

Cross-layer enhancement of error control techniques for adaptation layers of DVB satellites

Juan Cantillo^{1,*,\dagger}, Jérôme Lacan^{2,\ddagger} and Isabelle Buret^{3,\S}

¹TESA/ENSICA/ENST. 14-16 Port Saint Etienne, 31000 Toulouse, France

²ENSICA/TESA/LAAS. 1 Place Emile Blouin, 31056 Toulouse Cedex 5, France

³Alcatel Alenia Space. 26, Avenue JF Champollion BP 1187, Toulouse, France

SUMMARY

This paper assesses the way error control is managed jointly by Forward Error Codes (FEC) and Cyclic Redundancy Checks (CRC) in the lower layers of today's Digital Video Broadcasting (DVB) satellites. Mathematical and simulation results clearly show that the outer block codes of the coding schemes used in DVB-S and DVB-S2 (Reed–Solomon and Bose–Chaudhuri–Hocquenghem, respectively) can provide very accurate error-detection information to the receiver in addition to their basic correction task at virtually no cost, making an uncorrected error after decoding an extremely improbable event. For this reason, the workload of CRCs can be ensured safely by the FEC subsystem if a dedicated function allowing the physical layer to share its decoding information with the adaptation layer is set. This particular cross-layer mechanism would allow freeing up the bandwidth currently used by CRCs—which adds up to 10% for more than 35% of the total number of IP packets—and pave the way for an enhanced transport of IP over DVB-S2.

KEY WORDS: cross-layer; error control; encapsulation; adaptation layer; FEC; CRC

1. INTRODUCTION AND PROBLEM STATEMENT

Most satellite systems used for interactive services delivery inherit their architecture from a broadcast-oriented design, originally intended to provide media contents to a large panel of receivers in a point-to-multipoint network configuration using Digital Video Broadcasting (DVB) technology. Efficient data carriage over satellite suffers therefore from the inefficiencies and difficulties of properly mapping network layer packets—such as IP datagrams—into link-layer entities not initially intended for such use. This operation is classically ensured by the

*Correspondence to: Juan Cantillo, TESA, 14–16 Port Saint Etienne, 31000, Toulouse, France.

^{\dagger}E-mail: juan.cantillo@supaero.org

^{\ddagger}E-mail: jerome.lacan@ensica.fr

^{\S}E-mail: isabelle.buret@alcatelaleniaspace.com

‘adaptation layers’, such as the Multi-Protocol Encapsulation (MPE) [1], the Unidirectional Lightweight Encapsulation (ULE) [2] or the Adaptation Layer 5 for ATM (AAL5), network-to-link layer interfaces having a major impact on the overall transmission efficiency through their added overhead and complexity.

Segmentation and reassembly (SAR) of network-level datagrams into fragments of sizes supported by link-layer frames is one of the most important tasks done by adaptation layers. During this process, at the transmitter a Cyclic Redundancy Check (CRC) is classically appended to every datagram prior to segmentation, and used at the receiver to check the integrity of the sent datagram upon reassembly. CRCs detect and discard datagrams with one or more fragments corrupted by resilient errors of the satellite channel [3]. The necessity for such mechanism has never been called into question, although the reliability of physical layers and the performances of Forward Error Coding (FEC) schemes have greatly improved in the last years. Unfortunately, the price to pay for the extra protection of CRCs is double: first, they add complexity to the overall system, and second, they consume a non-negligible part of the available bandwidth and of the processing load.

This paper describes a realistic cross-layer mechanism able to reduce the role of CRCs in the overall error control process, focusing on the DVB-S [4] and DVB-S2 [5] standards. Indeed, the outer block codes of their FEC schemes (Reed–Solomon (RS) and Bose–Chaudhuri–Hocquenghem (BCH), respectively) can provide very accurate error-detection information to the receiver in addition to their correction capabilities, at virtually no cost. Could this physical-level information be taken into account by the adaptation layer, theoretical and experimental results show that CRCs could be safely bypassed, incurring in a significant saving of radio resources for short packets and for the overall transmission. Additional low-layer mechanisms known to enhance TCP performance such as e.g. explicit loss notification (ELN) [6] or combined FEC/Automated Repeat Request (ARQ) could be teamed up with this solution, and improve therefore the global throughput at user level [7].

After recapitulating some known results on linear block codes, the paper will discuss and justify to which extent a cross-layer optimization of error control can be achieved over DVB-S satellite links. The paper will then focus more precisely on the specific case of the DVB-S2 standard. In addition to its enhanced error robustness, DVB-S2 contains innovative features such as adaptive coding/modulation and particularly, new link layer frames definition with long payload sizes, which can lead to a reduction of the average frequency at which datagram SAR—and therefore CRC checks—should occur upon analysis of the incoming datagram flow. For this, questioning the role of CRCs is all the more relevant when it comes to address the IP over DVB-S2 mapping, as no standard adaptation layer has been specified yet and as several cross-layer mechanisms optimizing the overall resources usage are likely to be integrated in its definition.

2. LINEAR BLOCK CODES AND CYCLIC REDUNDANCY CHECKS

Consider a systematic linear (n, k) block code C over $GF(q)^n$ with minimum distance d_{\min} in a discrete memoryless channel with q inputs and q outputs, and a q -ary error probability ε . Linearity implies that the $n - k$ redundancy symbols added to the message are linear combinations of the original k information symbols. Suppose that a codeword

$\bar{x} = (x_0, x_1, \dots, x_{n-1})$ is transmitted and let $\bar{y} = (y_0, y_1, \dots, y_{n-1})$ be the corresponding received vector. Then

$$\bar{y} = \bar{x} + \bar{e} \quad (1)$$

where \bar{e} is the *error pattern* caused by the channel noise and '+' is the component-wise addition of vectors with elements in $GF(q)$. In digital communications systems, the analysis and decoding of \bar{y} can be done in three different ways. Those are pure error detection, pure error correction, and combined error correction and detection [8].

2.1. Combined error correction and detection

A *correct decoding* occurs when \bar{y} is closer to \bar{x} than to any other codeword of C in the space $GF(q)^n$, using the Hamming distance $d(\bar{x}, \bar{y})$. The received message \bar{y} is said to be contained in the correcting sphere of radius $t = \lfloor (d_{\min} - 1)/2 \rfloor$ centred on \bar{x} , where t is the *correction capacity* of C and $\lfloor a \rfloor$ represents the greatest integer less than or equal to a . The probability P_c of *correct decoding* is given by

$$P_c(C, \varepsilon) = \sum_{i=0}^t \binom{n}{i} \varepsilon^i (1 - \varepsilon)^{n-i} \quad (2)$$

If the received codeword does not lie in the decoding sphere of \bar{x} , a *codeword error* occurs with probability $P_w = 1 - P_c$. Depending on the error pattern \bar{e} , codeword errors take two forms, as shown in Figure 1. If \bar{y} lies within the decoding sphere of a codeword \bar{z} with $\bar{z} \neq \bar{x}$, the decoder assumes that the transmitted codeword was \bar{z} and the error is therefore *undetectable*, which occurs with probability P_u . However, if \bar{y} does not lie in any of the correcting spheres of the space $GF(q)^n$, the decoder cannot associate any valid codeword to the sent message and the error is *detectable*, which happens with probability P_d . Naturally, $P_w = P_u + P_d$, with P_u not accepting a simple form in the general case. However, it will be shown in Sections 3 and 4 that P_u can be evaluated for the particular RS and BCH codes we study here. What particular output from the FEC decoder is associated with a detectable error, and how this information is later

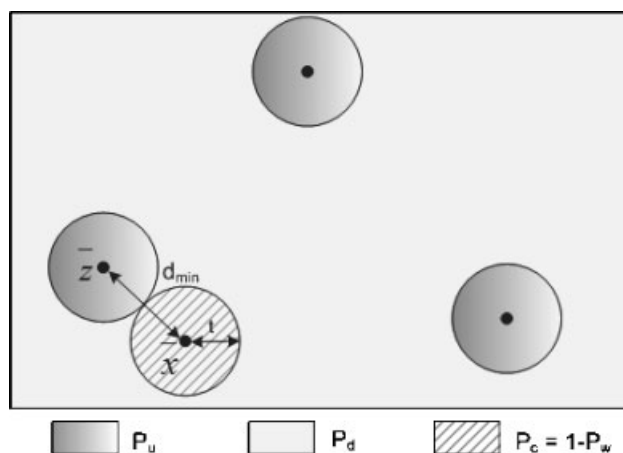


Figure 1. Error probabilities and decoding spheres for a linear block code in the space $GF(q)^n$.

shared with the communication system depends on its implementation, and several important issues arise in relation with this particular point.

2.2. Pure error detection

Error detection can be viewed as a particular case of combined correction and detection, in which the decoding spheres are reduced to a singleton, i.e. $t = 0$. This particular fact greatly reduces the undetectable error probability P_u , since such errors occur only when \bar{y} is identical to a codeword of C different from \bar{x} . It has been shown [9] that P_u can be written in a closed way for $t = 0$ using the weight distribution of the q^k codewords of C , or the weight distribution of the q^{n-k} codewords of its dual code C^\perp . For C to be good in error detection, P_u should be small for all ε . An upper bound for this probability can be given in the general case of regularly distributed codes [11] in the space $GF(q)^n$, assuming that the worst decoding conditions occur when $\varepsilon = (q - 1)/q$. For this particular value, every symbol of the q -ary alphabet occurs with equal probability making the channel completely random, and

$$P_u(C) \leq q^{-(n-k)} \quad (3)$$

Cyclic redundancy checks used in Ethernet, data storage devices and classical adaptation layers such as AAL5, MPE and ULE are binary ($q = 2$) linear block codes (n, k) used for pure error detection [8]. Numerical simulations carried on variable-size datagrams sent over a binary symmetric channel show that the bound given by Equation (3) is almost always verified for the most widely used CRCs (CRC-4, CRC-8, CRC-16 and CRC-32) [10], or at least, not very badly violated [11]. Note that the checksums used e.g. in IP, TCP or UDP [12] are not linear codes.

2.3. Pure error correction

In pure correction approaches, the decoder always associates \bar{y} with a word of the code, even when the received message does not lie in any of the decoding spheres. Some good examples of such codes are turbo codes or convolutional codes. However, such a decoding is only efficient when the channel provides soft information on the decoding confidence level, and when the decoding algorithm is able to perform maximum likelihood decoding. The RS or the BCH codes, respectively, used in DVB-S and DVB-S2 cannot be used in this mode, since there does not exist such computationally tractable algorithms for them.

3. CROSS-LAYER ENHANCEMENT OF ERROR CONTROL FOR DVB-S

In the DVB-S standard, an outer RS ($n = 204, k = 188, t = 8$, shortened from the original code $n = 255$) code with $q = 2^8$ and a punctured convolutional code with interleaving are concatenated to achieve *quasi-error-free* (QEF) performances for E_b/N_0 above the operating threshold. The QEF target of the DVB-S standard is defined as ‘less than an uncorrected error event per hour’ corresponding to a frame error rate (MPEG-2 level) $FER \leq 10^{-7}$ after FEC decoding. The FEC subsystem of the DVB-S standard is used for combined error detection and correction, and ‘uncorrected events’ stand for *codeword errors*. Although some errors are *detectable* and some other errors are *undetectable*, as explained in Section 2, the CRC of the adaptation layer is eventually responsible for dealing indiscriminately with both.

3.1. Error control management in the DVB-S adaptation layer

Every datagram to be sent receives an encapsulation header and a CRC, to form a sub-network data unit (SNDU), whose fragments are carried by different MPEG-2 packets. Upon reception, CRCs detect with great accuracy the presence of any wrong data in reassembled SNDUs, and they are therefore used today as the last protection against FEC errors climbing up the upper layers of the protocol stack. When it comes to frame errors *undetectable* by the FEC code, CRCs fulfil their role greatly.

As for *detectable* errors handling, implementations vary. Some produce an erroneous 188-byte frame representative of the final state/iteration of the decoding algorithm, sometimes even containing correctly positioned bits. Other FEC implementations simply replace the packet that could not be decoded with a null packet (e.g. all zeroes or all ones) in the binary flow. Note, however, that in both cases the decoder is aware that the produced output is not a valid codeword and therefore, that there is a detectable error, since this detection is an integral part of the decoding algorithm.

Upon analysis of the incoming flow, CRCs are therefore able to catch both *undetectable* and *detectable* errors coming out from the FEC decoder, regardless of their original nature. However, this implies that although the presence of detectable errors is known from the FEC decoder, the CRC has to detect the corresponding series of corrupted SNDUs alone. In other words, the information generated at the FEC decoder concerning the presence of a detectable error is *never* exploited by the CRC. How often this happens in actual systems is of the greatest importance.

3.2. Decoding error patterns for the Reed–Solomon code of DVB-S

3.2.1. Hypotheses. Let us consider $\eta = P_u/P_d$, the relative frequency of undetectable and detectable erroneous MPEG-2 packets (or simply, frames) after FEC decoding. Since MPEG-2 packets and classical SNDUs (such as e.g. IP packets) have similar average sizes of few hundreds of bytes, their error rates are in the same magnitude orders. For the sake of clarity, a 1:1 relation will be supposed to exist between them, so that an MPEG-2 error will be said to cause in average one SNDU error.

On the other hand, although the FEC subsystem contains a punctured convolutional code, an interleaver and a RS code, it is assumed that the error-detection capabilities of the overall FEC are those of the RS code, so that the overall η is in fact the one of the RS code. Indeed, the DVB-S specification precises that from a functional point of view, the role of the inner convolutional code is to lower the perceived bit error rate (BER) at the input of the RS decoder from 10^{-1} or 10^{-2} (actual BER seen at the receiver antenna for a functioning point of E_b/N_0 around 4.5 dB) to 2×10^{-4} .

Finally, it is assumed that the only errors to be dealt with are those encountered at the output of the FEC decoder, since there is no evidence that unexpected hardware/software malfunctioning introduces further errors in the binary flow between the FEC output and the decapsulator input.

3.2.2. Theoretical and experimental analysis. Reed–Solomon codes belong to the family of maximum distance separable codes, for which it has been shown [9] that the general expression of P_u can be simplified assuming ε is large. The ratio η can be therefore easily found, using the

results of Section 2.1

$$\eta \approx q^{-(n-k)} \times \sum_{i=0}^t \binom{n}{i} (q-1)^i \quad \text{for large } \varepsilon \quad (4)$$

In addition, known mathematical properties of the weight distribution of RS codes allow extracting an approximation of η for small values of ε

$$\eta \approx \frac{1}{t!} \times \left(\frac{n - \frac{3}{2}t}{q-1} \right)^t \quad \text{for small } \varepsilon \quad (5)$$

For $q = 2^8 = 256$, $t = 8$ and $n = 255$, η is in the magnitude of 10^{-5} for any ε value using any modulation, meaning that undetectable error events are statistically 10^5 times less frequent than detectable errors under any E_b/N_0 conditions.

Experimentally, a RS code was configured to count the number of times it dealt with detectable error patterns, and a DVB-S link integrating it was modelled with the IT++ library [13]. Extensive simulations run over more than 100 million IP packets encapsulated with MPE allowed to compare this result with the total number of failed CRC checks, and confirmed the theoretical magnitude of η under E_b/N_0 values of 1.6, 1.9 and 2.1 dB, poor link conditions chosen to trigger a large amount of codeword errors upon FEC decoding.

3.3. Conclusions and system enhancement possibilities

Theoretical and experimental results show that in DVB-S systems, detectable errors at FEC level represent the vast majority of the frame errors encountered after FEC decoding, 10^5 times more frequent than undetectable errors. Therefore, and provided that no further errors affect the binary flow, *99,999% of the failed integrity checks occurring in the adaptation layers can be predicted by the FEC decoder in average.* In other words, CRCs provide original information only 0.001% of the times an integrity check fails in the adaptation layers. Keeping in mind that the QEF target demands $FER = 10^{-7}$ at the output of the FEC decoder for the system to work, this means that CRCs are being really useful only $10^{-5} \times 10^{-7} = 10^{-12}$ of the time the DVB-S link is used. Statistically, this represents an event occurring once every 11 years for a 24 h/day continuous DVB-S transmission.

Under the light of such facts, it seems interesting to set up a dialog between the FEC decoder and the adaptation layer, in order to optimize or reallocate the resources used today by CRCs. This simple mechanism could consist e.g. in a function able to tag the MPEG-2 packets detected as erroneous at the output of the FEC decoder, allowing early discarding of bad SNDUs without the need of a systematic CRC check. Note that although the MPEG-2 standard [14] defines a 1-bit field in the MPEG-2 header for this particular purpose (TEI, standing for Transport Error Indicator bit), its use in real FEC decoders is uncertain. Indeed, according to the principles of a classical layered architecture, the FEC decoder (physical layer) should not know the structure of the data it decodes, let alone modify on purpose any of the header fields belonging to the scrambled MPEG-2 packets (link layer entities) it deals with. In another possible architecture, the dialog between FEC and the adaptation layer could be implemented *via* more complex tools, such as a dedicated off-band channel or a *cross-layer manager* able to relay messages from the FEC decoder to the adaptation layer.

Note that regardless of the implementation choice, such cross-layer mechanisms would guarantee a packet error rate of 10^{-12} (probability of an undetectable error under QEF) at the

adaptation layer at virtually no cost, a bound 100 to 1000 times tighter than the common best practices defined in RFC 3819 [15]. A step further, the pure suppression of integrity checks in the adaptation layers could lead to the gain of 4 bytes per transmitted packet: this means up to +10% of bandwidth for small packets such as VoIP or TCP ACKs, which account for more than 35% (and growing) of the number of IP packets found in the US backbone according to recent CAIDA measurements [16]. Assuming similar size distributions of IP datagrams for a typical satellite beacon, the overall bandwidth gain of a CRC suppression can be evaluated around 5%.

4. THE CASE OF DVB-S2

A detailed description of DVB-S2 is out of the scope of this paper, although a brief description of relevant features for our study is presented here.

4.1. Framing and FEC considerations

4.1.1. Generic stream framing. In addition to the classical transport streams based on MPEG-2, the optional generic streams (GS) framing scheme allows packing network data into a selection of 21 bearers of variable payload sizes—11 long, 10 short—ranging from 0.4 to 7 kbytes, offering different payload vs error protection trade-offs. While broadcast contents are likely to continue using MPEG-2 framing, GS are expected to be privileged carriers for interactive services and data, because of their higher efficiency and flexibility as compared to a MPEG-2 mapping using ULE or MPE. The new adaptation layer to be used over the GS is currently under definition at the DVB consortium, and it is likely to integrate legacy mechanisms found in previous encapsulation schemes such as ULE or MPE.

4.1.2. Enhanced LDPC-BCH FEC. Concatenated Low Density Parity Check (LDPC) and BCH codes are responsible for providing the different error protection levels of the 21 bearers, as their overall coding rate is adapted jointly with the modulation scheme according to the radio-link propagation conditions on a frame-by-frame basis. Coded frames (called FECFRAMEs or simply FF) are then modulated with one of the four available modulation schemes (QPSK, 8PSK, 16APSK and 32APSK) defining a wide range of spectral efficiency vs error protection levels, that can be dynamically allocated for every receiver by an adaptive feedback control loop. Note finally that the overall scheme of the new standard is more powerful than its predecessor, since only 0.4 to 0.7 dB away from the Shannon bound (to be compared to 2.5 to 3 dB for DVB-S).

4.1.3. Preliminary remarks. These aspects of the new standard influence strongly the way datagrams will be dealt with in the future adaptation layer. First, in average, longer bearers are expected to pack more datagrams together than with classical 188-byte MPEG-2 containers, probably reducing the relative frequency at which segmentation/reassembly of SNDUs—and therefore failed CRC checks—should occur. In addition, stronger error protection is expected to decrease dramatically the number of codeword errors at the output of the FEC decoder, and therefore the number of failed CRC checks as well. Finally, the use of cross-layer techniques seems natural in DVB-S2, and the above described Adaptive Coding and Modulation (ACM) is

a good example of this. Furthermore, in the near future, the definition of an intelligent link layer framing based on upper layers QoS requirements is likely to bring more interesting cross-layer material to the new standard.

4.2. On the BCH codes of DVB-S2

4.2.1. Hypotheses. Let us consider again the ratio $\eta = P_u/P_d$ between the undetectable and the detectable errors at the output of a BCH decoder, relative to FECFRAMEs. Given the wide range of FECFRAME sizes and the lack of an adaptation layer, a straightforward relation between the FECFRAME error rate and the SNDU is harder to precise than for DVB-S, although a 1:10 ratio seems realistic (that is, one bad FECFRAME affects 10 SNDUs in average). As in DVB-S, the essential role of the inner LDPC code is to lower the perceived BER at the input of the BCH, for which it will be considered again that the overall FEC error detection capabilities are those of the outer code. Finally, although no GS adaptation layer nor public implementations of complete GS over DVB-S2 systems exist yet, we will suppose for this study that a CRC per SNDU is responsible for catching all the codeword errors generated at the FEC decoder, exactly as for DVB-S encapsulation schemes.

4.2.2. Analytical considerations. For any chosen FEC rate, an inner LDPC code is concatenated with an outer BCH code, in a scheme integrating again both error correction and detection. The BCH(n, k) codes used in DVB-S2 are all shortened from primitive binary BCH codes with $n = 2^m - 1$, m taking the values 16 and 14 for long FFs and short FFs, respectively. Finally, $t = 12$ for all the codes applied to short FFs, whereas codes used on long FFs have $t = 12, 10$ or 8 , defining four big families of BCH codes identified by the couples $(m, t) = (16, 12), (16, 10), (16, 8)$ and $(14, 12)$. Kim and Lee [17] have shown that for primitive BCH codes having binomial-like weight distributions, as large subclasses of BCH codes including those used in DVB-S2 [8], P_u can be approached by

$$P_u(C, \varepsilon) \approx \left[2^{-mt} \sum_{i=0}^t \binom{n}{i} \right] \times 2^{-nE(\lambda, \varepsilon)} \quad (6)$$

where $\lambda n = (t + 1)$ and $E(\lambda, \varepsilon)$ are the relative entropies between the binary distribution λ and ε . Since P_w was given in Section 2.1 and $P_w = P_u + P_d$, the ratio η can be easily calculated. Unlike for the RS codes of DVB-S, η depends on ε and therefore on E_b/N_0 . Its variations using a stand-alone BCH code (without LDPC) for QPSK modulation over an AWGN channel are presented for the four families of BCH codes introduced above in Figure 2.

For 17 out of the 21 codes, the ratio between undetectable and detectable errors is lower than 10^{-8} for the whole E_b/N_0 range, reaching its maximum for a given E_b/N_0 value and decreasing rapidly around it. The four remaining codes (those with low t) present also good figures for η , between 10^{-4} and 10^{-6} , making their performances similar to those of the RS code in DVB-S. The concatenation with an inner LDPC code is expected to decrease the particular E_b/N_0 value for which the maximum η is reached for every code, without fundamentally changing its variations.

4.3. Partial conclusions and perspectives

For the 17 codes mentioned above, detectable FF errors will be 10^8 times more frequent than undetectable errors, and a bit less for the remaining four ones. Since detectable errors are known

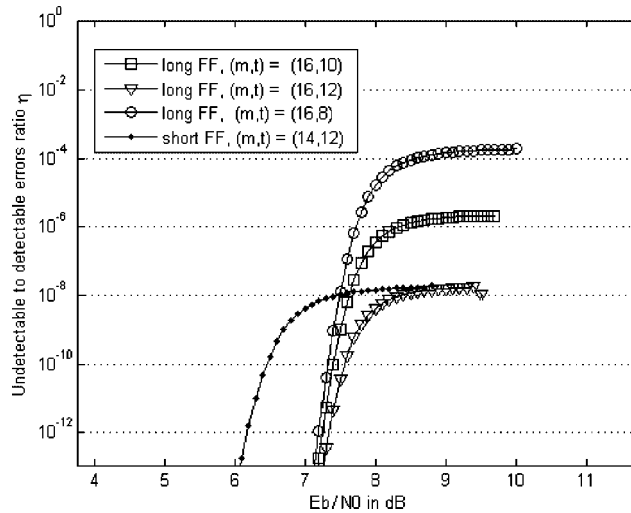


Figure 2. Undetectable to detectable errors frequency ratio η for the BCH codes used in DVB-S2—without the LDPC contribution—over an AWGN channel using QPSK modulation.

from the FEC decoder, a CRC per SNDU in the adaptation layer would produce redundant information almost always. For the 17 strongest codes, statistically, defining the QEF target in the same way as for DVB-S (FECFRAME error rate $\leq 10^{-7}$ at the input of the demultiplexer), the discarding (or loss) of 10 SNDUs due to an undetected FF error has therefore a probability equal to $10^{-8} \times 10^{-7} = 10^{-15}$, representing an event occurring every 11 000 years of full-time transmission. Although numerical simulations similar to those done for DVB-S2 have been carried out, no experimental results have been obtained yet, due to the very low frequency of the studied phenomena.

These results suggest that the new adaptation layer can also benefit from enhanced performance if the information concerning the nature of the codeword error is taken into account at the decapsulator, before SNDU reassembly. If a received FF could be tagged as a ‘detectable error’, the adaptation layer could then drop it and take the appropriate decisions on the concerned SNDUs (such as discarding them or re-asking for the missing chunks if ARQ is implemented) without even consulting their CRCs. Error control would be managed globally by the FEC decoder, and the error-detection function could be simply offloaded from the adaptation layer. As for DVB-S, a cross-layer manager or an off-band channel linking FEC and the adaptation layer could also provide similar functionality. Throwing entire frames may in principle imply also the collateral loss of good SNDUs contained in it (or part of them). However, preliminary experimental analysis of corrupted FECFRAMEs show that their bit errors are scattered all over, so that collateral losses do not occur in practice. For these reasons, a frame-by-frame global error management might be an interesting design alternative for the new adaptation layer. In any case, the key for improving the overall system is setting up a dedicated dialog between the FEC decoder and the decapsulator unit, with a bandwidth increase (reaching 10% locally for short packets, 5% globally for the overall transmission) and a processing load reduction at stake.

With the new challenges of DVB-S2 come also new concerns and variables to be taken into account as well. The possibility exists e.g. that real-time adaptation of the physical layer to the link conditions may bring new error patterns or unexpected frame corruption/loss that have not been considered here. In order to guarantee the unconditional validity of the frames under such hypotheses, some intermediary alternatives for improving the end-to-end reliability in the DVB-S2 sub-network could be imagined on top of the FEC detection information. One of them could be e.g. using a single CRC per frame, covering the frame's contents, or restricting the use of CRCs to fragmented SNDUs only (after all, if a frame containing a complete SNDU is lost, the SNDU itself is lost). Such possibilities are currently under consideration for the design of a standard adaptation layer for IP/DVB-S2, and coming implementations will certainly throw some light at these issues.

5. CONCLUSIONS

This paper assessed the way error control is managed in the lower layers of DVB satellite networks, by studying how FEC and adaptation layer CRCs interact to provide error-free data to the network layer.

By studying the error patterns at the output of a DVB-S FEC receiver, it was shown that the outer RS decoder is aware of the vast majority of frame errors occurring upon decoding and SNDU reassembly, and that resilient or undetectable errors account for less than 10^{-5} (or 0.001%) of the times a CRC check fails in the adaptation layers. Unfortunately, this information is unknown by CRCs, who have to find all the errors on their own after thorough analysis of every single SNDU. This suggests that the bandwidth and CPU-consuming task of the SNDU integrity check could be at least partially offloaded to the FEC subsystem, at no extra-cost and safely, with the condition of implementing a cross-layer mechanism authorizing the FEC decoder to share its decoding information with the adaptation layer.

The enhanced FEC protection of DVB-S2 has lowered the ratio of undetectable to detectable frame errors to 10^{-8} in new generation satellites, making an undetected error event after FEC decoding extremely rare. For this reason the definition of a new adaptation layer implementing one CRC per SNDU following legacy considerations appears to be redundant and non-optimal, and the interest of implementing the above-mentioned cross-layer mechanism becomes greater.

Finally, although the pure suppression of CRCs seems conceivable in new adaptation layers under the lights of the above facts, many other cross-layer schemes making good use of the above presented results could be implemented (e.g. discrete use of CRCs, on a frame by frame basis, etc) as well, at least until more precise data become available on live DVB-S2 networks.

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AUTHORS' BIOGRAPHIES



Juan Cantillo holds a Master of Science in Aerospace Engineering from SUPAERO, Toulouse (2004), and is currently preparing a PhD on Satellite Communications Systems at ENST (Ecole Nationale Supérieure des Télécommunications), Paris. He has worked at the Japanese Aerospace Exploration Agency in Tokyo (JAXA, 2002) and is a current member of the IPDVB working group of the Internet Engineering Task Force (IETF). His current research fields are in the areas of satellite transmission techniques, cross-layer optimization, forward error coding and encapsulation.



Jérôme Lacan received his ME and PhD degrees in Computer Science from University Paul Sabatier, Toulouse, France in 1994 and 1997. In 1996–2000, he was Assistant Professor in University of Franche-Comté, France, in Computer Science. Since 2001, he is with the Department of Applied Mathematics and Information Technology of ENSICA. He is also with the Cooperative Laboratory in Telecommunications for Space and Aeronautics (TESA) and the LAAS/CNRS in Toulouse, France. His research interests are coding theory and network protocols.



Isabelle Buret is currently at the head of the Advanced Telecom Satellite Systems section, in the Research Department of Alcatel Alenia Space in Toulouse. She graduated from the Ecole Nationale Supérieure des Télécommunications of Paris in 1990. She has been working for 16 years in space telecommunications, starting at NTT Personal communication Systems labs, in Japan, working on modulation schemes for satellite access networks. She joined Alcatel Space in 1993 as system engineer on the GLOBALSTAR program. She then moved to satellite OBP equipments design and development, being responsible for digital front-end receivers developments for WORLDSTAR DAB processor and STENTOR DVB processor. In 1997 she became in charge of R&D studies on next generation OBP products for satellite multimedia applications. Since 2000, she has been leading research activities on advanced telecommunication satellite systems, addressing future broadband and mobile satellite systems. She is also a regular member of the Alcatel Technical Academy.