A CRC Usefulness Assessment for Adaptation Layers in Satellite Systems

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This paper assesses the real usefulness of CRCs in today's satellite network-to-link adaptation layers under the lights of enhanced error control and framing techniques, focusing on the DVB-S and DVB-S2 standards. Indeed, the outer block codes of their FEC schemes (Reed-Solomon and BCH, respectively) can provide very accurate error-detection information to the receiver in addition to their correction capabilities, at virtually no cost. This handy feature could be used to manage on a frame-by-frame basis what CRCs do locally, on the frames' contents, saving the bandwidth and processing load associated with them, and paving the way for enhanced transport of IP over DVB-S2. Mathematical and experimental results clearly show that if FEC has been properly configured for combined error correction and detection, having an uncorrected event after FEC decoding is likely to be an extremely improbable event. Under such conditions, it seems possible and attractive to optimize the way global error-control is done over satellite links by reducing the role of CRCs, or even by removing them from the overall encapsulation process.

Nomenclature

E_b/N_0	Energy per bit to spectral noise density ratio
FEC	Forward Error Coding
CRC_r	r-bit Cyclic Redundancy Check
$d(\overline{x},\overline{y})$	Hamming distance between vectors $\overline{x}$ and $\overline{y}$
$[b]$	Greatest integer less than or equal to b

I. 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 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. Such operation is classically ensured by the "adaptation layers" such as MPE,[1] ULE[2] and AAL5, network-to-link layer interfaces having a major impact on the overall transmission efficiency through their added overhead (protocol control information, integrity checks, padding) 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

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discard datagrams with one or more fragments corrupted by resilient errors of the satellite channel. 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 intends to assess the real usefulness of CRCs in today's satellite adaptation layers under the lights of enhanced error control and framing techniques, focusing on the DVB-S[3] and DVB-S2[4] standards. Indeed, the outer block codes of their FEC schemes (Reed-Solomon and BCH, respectively) can provide very accurate error-detection information to the receiver in addition to their correction capabilities, at virtually no cost. After recapitulating some known results on linear block codes, the document will discuss and justify to which extend an optimization of global error control can be achieved over DVB-S satellite links by reducing the role of CRCs, or even by removing them from the overall process while optimizing the bandwidth use.

The paper will then focus more precisely on the specific case of the DVB-S2 standard. Indeed, 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 been specified yet and as several cross-layer mechanisms optimizing the overall resources usage are likely to be integrated in its definition. In addition to its enhanced error robustness, the new standard contains interesting 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.

II. Linear Block Codes and Cyclic Redundancy Checks

Consider a systematic linear (n,k) block code C with minimum distance d_{min} in a discrete memory channel (DMC) 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 functions of the original k information symbols. Suppose that a codeword $\overline{x} = (x_0, x_1, ..., x_{n-1})$ is transmitted and let $\overline{y} = (y_0, y_1, ..., y_{n-1})$ be the corresponding received vector. Then

$$\overline{y} = \overline{x} + \overline{e} \tag{1}$$

where $\overline{e}$ 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 $\overline{y}$ can be done in three different ways. Those are pure error detection, pure error correction, and combined error correction and detection.[5]

A. Combined Error Correction and Detection

A *correct decoding* occurs when $\overline{y}$ is closer to $\overline{x}$ than to any other codeword of C in the space $GF(q)^n$, using the Hamming distance $d(\overline{x}, \overline{y})$. The received message $\overline{y}$ is said to be contained in the correcting sphere of radius $t = [(d_{min}-1)/2]$ centered on $\overline{x}$, where t is the *correction capacity* of C. The probability P_c of *correct decoding* is given by :

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

If the received codeword does not lie in the decoding sphere of $\overline{x}$, a *codeword error* occurs with probability $P_w = 1 - P_c$. This probability is also given by :

$$P_w\left(C,\varepsilon\right) = \sum_{i=t+1}^{n} \binom{n}{i} \varepsilon^i \left(1-\varepsilon\right)^{n-i} \tag{3}$$

Depending on the error pattern $\overline{e}$, codeword errors take two forms, as shown in Figure 1. If $\overline{y}$ lies within the decoding sphere of a codeword $\overline{z}$ with $\overline{z} \neq \overline{x}$, the decoder assumes that the transmitted codeword was $\overline{z}$ and the error is therefore *undetectable*, which occurs with probability P_u. However, if $\overline{y}$ 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. What particular output from the FEC decoder is associated with a detectable error, and how this information is later shared with the communication system depends on its implementation, and several important issues arise in relation with this particular point. Naturally, $P_w = P_u + P_d$, with P_u given by :

$$P_u\left(C,\varepsilon\right) = \sum_{i=d_{\min}}^{n} A_i \sum_{s=0}^{t} \sum_{l=i-s}^{i+s} N\left(l,s,i\right) \cdot p\left(l\right) \tag{4}$$

where A_i represents the weight distribution of C and the term $N(l,s,i)$ denotes the number of error patterns of weight l that are at Hamming distance s to a specific codeword $\overline{z}$ of weight i (the definition of $N(l,s,i)$ is independent of the choice of $\overline{z}$). The term $p(l)$ denotes the probability of a specific error pattern of weight l. While $p(l)$ accepts a simple form, $N(l,s,i)$ cannot be calculated simply in the general case. However, it will be shown in sections III and IV that P_u can be simplified for the particular Reed-Solomon and BCH codes we study here.

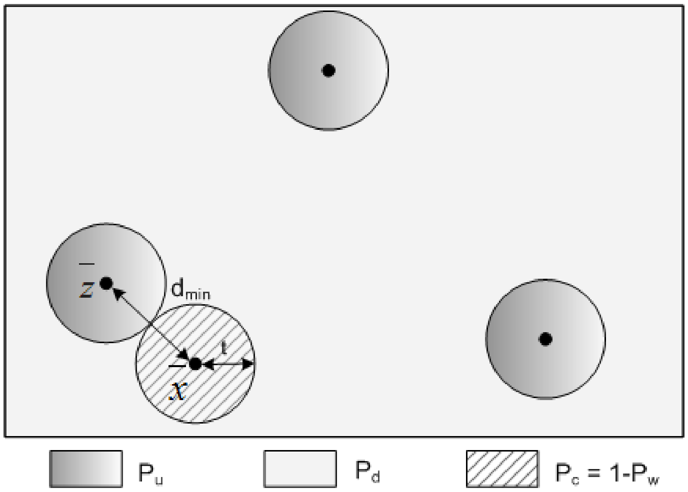

Fig. 1. Error probabilities and decoding spheres for a linear block code in the space $GF(q)^n$.

B. Pure Error Detection

Error detection is a particular case of combined correction and detection, in which the decoding spheres are reduced to a singleton, i.e. $t = 0$. The probabilities P_c and P_w of *correct decoding* and of *codeword error* are therefore given by :

$$P_c(C,\varepsilon) = (1-\varepsilon)^n \tag{5}$$

$$P_w(C,\varepsilon) = 1-(1-\varepsilon)^n \tag{6}$$

The particular fact that the spheres are reduced to a single element greatly reduces the undetectable error probability P_u, since such errors occur only when $\overline{y}$ is identical to a codeword of C different from $\overline{x}$. It has been shown[6] that (4) can be rewritten for $t = 0$ using the weight distribution A_i of the q^k codewords of C, or the weight distribution B_i of the q^{n-k} codewords of its dual code $C^{\perp}$:

$$P_u\left(C,\varepsilon\right) = \sum_{i=1}^{n} A_i \left(\frac{\varepsilon}{q-1}\right)^i (1-\varepsilon)^{n-i} = q^{-(n-k)} \sum_{i=0}^{n} B_i \left(1-\frac{q\varepsilon}{q-1}\right)^i - (1-\varepsilon)^n \tag{7}$$

For C to be good in error detection, this probability should be small for all ε. An upper bound for P_u can be given in the general case of regularly distributed codes[7] 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. Using the second part of equation (7),

$$|P_u(C)| = P_u\left(C, \frac{q-1}{q}\right) = q^{-(n-k)} - q^{-n} \leq q^{-(n-k)} \tag{8}$$

C. Pure Error Correction

In pure correction approaches, the decoder always associates $\overline{y}$ 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 Reed-Solomon 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.

D. The Case of Cyclic Redundancy Checks

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. A CRC_r computed on a k-bit long original Packet Data Unit (PDU) generates r parity bits, classically appended to the initial message to form a n-bit codeword where $r = n - k$. Since CRCs behave as error detection codes, (8) applies and :

$$|P_u\left(CRC_r\right)| \leq 2^{-r} \tag{9}$$

This makes them excellent error-detection devices (e.g. for $r = 32, |P_u(CRC_{32})| \leq 2^{-32} \simeq 10^{-9.6}$), with widespread use in data subnetworks end-to-end checks. Numerical simulations carried on variable-size datagrams sent over a binary symmetric channel show that the 2^{-r} bound is almost always verified for the most widely used CRCs (CRC-4, CRC-8, CRC-16 and CRC-32), or at least, not very badly violated.[7] An example using the generator polynomial $x^{16} + x^{12} + x^5 + 1$ (CRC CCITT-16) is shown in Figure 2.

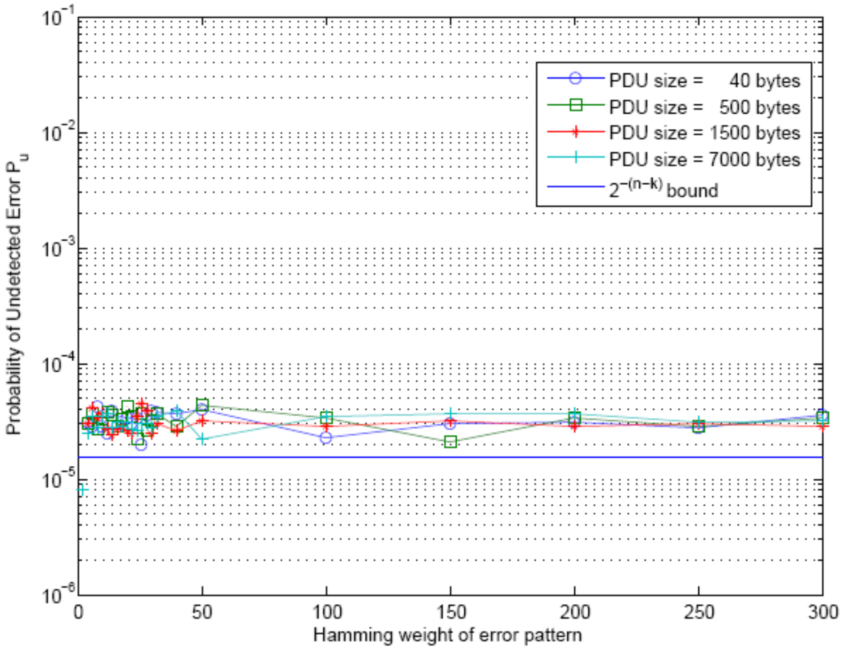

FIG. 2. Probability of undetected error P_u for the CCITT-16 cyclic redundancy check. Note that P_u does not depend on the size of the protected PDU, and that it is slightly greater than the bound $2^{-16} = 10^{-4.8}$, regardless of the weight of the error pattern $\overline{e}$.

III. FEC Enhanced Error Control for DVB-S Systems

In the DVB-S standard, an outer Reed-Solomon RS($n = 204, k = 188, t = 8$) code over $GF(2^8)$ (shortened from the original code $n = 255$) 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 are *detectable* and some others *undetectable*, as explained in section II, upper layer CRCs are eventually responsible for dealing indiscriminately with both.

A. 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 *undetectable* frame errors, CRCs fulfill 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 zeros 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, no matter 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 by himself. 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.

B. Decoding Error Patterns for the Reed-Solomon Code of DVB-S

1. *Hypotheses*

Let's 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 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.

2. *Theoretical and experimental analysis*

Reed-Solomon codes belong to the family of Maximum Distance Separable codes, for which it has been shown[6] that (4) can be simplified assuming ε is large. Using (3) the ratio η can be therefore easily found, keeping in mind that $P_w = P_u + P_d$:

$$\eta \approx q^{-(n-k)} \cdot \sum_{i=0}^{t} \left(\begin{array}{c} n \\ i \end{array} \right) (q-1)^i \qquad \text{for large } \varepsilon \tag{10}$$

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

$$\eta \approx \frac{1}{t!} \cdot \left(\frac{n - \frac{3}{2}t}{q-1} \right)^t \qquad \text{for small } \varepsilon \tag{11}$$

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 Reed-Solomon 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.[8] 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.

C. Conclusions and System Enhancement Perspectives

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 layers, in order optimize or reallocate the resources used today by CRCs. This could consist e.g. in a simple 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 such a simple cross-layer mechanism would guarantee a packet error rate of 10^{-12} at the adaptation layer at virtually no cost, a bound 100 to 1000 times tighter than the common best practices defined in RFC 3819.[9] A step further, the pure suppression of integrity checks in the adaptation layers could lead to the gain of 4 bytes per transmitted packet, meaning up to +10 % of bandwidth for small packets such as VoIP or TCP ACKs, and in a reasonable reduction of the processing load.

IV. 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.

A. Framing and FEC Considerations

1. *Generic Stream framing*

In addition to the classical Transport Streams based on MPEG-2, the optional "Generic Streams" 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, Generic Streams 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 Generic Streams 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.

2. *Enhanced LDPC-BCH FEC*

Concatenated 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 (also called FECFRAMEs or simply FF) are then modulated with one of 4 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).

3. *Preliminary remarks*

These aspects of the new standard influence strongly the way datagrams will be dealt with in the future adaptation layer. 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. The new adaptation layer of DVB-S2 seems therefore a good place to continue our analysis.

B. On the BCH Codes of DVB-S2

1. *Hypotheses*

Let's 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 FF sizes and the lack of an adaptation layer, a straightforward relation between the FF error rate and the SNDU is harder to precise than for DVB-S, although a $1:10$ ratio seems realistic (that is, one bad FF 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.

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 $t = 12$, $t = 10$ or $t = 8$, defining 4 big families of BCH codes identified by the couples $(m,t) = (16,12), (16,10), (16,8)$ and $(14,12)$. Kim and Lee[10] have shown that for primitive BCH codes having binomial-like weight distributions, as large subclasses of BCH codes including those used in DVB-S2 do,[5] equation (4) can be reduced to :

$$P_u\left(C,\varepsilon\right) \approx \left[2^{-mt}\sum_{i=0}^{t}\begin{pmatrix} n \\ i \end{pmatrix}\right]\cdot 2^{-nE(\lambda,\varepsilon)} \tag{12}$$

where $\lambda n = (t+1)$ and $E\left(\lambda,\varepsilon\right)$ is the relative entropy between the binary distribution λ and ε, i.e.

$$E\left(\lambda,\varepsilon\right) = \lambda\log_2\left(\frac{\lambda}{\varepsilon}\right) + (1-\lambda)\log_2\left(\frac{1-\lambda}{1-\varepsilon}\right) \tag{13}$$

Since P_w is known by equation (3) 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 4 families of BCH codes introduced above in Figure 3.

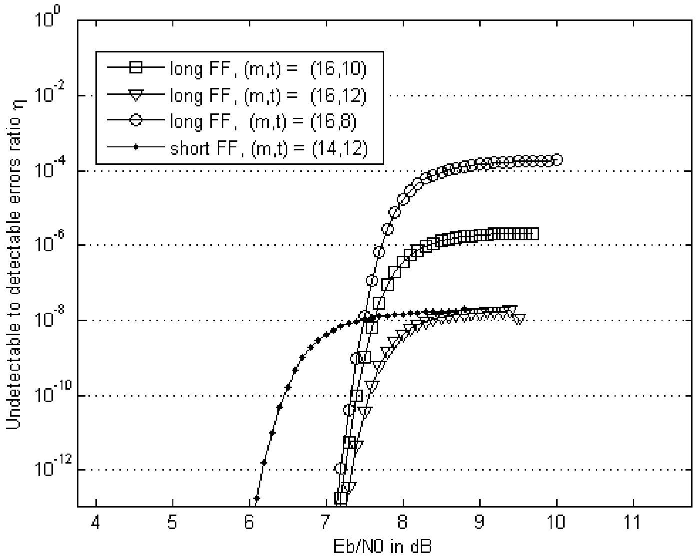

Fig. 3. Undetectable to detectable errors frequency ratio η for the BCH codes used in DVB-S2 -without the LDPC contribution- over an AWGN channel using QPSK modulation.

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 4 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 Reed-Solomon 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. Maximum values of η for each code can be found in Table 1.

C. 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 4 ones. Since detectable errors are known 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 ($FF.ER \leq 10^{-7}$ 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 in account at the decapsulator, before SNDU reassembly. If a received frame 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. 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 FFs show that its 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

n_{LDPC}	LDPC rate	k_{BCH}	n_{BCH}	m	t	η_{max}
long FF	1/4	16008	16200	16	12	**1.88E-08**
	1/3	21408	21600	16	12	**1.88E-08**
	2/5	25728	25920	16	12	**1.88E-08**
	1/2	32208	32400	16	12	**1.88E-08**
	3/5	38688	38880	16	12	**1.88E-08**
	2/3	43040	43200	16	10	**2.10E-06**
	3/4	48408	48600	16	12	**1.88E-08**
	4/5	51648	51840	16	12	**1.88E-08**
	5/6	53840	54000	16	10	**2.10E-06**
	8/9	57472	57600	16	8	**2.00E-04**
	9/10	58192	58320	16	8	**2.00E-04**
short FF	1/4	3072	3240	14	12	**2.00E-08**
	1/3	5232	5400	14	12	**2.00E-08**
	2/5	6312	6480	14	12	**2.00E-08**
	1/2	7032	7200	14	12	**2.00E-08**
	3/5	9552	9720	14	12	**2.00E-08**
	2/3	10632	10800	14	12	**2.00E-08**
	3/4	11712	11880	14	12	**2.00E-08**
	4/5	12432	12600	14	12	**2.00E-08**
	5/6	13152	13320	14	12	**2.00E-08**
	8/9	14232	14400	14	12	**2.00E-08**
	9/10	na	na	na	na	na

Tab. 1. Maximum values of $\eta = P_u/P_d$ at FF level for the BCH codes of DVB-S2. The LDPC code rate with which they are concatenated in DVB-S2 is given for informative purposes.

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) 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). Coming implementations will certainly throw some some light at these issues.

V. Conclusion

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 Reed-Solomon 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. 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 becomes available on live DVB-S2 networks.

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