Analysis of Reed-Solomon Coding Combined with Cyclic Redundancy Check in DVB-H link layer

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Abstract— **DVB-H, which is an amendment of DVB-T, offers reliable high data rate reception for mobile handheld and battery-powered devices. A link layer with error correction was defined to work on top of the DVB-T physical layer. The DVB-H standard suggests to use Reed-Solomon coding combined with CRC-32 error detection as the link layer FEC. This paper investigates the performance of the proposed error correction scheme, which is first analyzed theoretically and then by computer simulations. Results are compared to conventional Reed-Solomon decoding without utilizing CRC-32 error detection to illustrate drawbacks of the decoding solution in DVB-H standard.**

Keywords - DVB-H, Reed-Solomon code, Cyclic Redundancy Check, simulation

I. Introduction

There were great expectations for UMTS all over Europe, but since it became clear that it will not fulfill the requirements for modern high bandwidth Internet applications, such as TV, the focus has turned to other technologies.

In December 2004 the European Telecommunications Standards Institute (ETSI) ratified the DVB-H standard [1], which is an amendment for handheld terminals. Changes were needed to enable low power consumption, more flexibility in network planning, better mobile performance and compatibility with IP networks. These were achieved by adding time-slicing, error correction and a new 4K FFT OFDM mode in addition to the 2K and 8K modes in DVB-T. Time-slicing operation means that transmission occurs in bursts. Power-saving feature is due to the fact, that receiver can switch off radio components between bursts. Conceptual diagram of the physical and link layers of a DVB-H system is illustrate in figure 1. The physical layer consists of the DVB-T modulator and demodulator and the link layer consists of the IP encapsulator and decapsulator. Operations performed by DVB-H link layer are illustrated in figure 2.

The size of the MPE-FEC (Multi-Protocol Encapsulation – Forward Error Correction) frame is service independent. The number of rows can be 256, 512, 768 or 1024, depending on the wanted burst size. The number of data columns is 1-191 and the number of redundancy columns is 0-64. The IP datagrams are encapsulated column-wise into the MPE-FEC frame and the data are encoded row-wise using RS(255,191) code.

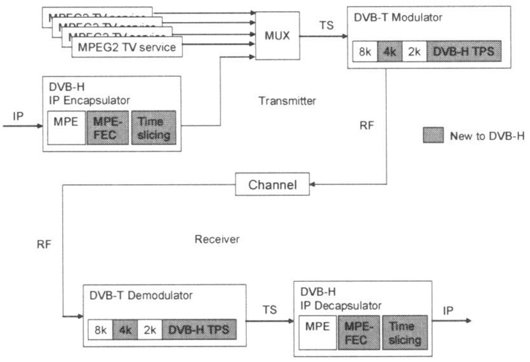

Figure 1. A conceptual description of the DVB-H system [1].

Different MPE-FEC code rates are achieved with code shortening and puncturing. The code rate is ¾ if all 191 data columns and 64 redundancy columns are used.

The frame is divided into sections so that an IP datagram forms the payload of an MPE-section and a redundancy column form the payload of a FEC-section. When the section header is attached, the CRC-32 redundancy bytes are calculated for the section. The sections are transmitted in a MPEG-2 transport stream (TS) format, where a TS packet consists of a 4 byte TS header and 184 bytes of payload. This procedure is illustrated in figure 2.

The receiver performs decapsulation of the received transport stream. The sections are decapsulated into the MPE-FEC frame and the bytes of a section are marked as "reliable" or "unreliable" depending on the CRC-32 decoding. The decoding is successful if a row of the MPE-FEC frame contains less than 65 erasures, i.e. unreliable bytes.

This paper investigates the performance of erasure coding chosen for DVB-H when compared to conventional Reed-Solomon decoding case, where the CRC-32 block is dropped from the decoding process. First, error correction is analysed theoretically based on expected decoding error probabilities. Finally, theoretical reasoning is supported with computer simulations.

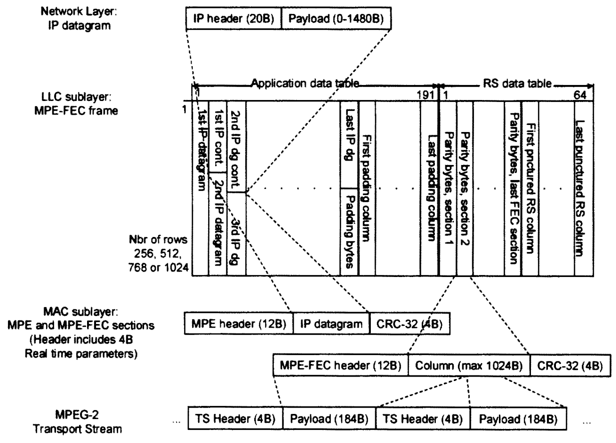

Figure 2. The link layer packets of DVB-H

II. THEORETICAL ANALYSIS

For the theoretical analysis let us assume a stationary memoryless channel model for the bit stream arriving at the link layer. This premise is justified due to several interleaving procedures preceding the link layer decoding stage.

Let us start with the case of the *non-erasure* RS decoding treating the physical layer bitstream as an output of binary symmetric channel with the bit error (crossover) probability p. Then the crossover probability p_s per one byte

$$p_s = 1-(1-p)^8 \approx 8p, \qquad (1)$$

approximation being valid whenever $p \ll 1$. Suppose t bytes of a received RS codeword are corrupted. Traditional algebraic algorithms of RS code decoding are distance-bounded [2, 3], meaning that all byte errors will be corrected if and only if their total number t is within the code correction capability $t_c = \lfloor (d-1)/2 \rfloor$, where d is the code minimum distance and $\lfloor\ \rfloor$ symbolizes rounding downward. Then, associating decoding error with any situation when the right codeword cannot be recovered by a decoder we have for the decoding error probability $P_{e,ne}$ of the non-erasure decoding algorithm [4]

$$P_{e,ne} = P(t \ge t_c) = \sum_{t=t_c+1}^{n} p(t) = \sum_{t=t_c+1}^{n} \binom{n}{t} p_s^t (1-p_s)^{n-t}, \qquad (2)$$

where n is RS code length in number of bytes and the probability distribution $p(t)$ of number of byte errors t for a memoryless stationary channel obeys the binomial law.

Let us now turn to the *erasure* decoding. As it was mentioned earlier, the sections of the FEC part of the MPE-FEC frame are always of the same length N_s coinciding with the number of rows. For the sake of simplicity we assume that all sections of the application part of the frame are as well of the same length N_s. This assumption does not affect the comparison of the considered decoding modes. In the course of CRC processing all the sections undergo testing on whether they are corrupted by bit crossovers or not. Then under the assumption above, every section erasure erases precisely one symbol (byte) in all RS codewords. Introduce designations p_e, p_u, t_e and t_u for the probability of detecting a corrupted section, probability of corrupted RS symbol missed by CRC, number of detected corrupted sections and number of all corrupted bytes in a decoded RS word ignored by CRC respectively. There are $\binom{n}{t_e}$ equiprobable patterns of t_e erasures within the code length n and for each of them $\binom{n-t_e}{t_u}$ equiprobable placements of t_u undetected symbol errors on the $n-t_e$ positions left. The probability of any specific combination of erasure and error patterns with given t_e, t_u is $p_e^{t_e} p_u^{t_u} (1-p_e-p_u)^{n-t_e-t_u}$ resulting in the probability of any combination of t_e, t_u (see also [5])

$$p(t_e, t_u) = \binom{n}{t_e}\binom{n-t_e}{t_u} p_e^{t_e} p_u^{t_u} (1-p_e-p_u)^{n-t_e-t_u}. \qquad (3)$$

It is well known and easily shown [2, 3] that any code of distance d corrects for sure t_e erasures and t_u errors whenever

$$t_e + 2t_u < d. \qquad (4)$$

Since we only consider decoding within code distance, every violation of (4) is treated as a decoding error. Every combination of $t_e \ge d, t_u = 0$ entails decoding error but many more combinations may lead to a decoding error, too. Also, the error detection capability of CRC-32 is pretty high and is not nearly exhausted by only detecting all errors of weight up to three [6]. Like any other binary linear code used for error detection it may miss only fraction 2^{-r} of all possible error patterns, r being the number of redundant bits [2]. For the CRC-32 $r = 32$, and the share of undetectable corrupted section patterns does not go beyond $2^{-32} < 3 \cdot 10^{-10}$, but probability of undetected corrupted symbol in an RS codeword appears to be even much smaller, since in a missed corrupted section not all bytes are obligatorily wrong. Therefore $p_u \ll 1 - p_e$ and we may neglect p_u and put $t_u = 0$ in (3). As a result the decoding error probability for erasure decoding $P_{e,er}$ appears to be lower-bordered as

$$P_{e,er} > \sum_{t_e=d}^{n} \binom{n}{t_e} p_e^{t_e} (1-p_e)^{n-t_e}. \qquad (5)$$

Believing in an absolute reliability of CRC, we may substitute for the erasure probability in the last equation

$$p_e \approx 1-(1-p_s)^{N_s} \qquad (6)$$

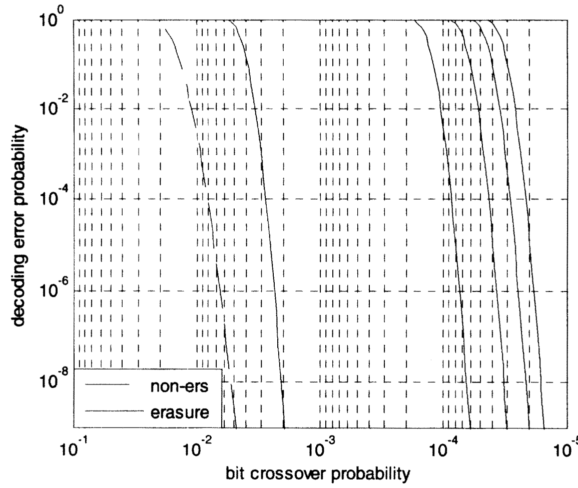

Figure 3. Error probabilities after decoding

Figure 3 presents the curves (solid lines) of dependence of lower bound of $P_{e.er}$ on bit crossover probability p computed directly from equation (5), where (6) and (1) are substituted, for five values of N_s = 8, 256, 512, 768, 1024 (left to right). Although according to DVB-H documents $N_s \geq 256$, the curve corresponding to $N_s = 8$ is also included to stress a universal character of the final conclusions. The curve for $P_{e,ne}$ calculated from equation (2), substituting (1), and shown by a dashed line goes remarkably lower. Looking at the figure one unequivocally deduces that the version of erasure decoding recommended in DVB-H documents yields significantly in the performance to the non-erasure decoding. The physical reason of this is rather obvious: CRC-protection of long sections causes deleting a great number of correct bytes only because they enter the sections where errors occur in some other bytes. Since the non-erasure decoding gain holds for even hypothetically short small values N_S, it is clear that the actual randomness of section lengths ignored above cannot cancel the conclusion on better performance of the non-erasure decoding.

III. Simulation Model and Results

Simulations were carried out to compare link layer frame error for erasure and non-erasure decoding as a function of bit error rate at the link layer input. First, to verify the results from theoretical analysis, AWGN (Additive White Gaussian Noise) channel is used in simulation. Next, a more realistic multipath channel is employed. For analysis in multipath propagation situation, two different cases are considered: stationary and bursty channel. Multipath channel model is COST207 TU6 [7], which is six-tap multipath channel corresponding to typical urban propagation conditions.

Criteria in the selection of simulation parameters were to choose parameters, which are likely to be adopted in commercial systems. Following link layer parameters were chosen for simulations: the MPE-FEC frame has 512 rows, the code rate is chosen to be 3/4, i.e. all 191 data columns and 64 RS columns are used. The input data to link layer is IP datagram. For these simulations the constant length 512-byte IP datagrams were chosen for simplicity, i.e. one IP datagram is transmitted in one section corresponding to one column of the MPE-FEC frame.

When studying conventional *non-erasure* RS decoding, a maximum of 32 erroneous RS symbols (bytes) are allowed on each row of the MPE-FEC frame declared received correctly. Frames consisting of at least one row with more than 32 errors are considered erroneous.

When studying *erasure* decoding, a complete section is marked as unreliable, if it contains an error. One section erasure leads to one column erasure in the MPE-FEC frame, when IP datagram length equals number of rows in the MPE-FEC frame. For erasure decoding a maximum of 64 erasures are allowed on one row in the MPE-FEC frame. Frames consisting of at least one row with more than 64 erasures are considered erroneous.

The results of the simulations are presented as MPE-FEC Frame Error Rate (FER) as a function of the Bit Error Rate (BER) at the link layer input. FER range chosen for inspection is from 1% to 10%. It is expected that sufficient quality of service for streaming video applications is achieved with FER smaller than 5%.

The FER results from different simulations cannot be compared directly with each other, since the input BER for link layer is calculated differently for AWGN and multipath simulations. This is due to different setup for each simulation. The goal for simulations is to verify results from theoretical analysis in the previous section illustrated in figure 3, and to emphasize the difference in decoding performance between erasure and conventional Reed-Solomon decoding in diverse channel conditions.

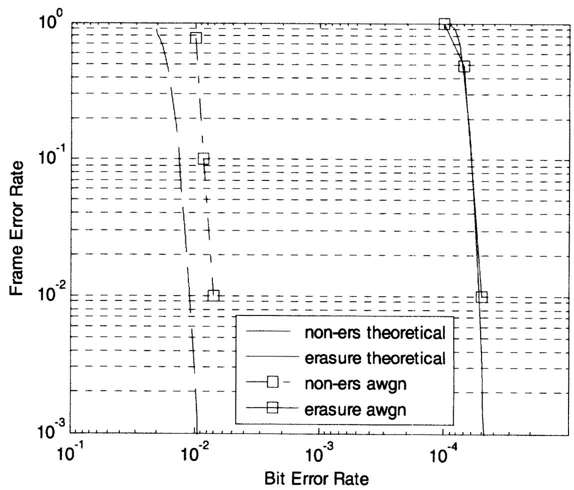

Figure 4. Theoretical versus AWGN simulations

A. Simulations in AWGN channel

The results from the simulations in AWGN channel are presented in figure 4 and compared to the theoretical calculations provided in the previous section. Results verify the mathematical formulation in section II. The curve showing the performance of erasure decoding is compatible with the theoretical calculations given in equation (5), and the non-erasure obeys the lower bound given in (2). The difference in performance between non-erasure and section erasure decoding is obvious.

B. Simulations in multipath channel

Physical layer performance in multipath case was measured from real DVB-T equipment when a hardware channel simulator was used due to excessive duration of bit-true computer simulations. The measurement setup is illustrated below.

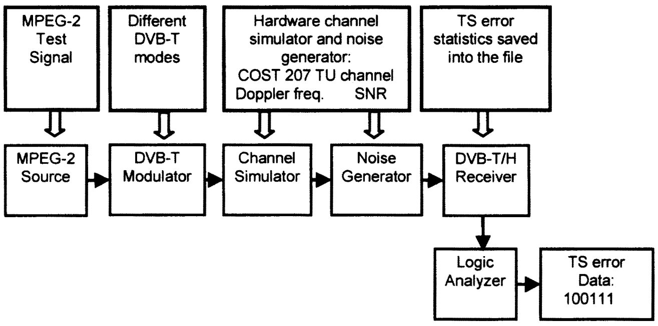

Figure 5. Measurement setup for obtaining TS packet error traces

In measurements MPEG-2 source data was transmitted using DVB-T modulator. Modulated signals were passed through the hardware channel simulator using six-tap multipath profile from [7]. Doppler shift caused by mobility of the receiver and signal-to-noise ratio (SNR) were adjustable parameters in the simulator. The noisy signal was input to DVB-T/H receiver followed by logic analyzer to produce TS error trace.

Header of TS packet includes the transport error indicator bit, which identifies whether physical layer error decoding was able to correct errors caused by multipath channel [8]. Measurement devices allowed record this indicator bit from each TS packet. Thus, for link layer simulations only the information about the correctness of the TS packet was available. The physical layer RS(204,188) decoder sets the transport error indicator to '1 if it is not able to decode the 188-byte TS packet, i.e. it contains more than 8 byte errors.

Since the byte error rate corresponding to a certain TS Packet Error Rate (TS PER) was known, an approximation about the amount of erroneous bytes in each erroneous TS packet was made. The amount of byte errors is 20-45 per erroneous TS packet for TS PER 0-20%, corresponding to BER 0-5%. The approximation applies well for all parameters considered in simulations. In the first simulation in multipath channel the errors are assumed to be uniformly distributed inside the erroneous TS packet. The approximation describes the average of byte errors in the erroneous TS packets. In the second simulation in multipath channel the byte errors occur in bursts.

Physical layer is the DVB-T physical layer defined in [9] with following parameters

- Modulation: QPSK, 16QAM
- Doppler frequency: 10 Hz
- Convolutional code rate: ½
- OFDM FFT size: 8K
- Guard interval: ¼

The simulation results are presented in table 1 and figures 6 and 7. QPSK is presented as dashed lines and 16QAM as solid lines. The non-erasure case is marked with a cross (x) and the erasure case with a circle (O). The simulations were run over 1000 MPE-FEC frames, which give reliable results up to FER of 0.5%.

The difference in decoding performance is studied in the two different multipath channel scenarios, namely in the cases where errors uniformly distributed inside TS packets and the case of burst errors, where several subsequent bytes are corrupted in the channel.

In table 1 the tolerance against bit errors, to achieve 1% FER is presented in both multipath scenarios. The same results are illustrated in figures 6 and 7. The performance of erasure decoding is quite the same in both cases. In the fourth column of table 1 the differences in tolerance against errors are presented comparing non-erasure decoding and erasure decoding. It can be seen that allowed BER at link layer input for using non-erasure decoding in uniformly distributed error channel is almost four times better in error tolerance with QPSK and three times better with 16QAM. In a bursty channel the allowed BER for non-erasure decoding at link layer input can be more than five times worse with QPSK and more than six times worse with 16QAM when compared to erasure decoding.

TABLE I. BIT ERROR RATE WHEN FRAME ERROR RATE = 10^{-2}

	non-erasure	section erasure	$\frac{non-ers}{erasure}$
QPSK unif.	0.0221	0.0057	3.88
16QAM unif.	0.0105	0.0037	2.84
QPSK bursty	0.0327	0.0062	5.27
16QAM bursty	0.0235	0.0037	6.35

A difference in error tolerance can also be seen between scenarios with uniformly distributed errors versus burst errors. When the errors are arranged to bursts, non-erasure decoding has better tolerance to bit errors than in channel with uniform error distribution.

As a conclusion from simulation results, based on table 1 and figures 6 and 7, it is apparent that non-erasure decoding has better performance than erasure decoding, also in multipath channels. Furthermore, in a bursty channel (figure 7) the gain of using non-erasure decoding is bigger than in a channel, where the errors are uniformly distributed.

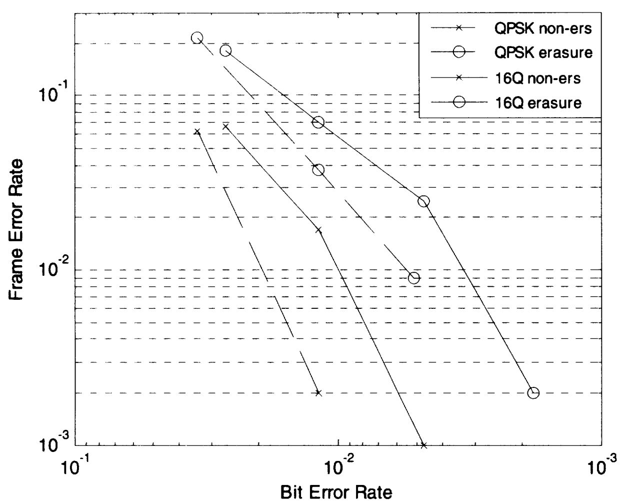

Figure 6. Non-erasure vs. erasure decoding in multipath channel, byte errors uniformly distributed in erroneous TS packet

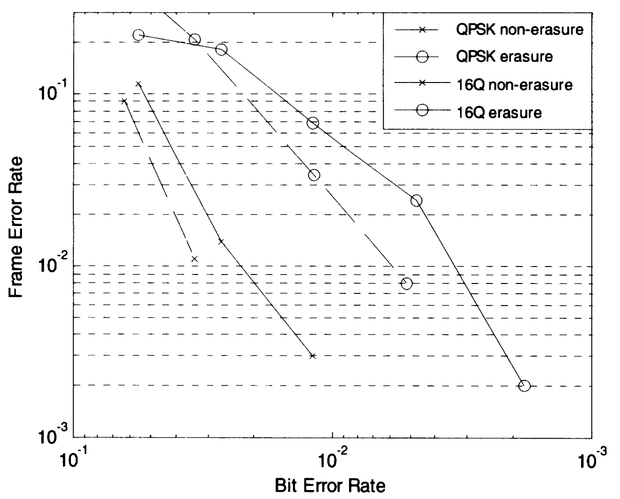

Figure 7. Non-erasure vs. erasure decoding in bursty multipath channel

IV. CONCLUSIONS

The efficiency of DVB-H link layer FEC with and without erasure decoding was analyzed in this paper. It is shown in this paper that arranging Reed-Solomon coding with cyclic redundancy check in the way it is suggested in the DVB-H standard [1] has inefficient decoding performance when compared to conventional Reed-Solomon decoding. This has been proved mathematically in section II. Results from theoretical analysis are supported by simulations, which confirm the inferior performance of erasure decoding when compared to conventional Reed-Solomon decoding.

The simulation results show that erasure decoding has about equal performance measures for either cases, i.e. if errors caused by multipath channel are uniformly distributed or errors occur in bursts inside TS packets. Furthermore, it can be emphasized that non-erasure decoding is substantially stronger in both cases. In a bursty channel non-erasure decoding has even better error tolerance than if the errors are uniformly distributed. This finding is significant, since the DVB-H channel is expected to be bursty and at the link layer this burstyness is not expected to be fully equalized by interleaving.

In addition to poor erasure decoding performance, CRC-32 adds extra complexity to communication system and overhead in signaling making it appear impractical for from the implementation point-of-view. The transmitted data always contains a checksum, in most cases CRC-32, but the standard leaves decoding method for each receiver designer to decide. In other words, the use of CRC-32 in the receiver is optional but the overhead caused by CRC-32 exists in any case.

Unfortunately, internal standardization documents were not available for this study. Therefore, the motivation in choosing erasure decoding for DVB-H is not clear for the authors. Probable reason for selection of erasure decoding has been the need to reduce the computational complexity of conventional Reed-Solomon decoding algorithms. This topic requires further investigation in order to make trade-offs between system complexity and performance. Also, as CRC-32 is already defined in standard it cannot be completely dropped from DVB-H systems. Therefore, more efficient methods to utilize signaling overhead caused by CRC or more powerful decoding methods should be sought.

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