PERFORMANCE ANALYSIS OF DIFFERENT REED-SOLOMON ERASURE DECODING STRATEGIES AT THE DVB-H LINK LAYER

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ABSTRACT

DVB-H is a new broadcasting standard, which offers reliable high data rate reception for mobile handheld and battery-powered devices. A link layer, including Reed-Solomon error correction combined with cyclic redundancy check (CRC), is defined in the standard to work on top of the DVB-T physical layer. The DVB-H suggests to use an erasure decoding method based on CRC information. Yet, the decoding method is not strictly determined in the standard. This paper investigates the performance of four different Reed-Solomon erasure decoding schemes for DVB-H link layer forward error correction.
Keywords: DVB-H, Reed-Solomon code, cyclic redundancy check, erasure decoding

I. INTRODUCTION

DVB-H (Digital Video Broadcasting for Handheld terminals) is a relatively new data broadcasting standard [1] that enables delivery of various Internet Protocol (IP) based services to mobile receivers and was ratified by European Telecommunications Standards Institute (ETSI) in November 2004. A good overview of DVB-H systems can be found in [2].

The DVB-H standard, which is based on and is compatible with DVB-T (Digital Video Broadcasting - Terrestrial [3]), introduces solutions to the problems caused by the mobility of the handheld terminals receiving digital broadcast. These solutions were required for low power consumption, flexibility in the network planning, good performance in mobile channels, and compatibility with IP networks. Enhancements to conventional DVB-T systems include the addition of time-slicing and one more stage of error correction called the MPE-FEC (Multi-Protocol Encapsulation - Forward Error Correction) at the link layer. Time-slicing means that the transmission is time division multiplexed, i.e. one service is sent in bursts separated in time. The power-saving is achieved due to the fact that the receiver can switch off radio components between the bursts. The MPE-FEC includes a utilization of Reed-Solomon (RS) code combined with time interleaving to combat channel fading. The changes in the DVB-T physical layer consist of new 4K OFDM (Orthogonal Frequency Division Multiplexing) mode, an in-depth interleaver and utilization of previously unused TPS (Transmission Parameter Signaling) bits informing receiver on the use of time-slicing and MPE-FEC.

The "DVB-H implementation guidelines" [4] defines the Reed-Solomon code used in the MPE-FEC and how to puncture or shorten it. The decoding method is, however, left open for each receiver manufacturer to decide. This paper investigates and compares four different decoding strategies for MPE-FEC. Decoding error probabilities are calculated as a function of error probability after physical layer error decoding.

For Reed-Solomon codes decoding with erasures is possible and recommended in [4] among primary options. Erasure in this context stands for an error, whose location in the codeword is known. The advantage of the erasure decoder is that it is capable of correcting more erroneous code symbols than the conventional non-erasure decoder. In DVB-H, different options exist to obtain erasure information. It is suggested in [4] that the erasure information could be obtained from the CRC (Cyclic Redundancy Check) error detection mechanism embedded in MPE and MPE-FEC sections in the encapsulation process. The erasure decoding based on CRC check is referred to in this paper as CRC-erasure (CE) decoding. Another option is to apply error information provided in the transport stream (TS) packet headers. This erasure decoding method is referred to as transport stream erasure (TSE). In [5] (originally in [6]) two decoding methods based on correcting both errors and erasures were proposed. These decoding methods were called hierarchical section erasure (HSE) decoding and hierarchical transport stream (HTS) erasure decoding. In this paper these methods are called MPE-header-erasure decoding (MHE) and PID-erasure decoding (PE) with respect to the way the erasure information is obtained. The main difference between the decoding methods analyzed in this paper from the performance point of view is the way the erasure information is obtained and how it is utilized.

The paper is organized as follows. A brief description of DVB-H system is given in section II. Different decoding schemes are analyzed by estimation of decoding error probabilities in section III. Theoretical analysis is confirmed with simulations that are discussed in section IV. A DVB-H simulator using AWGN (Additive White Gaussian Noise) channel is used to obtain results that are comparable with analytic results from section III. Finally, concluding remarks are presented in section V.

II. DVB-H SYSTEM DESCRIPTION

A conceptual diagram of the DVB-H system is illustrated in Fig. 1. The physical layer consists of the DVB-T modulator and demodulator, while the link layer is represented by the IP encapsulator and decapsulator. DVB-H services can optionally share the multiplex (mux) with DVB-T services as presented in

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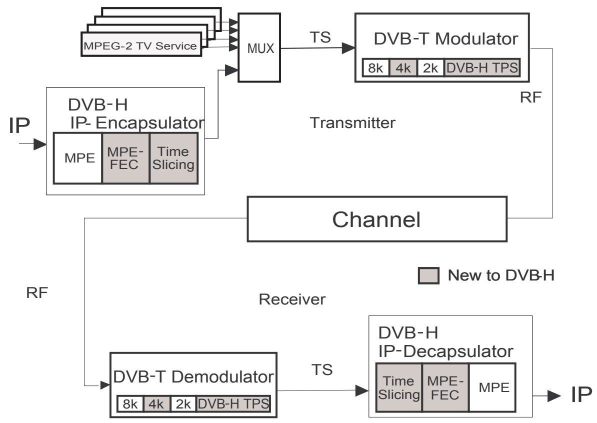

Figure 1: A conceptual description of the DVB-H system [1]

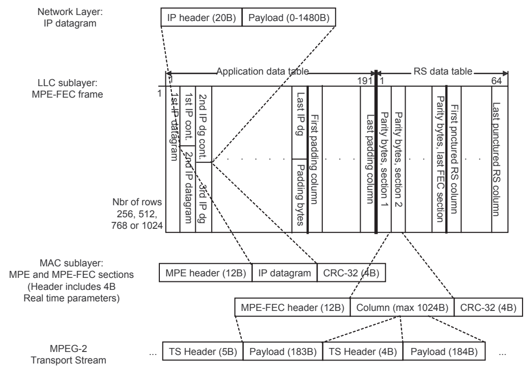

Figure 2: The link layer packets of DVB-H

Fig. 1.

The input to the DVB-H system link layer in the transmitter side is IP datagrams, which are inserted into a MPE-FEC frame column-wise (see Fig. 2) for the row-wise calculation of redundancy bytes with RS(255,191) code. The number of rows in the frame can be 256, 512, 768 or 1024. Time-slicing and MPE-FEC are closely related to one another, since exactly one MPE-FEC frame is transmitted during a time-slicing burst. The number of data columns is 1-191 and the number of redundancy columns is 0-64. A combination of code shortening and puncturing is used for achieving different MPE-FEC code rates. The code rate is about 3/4 if all 191 data columns and 64 redundancy columns are used.

For the transmission the frame is divided into sections so that an IP datagram forms the payload of a MPE section and a redundancy column forms the payload of a MPE-FEC section. After the section header is attached, the four CRC-32 redundancy bytes are calculated for the section. The sections are transmitted in MPEG-2 transport stream (TS) format defined in [7]. The operations performed by the link layer are illustrated in Fig. 2.

The input to the DVB-H physical layer is a TS packet stream, where each TS packet consists of 4-5 header bytes and 183-184 bytes of payload data. TS packets are protected in the DVB-T modulator by a concatenated Reed-Solomon and convolutional encoder combined with interleaving on several stages.

The output of the physical layer at the receiver consists of TS packets that are the input to the DVB-H link layer IP decapsulator. The receiver reconstructs the MPE and MPE-FEC sections from the TS packets. Decapsulation is performed by inserting IP datagrams and redundancy columns carried inside the sections to correct locations in the MPE-FEC frame. The RS decoding is then performed row-wise.

III. Error probabilities for decoding methods

In the following, the error correction capability of the RS based MPE-FEC at DVB-H link layer is analyzed theoretically based on decoding error probabilities for four different decoding methods. For the theoretical analysis a stationary memoryless channel for the bit stream arriving at the link layer is assumed. This starting point is justified by the interleaving procedures preceding the link layer decoding stage. The following analysis treats the physical layer bit stream as an output of a binary symmetric channel with the bit error (crossover) probability p. Then the probability of error p_s for one eight bit RS symbol (byte) is

$$p_s = 1 - (1-p)^8 \approx 8p, \tag{1}$$

approximation being valid whenever $p << 1$. The criterion to compare different decoding methods is MPE-FEC frame error rate (MFER). A frame is considered erroneus whenever the decoding of the frame is not successful (i.e. the decoder was unable to decode at least one row). The payloads of the sections belonging to the RS data table are always of the same length N_s coinciding with the number of rows in the frame (see Fig. 2). For the sake of simplicity we assume here that the length of the IP packets also coincides with the number of rows in the MPE-FEC frame. For this analysis $N_s = 535$ is chosen to enable simple and unified analysis of the different decoding methods (more on this in section B.). This assumption makes it possible to have an integer number of TS packets in a column of the MPE-FEC frame. Although this option is not defined in the standard, it gives results that are very close to the defined case with $N_s = 512$.

A. *CRC-erasure decoding (CE)*

Let us now turn to the erasure decoding. Introduce designations p_u, p_e, t_u and t_e for the probability of undetected corrupted RS symbol (byte in this case), the probability of an erased symbol, number of corrupted symbols in a RS codeword that were not detected and number of erased symbols in a codeword respectively. According to [8, 9] any code of distance d corrects t_e erasures and t_u errors whenever

$$t_e + 2t_u < d. \tag{2}$$

Since we only consider decoding within the code distance and lose MPE-FEC frame any time errors and erasures correction fails, every violation of (2) is treated as a decoding error. Now, for a code of length n there are $\binom{n}{t_e}$ equiprobable patterns of t_e erasures 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. Since probability of any fixed pattern of t_e erasures and t_u undetected errors is $p_e^{t_e} p_u^{t_u} (1 - p_e - p_u)^{n-t_e-t_u}$, the joint probability distribution of t_e, t_u is [10]:

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

As a result the probability of correct decoding of one codeword for erasure decoding is evaluated:

$$P_{cE} = P(t_e + 2t_u < d) = \sum_{t_e=0}^{d-1} \sum_{t_u=0}^{\frac{d-1-t_e}{2}} p(t_e, t_u). \quad (4)$$

In the course of CRC processing at the DVB-H link layer all the sections undergo testing on whether they are corrupted by bit crossovers or not. Thus, under the assumption of section length $N_s = 535$ coinciding with the number of rows, every section erasure erases precisely one symbol (byte) in every RS codeword in the frame.

Also, the error detection capability of CRC-32 is rather high and is not nearly exhausted by only detecting all errors of weight up to three [11]. 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 [8]. For the CRC-32 $r = 32$, and the share of undetectable corrupted section patterns does not go beyond $2^{-32} < 3 \cdot 10^{-10}$. Besides, the probability of an undetected corrupted symbol in a RS codeword appears to be much smaller against the probability of CRC fault, since in a missed corrupted section not all bytes are necessarily wrong. Therefore $p_u << 1 - p_e$ and we may neglect p_u and put $t_u = 0$ in (3). Assuming an absolute reliability of CRC, we may substitute for the erasure probability in (3)

$$p_e \approx 1 - (1 - p_s)^{N_s}. \quad (5)$$

Since the erasure patterns for each RS codewords are equal, the probability of erroneous CE decoding is calculated by

$$P_{eCE} = 1 - P_{cE} \quad (6)$$

B. *Transport stream packet erasure decoding (TSE)*

In the analysis of TSE (described in [12]) let us assume that when the TS packet is declared correct by the physical layer, the data carried inside the packet can always be decapsulated into the MPE-FEC frame (this could be accomplished for example with the help of the continuity counter in the TS header). The information on the correctness of the TS packets is obtained from one bit flag in TS header set by the physical layer to indicate the situation where an uncorrectable error pattern in

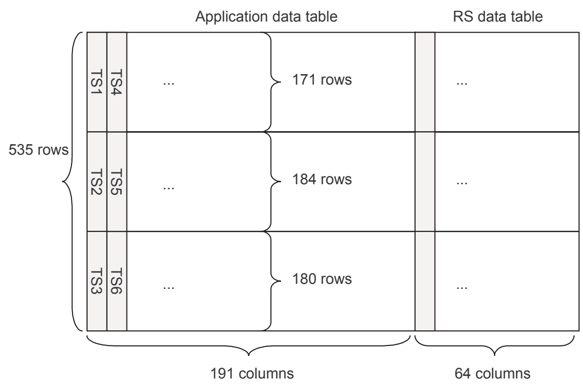

Figure 3: Structure of the frame used in calculations

the TS packet is recognized by the physical layer RS(204,188) decoder. When the flag is set the data carried inside the TS packet in question is marked as erased for the MPE-FEC decoder. To further simplify the calculations it is assumed that the frame consists of 3 subframes having 535 rows in total (see Fig. 3). The sizes of the subframes are 171, 184 and 180 rows, since following our assumptions the first TS packet carries the 12 byte MPE header and one byte payload unit start pointer and the third contains the 4 CRC-32 bytes. In this decoding scheme the information provided by the CRC-32 decoding is ignored. For our calculations the reliability of the erasure information obtained from the physical layer RS decoder needs to be evaluated first.

One way to estimate the probability of undetected error pattern in MDS (Maximum Distance Separable) codes is studied in [13], where results support an intuitive idea that the probability in question (if small enough) may be well approximated by the share of undetectable error patterns:

$$P_{decError} \cong \frac{\text{number of decodable words}}{\text{number of words}} = \frac{(q^k - 1)V_n(t)}{q^n} \approx q^{-(n-k)} V_n(t), \quad (7)$$

where k is the number of information symbols in a MDS codeword and $V_n(t)$ is the volume of a Hamming sphere of radius t, t being code correction capability. This result can be used for any MDS code, including shortened RS codes (such as the physical layer RS(204,188) code). Since $n - k = 2t$, we have

$$P_{decError} \approx q^{-2t} V_n(t). \quad (8)$$

For $V_n(t)$ the following estimate holds:

$$V_n(t) = \sum_{i=0}^{t} \binom{n}{i} (q-1)^i < q^t \sum_{i=0}^{t} \binom{n}{i} < q^t 2^{nh(\frac{t}{n})}, \quad (9)$$

where $h(x)$ is binary entropy [8]. Then from (8) and (9)

$$P_{decError} < q^{-t} 2^{nh(\frac{t}{n})}. \quad (10)$$

For $t = 8$, $n = 204$ and $q = 256$: $nh(\frac{t}{n}) - tlog_2 q \approx 204 \cdot 0.24 - 64 \approx -15$ so that $P_{decError} \approx 2^{-15} \approx 3 \cdot 10^{-5}$. This shows that any error pattern of weight greater than t will be almost for sure (i.e. with probability $\geq 1 - 3 \cdot 10^{-5}$) detected in the course of decoding so that in (3) p_u may be neglected and t_u put to zero.

Now the probability of erasure of one code symbol in every codeword in one of the three subframes is evaluated:

$$p_e \approx 1 - (1 - p_s)^{188}. \quad (11)$$

The probability of correct decoding of one subframe is evaluated by (4). The whole frame will be correct if decoding of all three subframes is successful leading to decoding error probability

$$P_{eTSE} = 1 - P_{cE}^3. \quad (12)$$

C. MPE-header-erasure decoding (MHE)

This decoding scheme is presented in [5] as Hierarchical Section decoding. The main idea in this decoding scheme is that on the contrary to what is suggested in [4] the data carried inside an unreliable section (or TS packet) having detected errors is inserted into the MPE-FEC frame for decoding whenever possible. In the case of MHE decoding it is assumed in this analysis that the payload of the section can be inserted into the frame for decoding whenever the MPE header is not corrupted. Thus from the decoder point of view the section is erased when an error hits the 12 byte section header leading to the probability of erased symbol in a codeword:

$$p_e \approx 1 - (1 - p_s)^{12}. \quad (13)$$

As described in [5] the decoding procedure has several stages, first one being the decoding using lost and unreliable sections as erasures. The performance of this first stage coincides with that of CE decoding. From the error correction capability point of view (and thus for this analysis) the second stage when all the data that has been put to the frame is considered reliable and only lost sections having errors in the MPE header are considered erased is more interesting. The probability of undetected symbol error in this situation is just the symbol error probability from the physical layer ($p_u = p_s$), since the information on payload errors within the section is discarded (i.e. CRC-32 information is not used). Using MPE-FEC frame having 535 rows the probability of erroneous decoding for MHE can be calculated after substituting p_e from (13) and $p_u = p_s$ in (3) by

$$P_{eMHE} = 1 - P_{cE}^{535}. \quad (14)$$

D. PID-erasure decoding (PE)

The idea of PE decoding scheme is presented in [5] as Hierarchical TS decoding. PE is rather similar to MHE, except that TS packet based information rather than section based is used. In the analysis of the PE decoding it is assumed that the payload of a TS packet can be put into the frame when the TS packet can be received. A TS packet can be received whenever the two byte (actually 13 bits, but approximated here to be two bytes) PID (Packet Identifier) in the TS header is correct. If the PID was not correct, the receiving equipment would not be able to recognize the packet to be a part of the received stream and thus would not receive it. When the packet is not received it is naturally erased. This way the probability of an erasure in each symbol of a codeword is approximated by the probability of the situation when an error hits the PID:

$$p_e \approx 1 - (1 - p_s)^2. \quad (15)$$

Again the interesting situation takes place when only completely lost TS packets (i.e. having errors in PID) are considered erased and knowledge of detected payload errors (information from the physical layer RS decoder and link layer CRC-32) is discarded. The probability of undetected error is now $p_u = p_s$. Using p_e (15) and $p_u = p_s$ in (3) the probability of erroneous decoding of one frame having three subframes (see Fig. 3) is evaluated by

$$P_{ePE} = 1 - P_{cE}^{171} P_{cE}^{184} P_{cE}^{180} = 1 - P_{cE}^{535}. \quad (16)$$

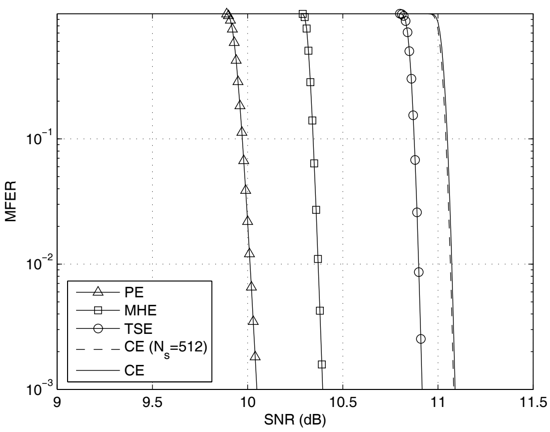

Figure 4: Comparison of different decoding methods

IV. Comparison of the decoding methods

To compare the performance of the different decoding methods for MPE-FEC code rate $3/4$ in terms of required SNR, MPE-FEC frame error rates are calculated from (6), (12), (14) and (16) using physical layer output byte error probabilities p_s related to SNR and provided by a DVB-T physical layer simulator. The results are shown in Fig. 4. The physical layer parameters assumed were: 16-QAM modulation, convolutional code rate $3/4$, 8K OFDM mode and guard interval duration equal to $1/4$ of "pure" OFDM symbol duration. The channel model used in the simulator is AWGN (Additive White Gaussian Noise) one. The curve for CE with $N_s = 512$ (dash line practically coinciding with a solid line for CE decoding with $N_s = 535$) is included to show the neglible effect of deviation of $N_s = 535$ from the standard frame size. The ranking of the

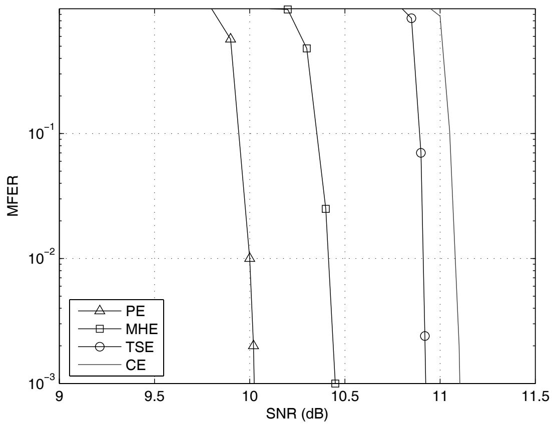

Figure 5: Simulation results for different decoding schemes

compared decoding methods follows from the order of frame error probabilities: $P_{ePE} < P_{eMHE} < P_{eTSE} < P_{eCE}$. The coding gains of the decoding methods over the CE decoding suggested in the standard are approximately PE=1, MHE=0.7 and TSE=0.2 dB at $MFER = 10^{-3}$ in the AWGN channel.

Example

Take for example SNR 10 dB for PE decoding. From physical layer simulations it is known that the symbol error probability for this SNR is $p_s = 0.033946$. Now we can calculate from (15) that $p_e = 1 - (1 - 0.033946)^2 = 0.066740$ and set $p_u = p_s = 0.033946$. Substituting these into (3) and furher in (4) for calculations results in $P_{cE} = 0.999959$ for MPE-FEC coderate $3/4$. Then, MPE-FEC frame error probability can be evaluated as $P_{ePE} = 1 - 0.999959^{535} \approx 0.022$.

Link layer simulation results using the same physical layer parameters are shown in Fig. 5. The link layer simulator generates the MPE-FEC frames, introduces errors according to the physical layer simulation, calculates the numbers of errors and erasures in rows of the frame and decides whether the frame in question can be decoded or not. As a result frame error rates are obtained. These simulations show similar results as the theoretical calculations in previous section thus confirming them.

Simulation results for the presented decoding methods in a mobile multipath channel can be found from [5]. The results of those simulations at different doppler frequencies indicate similar ranking of the decoding methods as obtained in this paper. The gain for the PE (HTS in [5]) over CE (SE in [5]) is also around 1 dB.

V. Conclusions

In this paper, the efficiency of the DVB-H link layer FEC with four different erasure decoding strategies (CE, TSE, MHE and PE) differing mainly in the way the erasure information is obtained was analyzed. First, the DVB-H system was briefly described. Then, the error probabilities for different decoding strategies were calculated. To support these analyses the probability of an error going undetected by the physical layer RS(204,188) decoder was also evaluated. For more easily approachable results the physical layer was simulated and the frame error rates were expressed as functions of SNR in AWGN channel. Further, the link layer was simulated to verify the theoretical calculations. It turned out that the PE decoding is the best of these four methods while CE decoding arranged as suggested in [4] has the worst decoding capability.

The significant result of this paper is that all other decoding methods including the TSE decoding that ignore the CRC-32 information perform better than the CE decoding. Therefore it would be of interest to find some other more benefitical use for the 4 byte overhead caused by the CRC-32 in MPE(-FEC) sections giving us no performance gain. For example, an error correcting code with 4 byte redundancy over each section could be used. The main reason why the performance of the CE decoding is worse than that of the others, is that using CRC-erasure information over rather long MPE(-FEC) sections erases many sound bytes along with the erroneous ones. If, for example, there is one real byte error in a section of length 512 bytes, 511 correct bytes are erased from the MPE-FEC frame when the CE decoding is performed.

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