsulation – inter-burst FEC), but moved down to the physical layer. This allows full transparency towards upper layers, as well as reduced signalling overhead and packet fragmentation. However, the major novelty is that it allows re-using the soft information at the output of the inner FEC decoder (i.e., the log-likelihood ratios, LLRs). Compared to hard decoding, this improves the performance at the expense of higher memory requirements at the receivers. Nevertheless, BB-iFEC allows to efficiently performing either soft or hard decoding, being thus a scalable solution. Another important advantage is that it can be introduced in future evolutions of existing systems, because it allows co-existence of terminals with and without long time interleaving support. The paper describes the main features of BB-iFEC and its implementation at the transmitter and receiver side. The paper also presents illustrative results for future evolutions of the digital terrestrial TV standard DVB-T2 (Second Generation Terrestrial), such as the next generation mobile broadcasting technology DVB-NGH (Next Generation Handheld).**

***Index Terms*—DVB-NGH, fast zapping, FEC, mobile TV, time interleaving.**

I. INTRODUCTION

TIME interleaving is key in any mobile broadcasting system to cope against impulse noise and benefit from time diversity in mobile scenarios. However, time interleaving increases the end-to-end latency and the channel change time, which is a crucial quality of service parameter, especially for TV usability. Generally, it is considered that channel change times around one second are satisfactory, whereas more than two seconds are felt as annoying. Therefore, fast zapping techniques are required in order to keep the zapping time in acceptable values with long time interleaving.

The current state-of-the art for the provisioning of long time interleaving with fast zapping is the hybrid satellite-terrestrial mobile broadcasting standard DVB-SH (Satellite to Handhelds) [1]. The reason is that this feature is a must for mobile TV satellite transmissions. The Land Mobile Satellite (LMS) channel is characterized by long signal outages due to the blockage of the line of sight with the satellite caused by tunnels, buildings, trees, etc., which can only be compensated with a long time interleaving duration (e.g., in the order of ten seconds) [2] But long time interleaving with fast zapping is also of interest for terrestrial transmissions, because it allows exploiting the time diversity of the mobile channel in both, high-speed (e.g., vehicles, trains) [3], and low-speed (e.g., pedestrian) reception scenarios [4].

DVB-SH specifies two complementary forward error correction (FEC) schemes capable of providing long time interleaving with fast zapping support: one at the physical layer using a turbo-code with a convolutional interleaver (CI), and other at the link layer known as MPE-iFEC (Multi Protocol Encapsulation inter-burst FEC) [5]. The CI can provide fast zapping with long time interleaving using a uniform-late profile or a uniform-early profile [5]. The uniform-late profile has the advantage that full protection is progressively and smoothly achieved with time. The robustness after zapping is given by the proportion of parity data transmitted in the late part. The larger the size of the late part, the better the performance after zapping. However, the overall performance in mobile channels is reduced because of the use of a non-uniform time interleaving. The size of the late part represents a trade-off between overall performance in mobile channels and performance after zapping.

MPE-iFEC supports reception in situations of long signal outages characteristic of the LMS channel while providing short tune-in delay [6]. It provides inter-burst FEC protection at the link layer, being possible to recover from completely erroneous bursts. Each burst contains source data and MPE-iFEC parity data, which allows terminals in good reception conditions to directly pass the source data to the upper layers without MPE-iFEC protection. The MPE-iFEC protection can be recovered later when transmission errors occur [7]. MPE-iFEC requires significantly less memory than terminals supporting long time interleaving at the physical layer because it performs erasure decoding instead of soft decoding. With erasure decoding each packet is treated at the input of the FEC decoder as completely correct or entirely lost, whereas soft decoding requires the storage of several bits per bit. However, MPE-iFEC does not improve the reception in static channels, and it actually degrades the performance compared to having all the protection in the physical layer.

This paper describes a novel FEC and time interleaving scheme, known as BB-iFEC (Base Band – inter-burst FEC)

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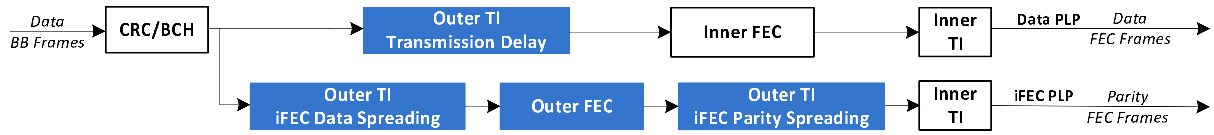

Fig. 1. BB-iFEC block diagram at the transmitter side, with two (inner and outer) FECs and TIs. The outer TI is divided in two (data and parity) spreading blocks. The iFEC physical layer pipe only transmits the parity generated by the Outer FEC, and it does not have an Inner FEC.

[8], aimed to provide long time interleaving with fast zapping support at the physical layer. BB-iFEC is based on the link layer scheme of DVB-SH MPE-iFEC, but its integration at the physical layer provides many benefits, such as full transparency towards upper layers, while still allowing hard decoding to reduce the memory requirements of the receivers. Furthermore, although BB-iFEC is a split FEC scheme which is sub-optimum in static channels, it employs uniform time interleaving, and it can outperform a single FEC with convolutional interleaving in mobile channels. Another important advantage of BB-iFEC is that it can be introduced in future evolutions of existing systems without affecting legacy receivers, because it allows the co-existence of terminals with and without BB-iFEC.

The rest of the paper is structured as follows: Section II provides an overview of BB-iFEC. Section III summarizes the main features of BB-iFEC. Section IV and Section V describe the implementation of BB-iFEC at the transmitter and the receiver, respectively. Section III presents some illustrative performance evaluation results of BB-iFEC and convolutional interleaving with single FEC using the physical layer of DVB-T2 (Second Generation Terrestrial) as reference. Finally, Section VII concludes the paper.

II. BB-iFEC Overview

BB-iFEC is based on the link layer FEC scheme of DVB-SH known as MPE-iFEC [6]. The main difference is that it is integrated in the physical layer. Fig. 1 shows the block diagram of BB-iFEC at the transmitter side. BB-iFEC is a split FEC scheme which consists on an outer FEC and an outer TI (time interleaver), concatenated to the inner FEC and inner TI. It the figure, it can be seen that BB-iFEC generates two physical layer pipes (PLPs): the Data PLP and the iFEC PLP. The iFEC PLP only transmits the parity generated by the Outer FEC, and it exploits long time interleaving. It has an Inner TI but it does not have an Inner FEC. The proposed scheme is configurable on a PLP basis, and it allows different levels of protection (interleaving duration and/or code rate) for each data PLPs.

The outer FEC and the inner FEC are in practice the same code, e.g. Low-Density Parity-Check (LDPC) or turbo-code, and only one hardware FEC chain is needed at the receivers. This is elaborated in the receiver implementation section. Usually, FEC codes at the physical layer are concatenated with weaker codes to remove potential error floors and/or to improve the error detection capability. Typical examples of these codes are BCH (Bose Chadhuri Hocquenghem) or CRC (Cyclic Redundancy Check).

The outer TI corresponds to the data and parity iFEC spreading blocks. Depending on the particular system implementation, the Inner TI can interleave bits (LLRs) or cells (constellation symbols), but the Outer TI interleaves bits for both hard and soft decoding. In Fig. 1, it can be noted that a transmission delay block is introduced in the Data PLP. This block is a memory buffer at the transmitter, and its operation is related to the Outer TI. It should be pointed out that this memory it is not necessary at the receivers.

BB-iFEC operates on a burst basis, being possible to recover from completely erroneous bursts (i.e., it provides inter-burst FEC protection). The recommended cycle time is one second, in order to provide fast zapping. The Inner TI can be limited to intra-burst interleaving for discontinuous transmissions (time-slicing), but it can also perform inter-burst interleaving within one second for continuous transmissions. This way, the Outer TI does not interleave physical layer packets (BB frames) which are already interleaved by the Inner TI. At the transmitter, after reception of a new data burst, all physical layer packets are first encoded with the FEC code used for error detection (e.g., BCH or CRC). Then, the original data burst is encoded with the Inner FEC, and a parity burst is generated after data spreading, outer FEC, and parity spreading. For each data burst, one parity burst is generated, which are simultaneously transmitted.

The outer TI of BB-iFEC is similar to the one of MPE-iFEC with sliding window Reed-Solomon (RS) encoding [6], although it is not identical. The main configuration parameters of each block related to the Outer TI are:

- Transmission delay block: data delay, D.
- Data spreading block: data spreading factor, B.
- Parity spreading block: parity spreading factor, S.

The interleaving depth in number of interleaved bursts, M, is given by the data and parity spreading processes ($M = B + S$), with two possible values of D: $D = 0$, where the parity bursts are transmitted after the data bursts, or $D = B + S$, where the parity bursts are transmitted before the data bursts. Fig. 2 depicts an example with the parity transmitted after the data. In the data spreading process, the sliding window encloses B Application Data Tables (ADTs) which receive data BB frames from one data burst. At the transmitter, there are M ADTs. After reception of one data burst, one ADT is completely filled, and one iFEC Data Table (iFDT) is generated by the Outer FEC. In the parity spreading process, the sliding window encloses S parity bursts which receive parity BB frames from the generated iFDT. Both windows are shifted one element after generating a parity burst.

In Fig. 1, it can be seen that with BB-iFEC there are three FEC encoding processes:

- BCH/CRC encoding of the data BB frames.
- Inner FEC encoding of the Data PLP.

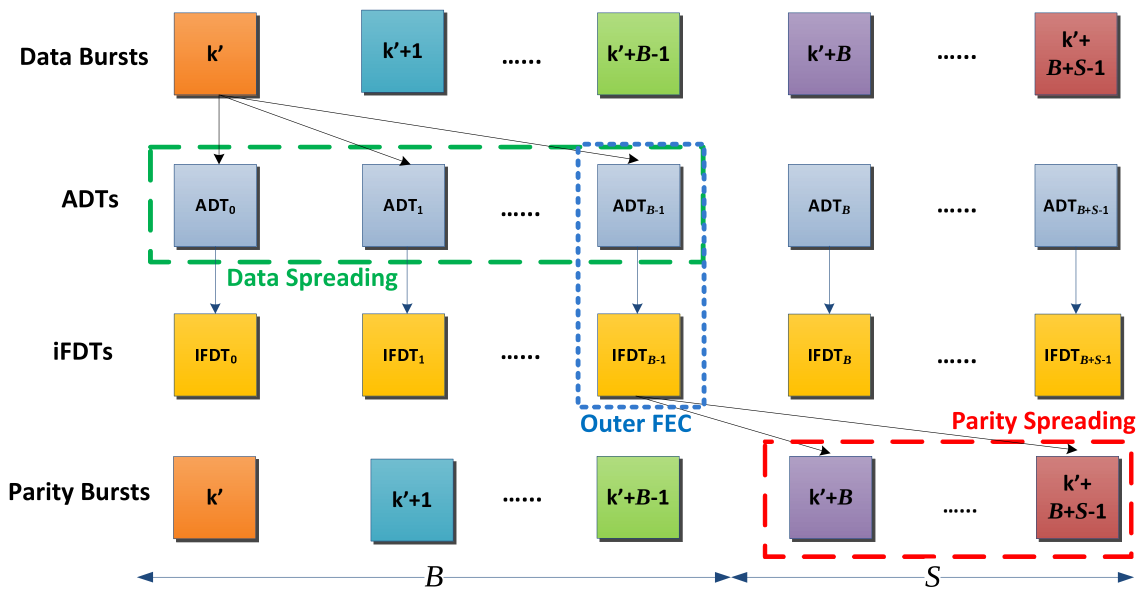

Fig. 2. Inter-burst interleaving with BB-iFEC with the parity transmitted after the data ($D = 0$). The interleaving depth in number of interleaved bursts M, is equal to the data spreading factor, B, plus the parity spreading factor, S. After the generation of a parity burst, the data and parity spreading windows are shifted one element.

TABLE I
EXAMPLES OF CODE RATE DISTRIBUTIONS FOR BB-IFEC.

CR_{total}	CR_{inner}	CR_{outer}
1/3	2/3	2/5
1/3	1/2	1/2
1/4	1/2	1/3
1/4	2/5	2/5
1/5	1/2	1/4
1/5	1/3	1/3

- Outer FEC encoding.

Without considering the overhead introduced by the BCH/CRC, the overall code rate can be expressed as follows:

$$CR_{total} = \frac{1}{\frac{1}{CR_{inner}} + \frac{1}{CR_{outer}} - 1}, \tag{1}$$

where CR_{inner} and CR_{outer} are the code rates of the Inner FEC and Outer FEC, respectively.

The code rate distribution represents a trade-off between fast zapping performance and overall performance. The protection after zapping is given by the Inner FEC of the Data PLP, whereas the Outer FEC exploits the long time interleaving. In general, it is recommended to put most of the protection in the Outer FEC[1]. BB-iFEC is a split FEC scheme, and hence there is a loss in performance with respect to single FEC encoding in static channels. Table I shows typical examples of code rates for BB-iFEC.

For a given outer code rate, CR_{outer}, and target interleaving depth, M, the interleaving parameters B, S, and D can be derived as follows:

$$B = \lfloor M \times CR_{outer} \rfloor, \tag{2}$$

$$S = M - B, \tag{3}$$

$$D = B + S, \tag{4}$$

where $\lfloor \cdot \rfloor$ denotes the *floor* function. This configuration minimizes the transition time between fast zapping mode and full protection mode, and guarantees a quasi-uniform time interleaving. This is elaborated in detail in the next Section.

[1]Note that in case there are terminals with and without long TI, the Inner FEC should be first adjusted to achieve the target coverage level for terminals without long TI, and the Outer FEC should be adjusted afterwards.

III. MAIN FEATURES OF BB-IFEC

A. Transparency towards Upper Layers

BB-iFEC is not an upper layer FEC scheme but a physical layer FEC. Therefore, it is *fully transparent to the upper layers*, being compatible with any encapsulation protocol used, e.g., MPEG-2 Transport Stream (TS) or Internet Protocol (IP).

B. Backwards-Compatibility with Terminals without Long Time Interleaving

Since BB-iFEC generates an additional PLP which exploits long time interleaving, it *allows the co-existence of terminals with and without long time interleaving*. The only modification to the Data PLP is a delay in the transmission by an entire number of bursts. This feature may allow to introduce BB-iFEC in evolutions of existing mobile broadcasting systems without affecting legacy receivers.

C. Soft and Hard Decoding Support

One of the main differences of BB-iFEC with respect to MPE-iFEC is that it allows to perform soft decoding, re-using the soft output of the Inner FEC decoder. But BB-iFEC *allows both hard and soft decoding at the receivers*, being thus a scalable solution. There is a trade-off between memory consumption and performance [9], [10]. For hard decoding, two memory bits are required per information bit, since it is needed to denote three possibilities: 0, 1, or erased. For soft decoding, typically five memory bits per LLR are required for terrestrial transmissions (for satellite transmissions, four memory bits per LLR is enough) [5]. Terminals with hard BB-iFEC decoding require thus at least half of the TDI memory. However, in static conditions, the protection is only given by the Inner FEC. The Outer FEC protection is only useful in mobile conditions, and there is also a degradation compared to soft decoding.

D. Reduced Signalling

BB-iFEC *requires very little signalling*. Only 12 bits are required to signal the value of the four BB-iFEC configuration parameters: outer FEC code rate CR_{outer} (3 bits), data and parity spreading factors B and S (4 bits each), and data delay D (1 bit). The rest of the parameters of the iFEC PLP would be the same than its associated Data PLP.

E. Reduced VBR Signalling

For Variable Bit Rate (VBR) services, BB-iFEC requires to signal information about previously transmitted bursts to help the receivers to perform the time de-interleaving. However, BB-iFEC *requires very little VBR signalling*. The reason is twofold. First of all, receivers only need help to perform the inverse of the parity spreading process (this is further elaborated in Section V). Secondly, the combination of two levels of inter-frame interleaving with the Inner TI and Outer TI reduces the required signalling compared to a single TI.

F. Reduced CRC/BCH and BB Frame Overhead

Generally speaking, physical layer packets have a header field. As an example, in DVB-T2, each 16K LDPC BB frame carries 168 bits for BCH and 80 bits for the BB frame header [11]. This overhead is fixed, regardless the code rate, but lower code rates imply higher overheads because more BB frames are transmitted for the same amount of data. BB-iFEC *achieves very robust code rates with reduced overhead due to CRC/BCH and BB frame header*. The reason is that the BB frames of the iFEC PLP do not carry CRC/BCH nor BB frame headers. The overhead is only due to the Inner FEC of the Data PLP.

G. TDI Memory Requirements

BB-iFEC is a very efficient solution from the TDI memory point of view, especially for low order constellations typical mobile broadcasting systems. First of all, BB-iFEC requires less memory than a sheer block TI, as for example the one adopted in DVB-T2 [11]. The memory requirement is similar to a convolutional interleaver with uniform profile, and it is proportional to the factor $(M+1)/2$ instead of M. Therefore, *the memory saving with respect a block interleaver tends to 50%*. The second reason is that BB-iFEC *iterleaves bits (LLRs) instead of cells (constellation symbols)*. This is more efficient for low order constellations (i.e., QPSK and 16-QAM). For cell interleaving, it is needed to store three components for each cell: real part, imaginary part, and channel state information. In DVB-T2, it is recommended to employ 10 memory bits for storing the real and imaginary parts [11]. BB-iFEC requires only 4 or 5 memory bits per bit/LLR (for soft decoding).

H. External TDI Memory Access

Today long TI at the physical layer requires an external TDI memory at the terminals. The power consumption when accessing the external TDI memory depends on the size of the Interleaving Units (IUs). The larger the IU size, the lower the power consumption. In DVB-SH, the IU length of the TI is 126 bits/LLRs [5]. The outer time de-interleaving of BB-iFEC operates with data BB frames after Inner FEC decoding, which size depends on the code rate of the Inner FEC, and with parity BB frames of constant size. The size of the BB frames depends on the FEC code used, but assuming the LDPCs codewords of DVB-T2 of size 16200 and 64200 bits, BB-iFEC *makes a very efficient access of the external TDI memory*, with IUs significantly larger than in DVB-SH.

I. Fast Zapping Support

The main feature of BB-iFEC is that *it allows fast zapping while providing long inter-frame interleaving* (e.g., one second zapping time, ten seconds time interleaving). BB-iFEC has two operation modes as MPE-iFEC, known as early decoding and late decoding [7]. In early decoding mode, the data is protected only with the Inner FEC of the Data PLP, and the zapping time is given by the Inner TI. For discontinuous transmissions, if the Inner TI performs only intra-frame interleaving it is possible to display the content after receiving the first burst (if the reception conditions are good enough, such that the Inner FEC of the Data PLP correctly decodes the data). Assuming one burst per second, the average zapping time would be half a second. For continuous transmission, it is recommended to perform inter-frame interleaving with the Inner TI within one second, keeping the operation frequency of the Outer FEC and thus a fast zapping time.

In late decoding mode, the protection is given by both Inner FEC and Outer FEC, but it cannot be achieved before receiving $B+S$ bursts. The transition time from early decoding to late decoding is $B-1$ bursts when the parity is transmitted before data (i.e., $D=B+S$), and $B+S-1$ bursts when the parity is transmitted after the data (i.e., $D=0$). The solution adopted to perform this transition for MPE-iFEC in DVB-SH is based slowing down the audio and video display rate, see [7] and [12]. For BB-iFEC, the same solutions can be employed. However, simpler solutions based on buffering and replaying may be acceptable. The key is that the transition time is much lower than in DVB-SH, because the Outer FEC of BB-iFEC has a stronger protection than in MPE-iFEC. When the parity is transmitted before the data, the lower the code rate, the lower the transition time between early and late decoding. For a time interleaving duration of ten seconds, the transition time is only one second for $CR_{outer} 1/4$, which can be considered to directly provide fast zapping, and three seconds for $CR_{outer} 2/5$.

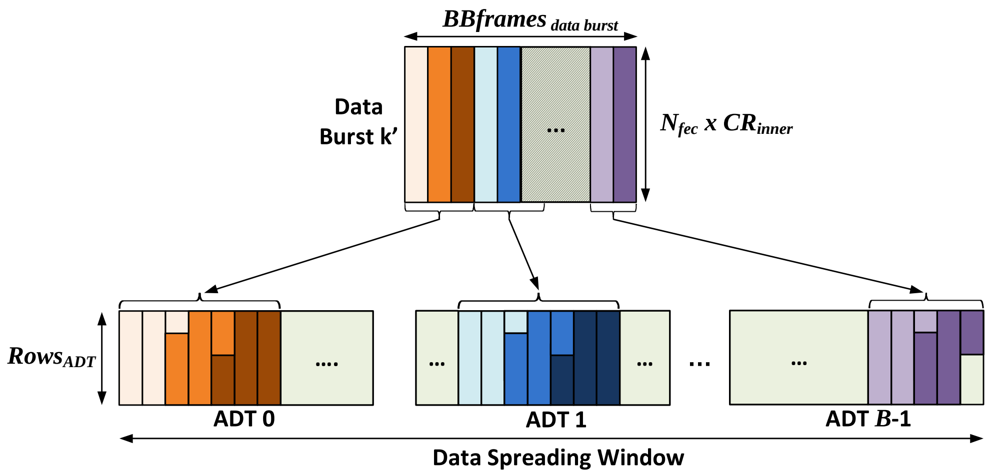

Fig. 3. Illustration of the data spreading process. The data spreading process is performed from one data burst to B ADTs (Application Data Tables). The parity spreading process is performed from one iFDT (iFEC Data Table) to S parity bursts. Each ADT/parity burst contains an entire number of consecutive BB frames of the data burst/iFDT. The maximum difference between ADTs/parity bursts is one BB frame.

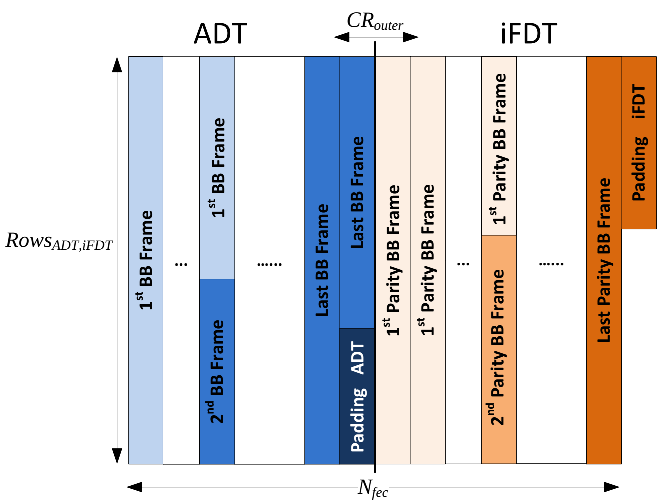

Fig. 4. BB-iFEC encoding matrix. ADT (Application Data Table) and iFDT (iFEC Data Table). The padding bits of the ADT are not transmitted. The padding bits of the iFDT can be used to transmit in-band L1 signalling.

IV. BB-iFEC Transmitter Implementation

A. Data Delay Buffer

The transmission delay block is the only modification to the Data PLP. This block is just a buffer, which delays the transmission of the data bursts an entire number of bursts, denoted with the parameter D, in analogy to the MPE-iFEC specification in DVB-SH [5]. It should be pointed out that there is no need for a buffer at the receivers.

Two vales are possible: $D = 0$, where the parity is transmitted after the data; and $D = B + S$, where the parity is transmitted before the data. The latter configuration reduces the transition time from early decoding mode to the late decoding mode. The transition period for $D = 0$ is $B + S - 1$ bursts, and for $D = B + S$, only $B - 1$ bursts.

B. Data Spreading

The data spreading process is the responsible for assigning the BB frames of each data burst to its corresponding B ADTs (Application Data Table) enclosed by the data spreading sliding window, see Fig. 2. Data bursts are split into B sub-blocks, in such a way that the maximum difference in the number of BB frames is only one BB frame. Each sub-block contains an entire number of consecutive BB frames (i.e., BB frames are not split into several ADTs). Each sub-block is then assigned to one ADT.

It should be noted that for Constant Bit Rate (CBR) services, the number of data BB frames per burst is constant, and the size of the ADTs is the same than the size of the data bursts. For Variable Bit Rate (VBR) services, the number of data BB frames per burst changes over time, and thus the size of the ADTs is not constant. The size of each ADT depends on the size of the B bursts that generate the ADT, but always corresponds to an entire number of BB frames.

C. Outer FEC

The Outer FEC process generates the parity data to fill one iFDT (iFEC Data Table) taking as input data one filled ADT. Fig. 5 shows the BB-iFEC encoding matrix (ADT + iFDT). The total number of columns is constant, and it is given by the size of the outer FEC N_{fec} (e.g., in DVB-T2, the size is 16200 or 64200 bits [11]). The number of columns of the ADT, $Columns_{ADT}$, and iFDT, $Columns_{iFDT}$, depend on the code rate of the outer LDPC:

$$Columns_{ADT} = N_{fec} \times CR_{outer}. \quad (5)$$

$$Columns_{iFDT} = N_{fec} \times (1 - CR_{outer}). \quad (6)$$

The number of rows of the ADT and iFDT, $Rows_{ADT,iFDT}$, is adjusted in such a way that the amount of padding in the ADT is minimized. The number of rows is fixed for CBR services and dynamic for VBR services. The amount of padding in the ADT is always lower

Fig. 5. Outer FEC process with bit interleaving of the ADT row before FEC encoding and bit interleaving of the generated parity bits before writing them into one row of the iFDT.

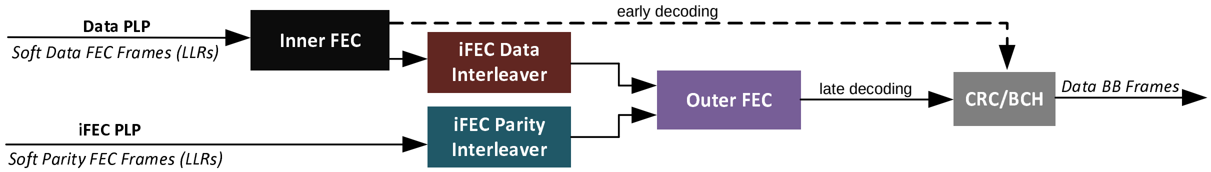

Fig. 6. BB-iFEC receiver block diagram. In early decoding mode the protection is given only by the Inner FEC. In late decoding mode the protection is given by both Inner FEC and Outer FEC.

than $(N_{fec} \times CR_{outer})$ bits. That is, it depends on the code rate of the Outer FEC, not the Inner FEC. It should be pointed out that the padding bits of the ADT are not transmitted, and thus they do not reduce the effective capacity.

Once known the number of data BB frames in the ADT, $BBframes_{ADT}$, the number of rows can be computed as:

$$Rows_{ADT,iFDT} = \lceil BBframes_{ADT} \times \frac{CR_{inner}}{CR_{outer}} \rceil, \quad (7)$$

where $\lceil \cdot \rceil$, denotes the *ceiling* function.

Once the ADT is filled (including padding), FEC encoding is performed row by row. Depending on the FEC code employed, it may be interesting to enhance the performance to interleave the data bits before encoding one row of the ADT, as depicted in Fig. 5. After decoding, the generated parity bits would be also interleaved before writing them into one row of the iFDT. A simple block interleaver could be employed, with the number of columns equal to the data or parity spreading factor (B for data interleaving, and S for parity interleaving). Data would be written by columns and read by rows.

Once the iFDT is written, it may be possible that some padding bits need to be included in the last parity BB frame. These bits need to be transmitted in order to avoid puncturing at the receivers. One interesting alternative is to use those bits to transmit in-band physical layer signalling.

D. Parity Spreading

Once the iFDT is filled, a second spreading process is performed to distribute the parity BB frames to the S parity bursts enclosed by the parity sliding window. The number of parity BB frames in the iFDT can be easily derived from the number of rows of the ADT and iFDT given in Eq. (7), and the code rate of the Outer FEC:

$$BBframes_{iFDT} = \lceil Rows_{ADT,iFDT} \times (1 - CR_{outer}) \rceil . \quad (8)$$

The spreading process from the iFDT to the parity bursts is exactly the same than the spreading process from one data burst to the ADTs, depicted in Fig. 3. The only difference is the number of elements enclosed by the sliding window (B ADTs in the data spreading process and S parity bursts in the parity spreading process). The iFDT is split into S sub-blocks. Each sub-block contains an entire number of consecutive parity BB frames. Each sub-block is then assigned to one parity burst.

V. BB-iFEC Decoding Process

Fig. 6 shows a block diagram of a BB-iFEC receiver. In early decoding mode, the protection is given only by the Inner FEC of the Data PLP, and the decoding process is Inner FEC first, and then outer CRC/BCH. The decoding process in late decoding mode, when the protection is given by both Inner FEC and Outer FEC, is the following (recall that BB-iFEC operates in a burst basis):

1) Perform Inner FEC decoding to all data BB frames of the burst of the Data PLP.
2) Send the decoded data, either soft or hard LLR values[2], to the Data De-Interleaver block, which performs exactly the same spreading process than the Data Spreading block at the transmitter (see Fig. 1).
3) Send the LLRs, either soft or hard values, of the parity BB frames of the iFEC PLP to the the Parity De-Interleaver block, which performs the inverse spreading process than the Parity Spreading block at the transmitter (see Fig. 1).
4) Perform the Outer FEC process, including bit de-interleaving of the data and parity.
5) Perform CRC/BCH decoding to all data BB frames.

The receivers do not need any information to perform the data spreading process, because it is the same procedure performed in the transmitter side. But for VBR services, the receivers need help for doing the inverse of parity spreading process. In particular, for each parity burst, the receiver needs to know the amount of BB frames that correspond to each of the S iFDTs enclosed by the parity sliding window. This information should be transmitted in the dynamic physical layer signalling.

It should be pointed out that the complete decoding process can be performed sequentially with only one FEC hardware chain. BB-iFEC increases the number of FEC decodings per burst with respect to a single FEC scheme. However, the Outer FEC is not always used (e.g., in early decoding mode and in good reception conditions). And in mobile conditions it is possible to benefit when the Inner FEC is correct to speed up

[2] In case of soft decoding in the Outer FEC, it is possible to store hard values (i.e., +/- ∞ LLRs) when the Inner FEC detects that all parity check nodes are correct. This improves the performance and reduces the number of iterations required by the Outer FEC to converge.

TABLE II
SIMULATION PARAMETERS LMS SUB-URBAN CHANNEL

Parameter	Value	Parameter	Value
FFT Size	2K	Guard Interval	1/4
Modulation	QPSK	Rotated	Disabled
Overall Code Rate	1/3	FEC Codeword	16200
Frame Size	200 ms	Cycle Time	1 s
Time Interleaving	10 s	Sub-slicing	Maximum
Service Data Rate	250 kbps	QoS criterion	ESR5(20) 90%
Velocity	60 km/h	Bandwidth	5 MHz
Simulation Time	1 hour	Ch. Estimation	Ideal

the convergence of the Outer FEC. In these cases, BB-iFEC can actually reduce the power consumption of the receivers

Regarding receiver implementation aspects, one possibility for implementing BB-iFEC is to use a double pointer structure, as described in the DVB-SH Implementation Guidelines for VBR memory management with MPE-iFEC [5]. But because of the regular structure of the BB-iFEC encoding process, the time de-interleaving at the receivers can be also implemented with ring buffers like traditional convolutional interleavers.

VI. PERFORMANCE EVALUATION

We have evaluated the performance of BB-iFEC, with soft and hard decoding, and convolutional interleaving with single FEC by means of physical layer simulations in the AWGN (Additive White Gaussian Noise) channel, a Rayleigh fading channel, the TU-6 (Typical Urban 6-path) mobile channel, and the SU (Sub-Urban) LMS channels [2]. Table II shows the simulation parameters for the LMS channel. The FEC codes used in the simulations are the 16K LDPC codes adopted in DVB-NGH. DVB-NGH has adopted new LDPC code rates compared to DVB-T2 from DVB-S2 (Second Generation Satellite) to allow for more robust transmissions with code rates down to 1/5, and with a performance gap between two consecutive code rates of around 1 dB in AWGN channel.

A. Performance in the AWGN Channel

Fig. 7 compares the continuous and fast zapping performance of BB-iFEC for two different code rate distributions which yield an overall code rate of $1/3$: (CR_{inner} $2/3$, CR_{outer} $2/5$), and (CR_{inner} $7/15$, CR_{outer} $8/15$). The performance of single FEC with a code rate $1/3$ with two sizes of the late part (40% and 50%) is also shown for comparison. The effective code rates after zapping are $5/6$ and $2/3$, respectively.

In late decoding mode (i.e., continuous performance), the protection of BB-iFEC is given by both Inner FEC and the Outer FEC. In the figure we can see that BB-iFEC performs worse than single FEC. The reason is that BB-iFEC has two independent FEC encoding processes. In static conditions, the overall performance with soft BB-iFEC decoding is dominated by the FEC with the most robust code rate (with hard BB-iFEC decoding, the performance in static conditions is only the protection given by the Inner FEC). The degradation with respect to single FEC is thus maximum when the parity is

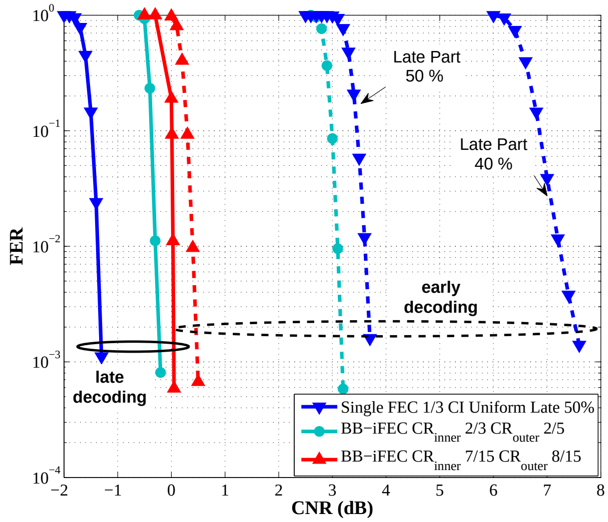

Fig. 7. Performance comparison between single FEC CR $1/3$ and soft BB-iFEC decoding (CR_{inner} $2/3$, CR_{outer} $2/5$) and (CR_{inner} $7/15$, CR_{outer} $8/15$) in the AWGN channel. Modulation is QPSK.

equally split among the Inner and Outer FECs. Therefore, in order to maximize the overall performance, it is recommended to put most of the protection in the Outer FEC, which also exploits long TI, loosing only around 1 dB Carrier-to-Noise Ratio (CNR) in the AWGN channel with respect to single FEC. Nevertheless, in the figure we can see that with another code rate distribution it is possible to significatively improve the fast zapping performance with very little impact in the overall performance.

In early decoding mode (i.e., performance after zapping), the protection of BB-iFEC is given only by the Inner FEC. We can see that the BB-iFEC configuration (CR_{inner} $7/15$, CR_{outer} $8/15$) provides the best performance, because its code rate after zapping is the most robust.

The performance of single FEC depends on the size of the late part, which determines the effective code rate after zapping. However, single FEC suffers a performance degradation because, unlike turbo-codes, LDPCs exhibit very poor performance with heavy puncturing (erasures). It should be noted that this puncturing in DVB-NGH is at cell level, and it cannot be optimized like the one performed for layer 1 signalling in DVB-T2 [11]. When the late part of the CI profile is 50%, there is an effective puncturing after zapping of 50% of the codeword. In this case, the degradation at frame error rate 10^{-3} is around 0.5 dB. The performance degradation increases for lower sizes of the late part, because the puncturing is higher, and it is also higher in fading channels (e.g., Rayleigh or TU6).

B. Performance in the LMS Channel

Fig. 8 shows simulation results in the LMS SU channel of the late decoding performance of BB-iFEC with soft and hard decoding for the two previously considered configurations, and for single FEC with two different configurations of the CI: uniform and uniform-late with 50% late part. The

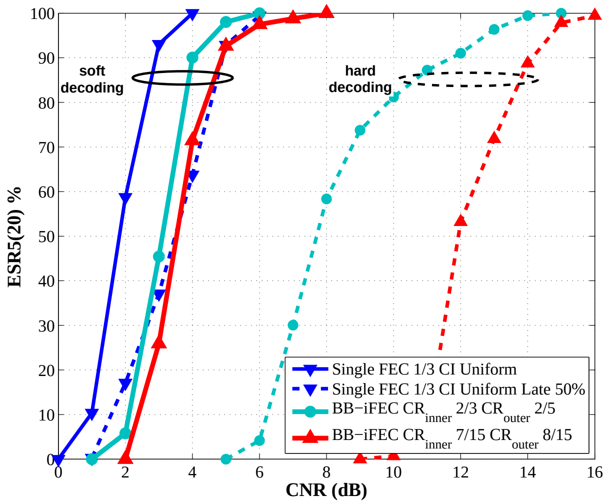

Fig. 8. Continuous performance comparison of single FEC CR 1/3 and BB-iFEC (CR_{inner} 2/3, CR_{outer} 2/5) and (CR_{inner} 7/15, CR_{outer} 8/15) in the Sub-Urban (SU) LMS channel.

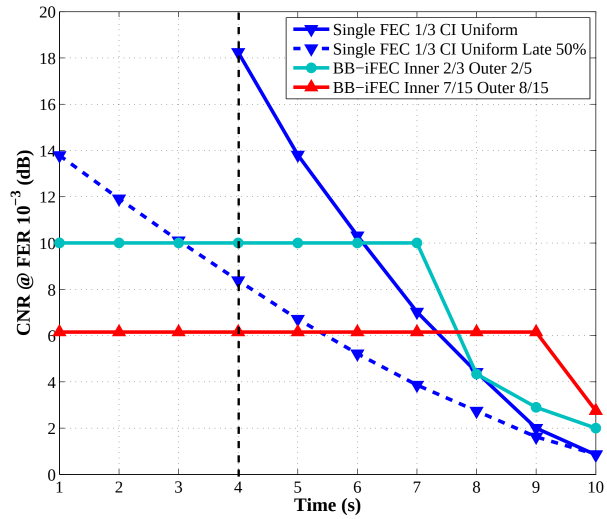

Fig. 9. Performance comparison between single FEC and BB-iFEC for an overall code rate CR 1/3 in the TU6 channel at 10 Hz Doppler. Modulation is QPSK.

$ESR5(20)$ quality of service (QoS) criteria represents the percentage of intervals of twenty seconds which contain at most one second with errors. In the figure, we can see that the worst performance is achieved by BB-iFEC with hard decoding (but it requires less memory that soft decoding), and that the best performance is achieved by single FEC with a uniform CI profile, as expected. It performs at $ESR5(20)$ 90% about 1 dB better than the best BB-iFEC configuration (CR_{inner} 2/3, CR_{outer} 2/5 with soft decoding), which is the one that has most of the protection in the Outer FEC that exploits long TI. This BB-iFEC configuration performs also about 1 dB better than the other soft decoding configuration (CR_{inner} 7/15, CR_{outer} 8/15). The difference in the LMS SU channel is considerably larger than the difference in the AWGN channel shown in Fig. 7 (around 0.2 dB at frame error rate 10^{-3}). Therefore, both static and mobile channels should be considered when deciding the code rate distribution of BB-iFEC. Nevertheless, from the shown results we can appreciate that BB-iFEC provides flexible trade-off between continuous performance and performance after zapping.

In Fig. 8, we can also note that the performance of single FEC with the CI uniform-late profile is reduced about 2 dB compared to the CI uniform profile. This configuration provides similar continuous performance in LMS than the BB-iFEC mode (CR_{inner} 7/15, CR_{outer} 8/15), but with a much worse performance after zapping (see Fig. 7), and 1 dB less than the BB-iFEC mode (CR_{inner} 2/3, CR_{outer} 2/5), with has a similar performance after zapping in AWGN.

C. Performance Discussion

Fig. 9 shows the performance over time of the previously considered configurations for BB-iFEC and single FEC with CI in the TU6 channel model at 10 Hz Doppler. In the figure, it can be observed that single FEC with a uniform CI profile is not capable of providing fast zapping. We can also see hat

TABLE III
SIMULATION RESULTS FOR AN OVERALL CODE RATE 1/5.

Configuration	E/L	AWGN	Rayleigh	LMS SU
BB-iFEC	Early	0.5 dB	1.4 dB	–
CR_i 7/15, CR_o 4/15	Late	-2.3 dB	-1.5 dB	1.8 dB
BB-iFEC	Early	-1.3 dB	-0.6 dB	–
CR_i 1/3, CR_o 1/3	Late	-2.1 dB	-1.4 dB	2 dB
Single FEC	Early	0.4 dB	1.1 dB	–
CI Uniform-Late 50%	Late	-3.5 dB	-3.1 dB	1.9 dB
Single FEC CI Uniform	Late	-3.5 dB	-3.1 dB	0.5 dB

the performance degradation of single FEC after zapping is significatively larger in fading channels than in AWGN. If in Fig. 7 the degradation for a 50% uniform-late CI was just 0.5 dB, in Fig. 9 the degradation is 4 dB.

Table III compares the performance of BB-iFEC with single FEC and CI for an overall code rate 1/5. From the results shown, it is clear that BB-iFEC provides the best trade-off between continuous performance and performance after zapping taking into account both static and mobile channels. The BB-iFEC configuration (CR_{inner} 1/3, CR_{outer} 1/3) is almost 2 dB better in early decoding than single FEC with CI uniform-late 50%, and has a similar performance in LMS.

VII. CONCLUSIONS

This paper has described BB-iFEC, a novel split FEC scheme at the physical layer for long time interleaving with fast zapping support. The main features are: transparency towards upper layers, backwards-compatibility with terminals without long TI support, possibility of efficiently performing both hard and soft BB-iFEC decoding at receivers, reduced TDI memory requirements and very efficient access to the external TDI memory, reduced signalling for BB-iFEC and for variable bit rate services, and reduced overhead due to

CRC/BCH and BB frame headers. Although BB-iFEC has two independent FEC encoding processes, it benefits of a uniform time interleaving, and it can outperform a single FEC wiht a convolutional interleaver with a uniform-late profile in mobile channels. Furthermore, the two encoding processes provide a flexible trade-off between continuous and fast zapping performance.

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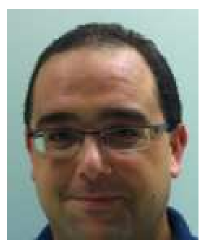

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