

COMPARISON OF FEC AND ARQ FOR PROTECTION OF VIDEO DATA OVER A WIRELESS RAYLEIGH FADING LINK

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ABSTRACT

Video content can be provided to an end user by transmitting video data as a sequence of internet protocol (IP) packets over the network. When the network contains a wireless link, packet erasures occur because of occasional deep fades. In order to maintain a sufficient video quality at the end user, video packets must be protected against erasures by means of a suitable form of error control.

In this contribution we investigate two types of application layer error control : (1) Forward Error Correction (FEC), and (2) the use of an Automatic Repeat reQuest (ARQ) protocol. We point out that FEC and ARQ considerably reduce the probability of unrecoverable packet loss, because both error control techniques provide a diversity gain, as compared to the case where no protection against erasures is applied.

1. INTRODUCTION

The Internet Protocol (IP) allows to provide a mix of multimedia services (video, audio, voice, data, gaming,...) to an end user, by breaking up the bitstreams generated by the various services into IP packets and sending these packets over the network. In this contribution, we consider the delivery of these multimedia services via a wireless channel, and focus on the reliability of the received video data.

The occurrence of fading on wireless channels makes reliable transmission a difficult task, because occasional deep fades give rise to bursts of bit errors at the receiver. IP packets affected by bit errors are erased at the receiver, yielding lost packets at the destination. These lost packets are likely to cause visual distortions when viewing the video content at the destination. Hence, in order to obtain a sufficient Quality of Experience (QoE) it is imperative to limit the video packet loss rate.

In order to alleviate the damaging impact of fading, one can reduce the probability of bit errors by means of coding on the physical (PHY) layer. Not only the video, but also the other services that are provided via the same wireless link stand to benefit from this coding. In this contribution, we restrict our attention to orthogonal space-time block codes [1].

In order to provide additional protection of the video packets against erasures, one can resort to Forward Error Correction (FEC) coding [2] or to Automatic Repeat reQuest (ARQ) protocols [3] on the application layer; these techniques involve the transmission of redundant packets (in addition to the video information packets) or sending a request for retransmitting erased video packets, respectively.

We select Reed-Solomon (RS) codes for protecting packets against erasures by means of FEC, because they are able to recover the maximum possible number of erasures for a given transmission overhead [2]. As far as ARQ protocols are concerned, we consider

Selective Repeat (SR) ARQ, which yields the minimum transmission overhead [3].

In this contribution we investigate to what extent the combination of the RS code or the SR ARQ protocol with the space-time PHY layer code improves the reliability of the video transmission over a wireless channel subject to Rayleigh fading. The paper is organized as follows. In Section 2, we introduce some basic concepts about video compression. We detail in Section 3 the RS erasure coding and the SR ARQ protocol. We provide in Section 4 the error performance analysis for various scenarios, involving space-time coding or no coding on the PHY layer, with or without protection (RS coding or SR ARQ) of the video packets. In Section 5 we present a case study pertaining to HDTV transmission over a 60 GHz indoor wireless link. Finally, in Section 6 conclusions are drawn regarding system performance and complexity.

2. VIDEO TRANSMISSION

In this section we describe the video packet transmission. First, the video source coding method is briefly mentioned. Next, at the physical (PHY) layer, we consider the wireless link between the video server to the end user.

2.1 Video source coding

The video stream is encoded (compressed) according to the MPEG-2 standard [4], which is commonly used as the format for digital television. The Video section of MPEG-2 (part 2) is designed to compress the video stream through appropriate coding by exploiting the existing redundancy in space and time. Uncompressed video can be seen as a sequence of picture frames (e.g. 25 frames per second). Typically, the scenes in successive pictures are very similar. One can take advantage of this similarity to compress the video into three types of frames: intra-coded frames (I-frames), predictive-coded frames (P-frames), and bidirectional-predictive-coded frames (B-frames). A commonly used frame pattern is IBBPBBPBBPBB, called a Group Of Pictures (GOP), which consists of 12 compressed frames and which is repeated. Such a GOP has a duration of 480 ms (25 frames per second).

2.2 Physical layer

On the PHY layer of the transmitter, the L bits to be sent for every data-link-layer packet are mapped onto an M -point signal constellation.

The fading gain is assumed to be piecewise constant over time; the fading gain does not change over a time interval equal to the channel coherence time T_{coh} , and is statistically independent of the fading gain in other intervals of duration T_{coh} . During an interval T_{coh} , several packets are transmitted, as indicated in Figure 1. Packets from other applications are located in between the packets with video data.

On the PHY layer of the receiver, the M -ary data symbols are detected, and demapped to bits. On the MAC sublayer, the recovered bits are grouped into packets of size L , and error detection based on the CRC is performed. When an error is detected, the

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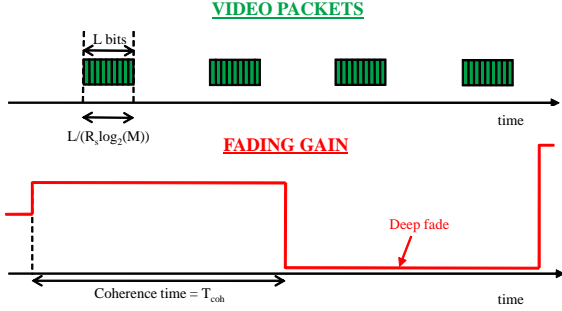


Figure 1: Video packet stream and fading gain versus time; in this example, 2 video packets are transmitted during the channel coherence time, in which case a packet group consists of 2 packets.

packet is erased; otherwise, the packet is passed to the higher layers.

Because of fading, the received signal is occasionally strongly attenuated. To alleviate the damaging impact of fading on the detection of the M -ary data symbols, we consider the use of multiple transmit and receive antennas. A multiple-input multiple-output (MIMO) system with N_t transmit and N_r receive antennas allows the introduction of space-time coding [1]. Whereas an uncoded single-input single-output (SISO) system, i.e. $N_t = N_r = 1$, provides only one wireless link between the transmitter and destination, the number of wireless links provided by an Orthogonal Space-Time Block-Coded (OSTBC) MIMO system equals $N_r N_t$. As compared to a SISO system, the larger number of links resulting from OSTBC MIMO gives rise to a considerably higher robustness against fading, and a much better error performance. Using an OSTBC MIMO system does not require additional bandwidth as compared to the SISO system, but comes at a substantial hardware cost that increases with the number of antennas. Optimum decoding of OSTBC MIMO reduces to linear processing and simple symbol-by-symbol detection at the receiver.

In this paper, we will consider the Alamouti space-time code [1], which requires 2 transmit antennas (and an arbitrary number N_r of receive antennas).

3. ADDITIONAL PROTECTION OF THE VIDEO DATA

As mentioned before, packets yielding an erroneous checksum are discarded (erased) on the MAC layer, because they have been affected by transmission errors; the other packets are assumed to be received correctly. Because of video packet erasures, visual distortions may occur when viewing the received video content. In order to guarantee a sufficient QoE to the end user, the rate of video packet erasures should be limited. When the packet erasure rate caused by transmission errors on the wireless link is too large, additional measures are needed to recover erased video packets. In this contribution we consider the combination of a PHY layer with either no coding or Alamouti space-time coding with 1 or 2 receive antennas, and additional packet protection by means of either RS erasure coding or SR ARQ on the application layer.

3.1 RS erasure coding

The RS code is defined over the Galois Field $GF(2^q)$ (typically $q = 8$). Per group of K video information packets, we transmit $N - K$ parity packets. This results in a packet codeword of N packets. The parity packets are constructed such that taking from each packet the i^{th} block of q bits yields an $RS(N, K)$ codeword, for all $i = 1, 2, \dots, L/q$. This construction is illustrated in Figure 2. Hence, when e packets from the packet codeword are erased, each of the L/q RS codewords is affected by exactly e symbol erasures.

The $RS(N, K)$ code is known to be Maximum Distance Separable (MDS), i.e. the code can recover up to $N - K$ erasures, which

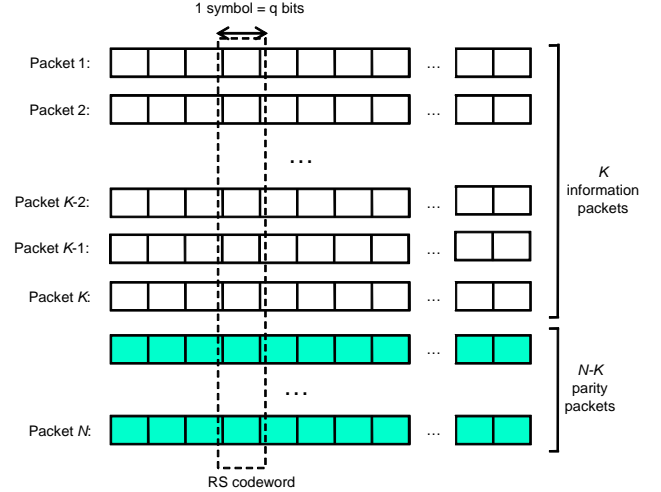


Figure 2: Construction of a packet codeword.

cannot be outperformed by any other code with the same number $N - K$ of parity symbols [2]. When the number of erasures is larger than $N - K$, erasure decoding fails and unrecoverable packet loss occurs.

The introduction of erasure coding yields an increase of both overhead and latency:

- Using an (N, K) block code gives rise to a transmission overhead ovh given by $ovh = (N - K)/K$, because for each K information packets, $N - K$ additional packets must be transmitted. Hence, denoting by R_{pack} (in packets per second) the rate of information packets, the packet transmission rate equals $(N/K)R_{pack}$. This indicates that because of the coding the fraction of time during which the channel is used for video transmission is increased by a factor N/K , leaving less room for the transmission of packets from other applications.
- The RS decoder must wait until all N packets of the codeword are received, before the erasure decoding can start. Hence, using the (N, K) block code introduces an additional latency T_{lat} which equals the duration of a packet codeword. Increasing the latency gives rise to a larger zapping delay¹, which might unfavorably affect the user's QoE.

Considering the above, the code parameters N and K should be selected such that the overhead and latency are limited to reasonable values.

3.2 Selective repeat ARQ

As far as ARQ is concerned, we consider an SR retransmission protocol. The receiver sends a retransmission request for each of the erased video packets, and only copies of the erased packets are retransmitted. Retransmissions are scheduled such that the time interval T_{retr} between the (re)transmission instants of copies of a same packet is not less than the channel coherence time T_{coh} . This way, the different copies experience statistically independent fading. When one would select $T_{retr} < T_{coh}$, the retransmission of a packet that has been erased because of a deep fade is experiencing the same deep fade, and therefore is likely to be erased as well. Such retransmissions should be avoided, as they are not useful, but rather contribute to the transmission overhead. Since each retransmission gives rise to a latency of T_{retr} , the maximum number N_{retr} of allowed retransmissions per packet is given by $N_{retr} = \lfloor T_{lat}/T_{retr} \rfloor$, in

¹The zapping delay is the time that elapses between giving the command to change the TV channel and the appearance of the new TV channel on the screen [5].

order that the total latency caused by the SR ARQ protocol does not exceed T_{lat} .

4. SYSTEM ANALYSIS

In this section we present the analysis of the system under study. We first investigate the PHY layer, followed by the additional packet protection by means of RS erasure coding or SR ARQ. As a performance measure, we consider the average number of GOPs that are affected by irrecoverable packet loss, over a reference time interval of 12 hours.

4.1 PHY layer

We consider the cases of uncoded SISO transmission, and Alamouti orthogonal space-time coding (2 transmit antennas) with 1 or 2 receive antennas. The probability $P_{bit}(x)$ that a bit is received in error, depends on the instantaneous channel state x . The channel state x is the sum of the squared fading gains that are involved in the transmission of the considered bit (1 fading gain for SISO, and 2 or 4 fading gains for Alamouti with 1 or 2 receive antennas). The probability density function $p(x)$ of the channel state is given by [6]

$$p(x) = \frac{x^{D-1} \exp(-x)}{(D-1)!} \quad (1)$$

with $D = 1$ for uncoded SISO and $D = 2$ or $D = 4$ for Alamouti with $N_r = 1$ or $N_r = 2$. The quantity D is the *diversity* provided by the PHY layer; basically, D equals the number of physical links between the transmitter and the receiver that are exploited by the transmission scheme. As we will shortly demonstrate, the error performance improves with increasing D ; this is intuitively clear, because all D links must fail for a packet erasure to occur.

The packet erasure probability $P_{pack}(x)$ conditioned on x equals:

$$P_{pack}(x) = 1 - (1 - P_{bit}(x))^L \quad (2)$$

To obtain (2) we have assumed that the packet duration is less than the channel coherence time, so that the channel state is the same for all L bits of a packet.

Before we consider in the next subsections the cases where RS erasure coding or SR ARQ is used in order to recover erased packets, we now investigate the system performance under the assumption that no such error control measures are taken.

We define a *packet group* as the set of packets that are transmitted consecutively in time during an interval of duration T_{coh} over which the fading is constant. We denote by N_{coh} the number of packets transmitted during the interval T_{coh} . For the example shown in Figure 1, we have $N_{coh} = 2$. The probability $P_{group}(e)$ that e packets are erased within a packet group of size N_{coh} , irrespective of the channel state, is given by

$$P_{group}(e) = \binom{N_{coh}}{e} \int_0^{+\infty} P_{pack}^e(x) (1 - P_{pack}(x))^{N_{coh}-e} p(x) dx, \quad (3)$$

$e = 0, \dots, N_{coh}$. We have $P_{group}(e) \propto (E_b/N_0)^{-D}$ for $e > 0$.

Let us now compute the probability P_{GOP} that a GOP is affected by unrecoverable packet loss. As no measures are taken to recover erased packets, each erased packet is lost. Denoting by T_{GOP} and N_{GOP} the duration of one GOP and the number of packet groups that fit within the duration of one GOP, respectively, we have

$$\begin{aligned} P_{GOP} &= 1 - (P_{group}(0))^{N_{GOP}} = 1 - \left(1 - \sum_{e=1}^{N_{coh}} P_{group}(e)\right)^{N_{GOP}} \\ &\approx N_{GOP} \sum_{e=1}^{N_{coh}} P_{group}(e) = N_{GOP} (1 - P_{group}(0)) \end{aligned} \quad (4)$$

Hence, for large E_b/N_0 , we obtain $P_{GOP} \propto (E_b/N_0)^{-D}$. This illustrates the impact of the PHY layer diversity D : the larger D , the smaller the probability that a GOP is affected by packet erasures.

From (4), we compute the average number $E[\#GOP_{unrec}]$ of GOPs that are affected by unrecoverable packet loss in a reference interval T_{ref} of 12 hours. Denoting by N_{ref} the number of GOP intervals in T_{ref} , we have $T_{ref} = N_{ref} T_{GOP} = N_{ref} N_{GOP} T_{coh}$. Hence,

$$\begin{aligned} E[\#GOP_{unrec}] &= N_{ref} P_{GOP} \\ &\approx N_{ref} N_{GOP} (1 - P_{group}(0)) \\ &= \frac{T_{ref}}{T_{coh}} (1 - P_{group}(0)) \end{aligned} \quad (5)$$

The approximation in (5) holds for large E_b/N_0 . Note that, at high E_b/N_0 , $E[\#GOP_{unrec}]$ is independent of the GOP duration, and proportional to $(E_b/N_0)^{-D}$.

4.2 Packet protection by means of RS erasure coding

Now we consider the case where $(N - K)$ parity packets are added to K information packets, yielding a (N, K) RS packet codeword. The number N_{coh} of packets transmitted during the interval T_{coh} denotes the size of a packet group. We assume that the N packets of the packet codeword are distributed over N_{group} packet groups, to which we associate the indices $1, 2, \dots$ and N_{group} . We denote by e_n the number of erased packets in the packet group with index n ($n = 1, \dots, N_{group}$), and introduce the vector $\mathbf{e} = (e_1, \dots, e_{N_{group}})$. We define by $Pr(\mathbf{e})$ the probability that the number of erased packets in the groups with indices $1, 2, \dots$ and N_{group} equals e_1, e_2, \dots and $e_{N_{group}}$, respectively. We obtain

$$Pr(\mathbf{e}) = \prod_{n=1}^{N_{group}} P_{group}(e_n) \quad (6)$$

From (6), the probability $P_{RS}(e_{tot})$ that e_{tot} erasures occur in the packet codeword is given by

$$P_{RS}(e_{tot}) = \sum_{e_1+e_2+\dots+e_{N_{group}}=e_{tot}} Pr(\mathbf{e}) \quad (7)$$

Finally, the probability $Pr[\text{decoding failure}]$ that the erasures cannot be recovered by the RS decoder (because e_{tot} is larger than $N - K$) becomes

$$Pr[\text{decoding failure}] = \sum_{e_{tot}=N-K+1}^N P_{RS}(e_{tot}) \quad (8)$$

In order to obtain at least $(N - K + 1)$ erasures in the codeword, at least $\gamma_{RS} = \lceil (N - K + 1)/N_{coh} \rceil$ packet groups must contain erased packets; this implies that the vectors \mathbf{e} in (7) must have at least γ_{RS} nonzero entries. Hence, for large E_b/N_0 , $Pr[\text{decoding failure}]$ is proportional to $(E_b/N_0)^{-\gamma_{RS}D}$. Taking into account that $ovh = (N - K)/K$, $T_{lat} = K/R_{pack}$ and $N_{coh} = \lceil (N/K)T_{coh}R_{pack} \rceil = \lceil NT_{coh}/T_{lat} \rceil \approx NT_{coh}/T_{lat}$, γ_{RS} can be expressed as

$$\gamma_{RS} = \left\lceil \frac{N - K - 1}{N_{coh}} \right\rceil \approx \left\lceil \frac{N - K}{N_{coh}} \right\rceil \approx \left\lceil \frac{ovh}{1 + ovh} \cdot \frac{T_{lat}}{T_{coh}} \right\rceil \quad (9)$$

Note that γ_{RS} is an increasing function of both ovh and T_{lat} .

Now we consider the probability P_{GOP} that a GOP is affected by unrecoverable packet loss. Denoting by N_{RS} the number of packet codewords in one GOP interval T_{GOP} , we have

$$\begin{aligned} P_{GOP} &= 1 - (1 - Pr[\text{decoding failure}])^{N_{RS}} \\ &\approx N_{RS} Pr[\text{decoding failure}] \end{aligned} \quad (10)$$

Similarly, the average number of GOPs that are affected by unrecoverable packet loss during a reference period T_{ref} of 12 hours is given by

$$\begin{aligned} E[\#GOP_{unrec}] &= N_{ref} P_{GOP} \\ &\approx N_{ref} N_{RS} Pr[\text{decoding failure}] \\ &= \frac{T_{ref}}{T_{lat}} Pr[\text{decoding failure}] \end{aligned} \quad (11)$$

where $T_{ref} = N_{ref} T_{GOP} = N_{ref} N_{RS} T_{lat}$. The approximations in (10) and (11) are valid for large E_b/N_0 . We deduce from (10) and (11) that both P_{GOP} and $E[\#GOP_{unrec}]$ are proportional to $(E_b/N_0)^{-\gamma_{RS}D}$. Hence, as compared to the case where no erasure coding is used, the effect of the RS(N, K) code is to increase the diversity order from D to $\gamma_{RS}D$: erasure coding introduces a diversity gain of γ_{RS} .

4.3 Packet protection by means of selective repeat ARQ

With the proposed retransmission strategy, a packet will be lost definitively when it has been erased during the first transmission and during N_{retr} successive retransmissions. The probability $P_{ARQ,unrec}(\mathbf{x})$ of this event is given by

$$P_{ARQ,unrec}(\mathbf{x}) = \prod_{i=0}^{N_{retr}} P_{pack}(x_i) \quad (12)$$

where $P_{pack}(x)$ is the packet erasure probability corresponding to a channel state x (see (2)), and $\mathbf{x} = (x_0, \dots, x_{N_{retr,max}})$ contains the values of the channel state at the first transmission and the subsequent N_{retr} retransmissions of the considered packet. The probability $P_{group,unrec}(\mathbf{x})$ that at least one packet from a packet group of $N_{coh} = \lceil T_{coh} R_{pack} \rceil$ packets (which all experience the same channel state) is erased definitively is given by:

$$P_{group,unrec}(\mathbf{x}) = \sum_{j=1}^{N_{coh}} \binom{N_{coh}}{j} (-1)^{j-1} P_{ARQ,unrec}^j(\mathbf{x})$$

Averaging $P_{group,unrec}(\mathbf{x})$ over the channel gain statistics yields the probability $\bar{P}_{group,unrec}$ that at least one packet in a packet group is definitively lost, irrespective of the channel state values:

$$\bar{P}_{group,unrec} = \sum_{j=1}^{N_{coh}} \binom{N_{coh}}{j} (-1)^{j-1} (E[P_{pack}^j(x)])^{N_{retr}+1}$$

For large E_b/N_0 , we have $E[P_{pack}^j(x)] \propto (E_b/N_0)^{-D}$, so that $\bar{P}_{group,unrec}$ is proportional to $(E_b/N_0)^{-(1+N_{retr})D}$.

Following the same reasoning as in subsection 4.1, the quantities P_{GOP} and $E[\#GOP_{unrec}]$ are given by

$$P_{GOP} = 1 - (1 - \bar{P}_{group,unrec})^{N_{GOP}} \approx N_{GOP} \bar{P}_{group,unrec} \quad (13)$$

$$\begin{aligned} E[\#GOP_{unrec}] &= N_{ref} P_{GOP} \\ &\approx N_{ref} N_{GOP} \bar{P}_{group,unrec} \\ &= \frac{T_{ref}}{T_{lat}} \bar{P}_{group,unrec} \end{aligned} \quad (14)$$

For large E_b/N_0 , both P_{GOP} and $E[\#GOP_{unrec}]$ are proportional to $(E_b/N_0)^{-(1+N_{retr})D}$. Hence, as compared to the case of no retransmissions, the use of SR ARQ provides a diversity gain γ_{ARQ} which is given by $\gamma_{ARQ} = 1 + N_{retr} = 1 + \lceil T_{lat}/T_{retr} \rceil$.

5. RESULTS APPLIED TO HDTV TRANSMISSION OVER A 60 GHZ INDOOR WIRELESS LINK

Now we consider the transmission of compressed HDTV [7] according to the configuration shown in Figure 3. The compressed video bitrate equals 7.5 Mbit/s. The link between the HG and the STB is a 60 GHz indoor wireless connection; assuming Non-Line-Of-Sight (NLOS) conditions, this connection is modeled as a Rayleigh fading channel, with a coherence time $T_{coh} = 20$ ms (corresponding to slow motion of about 0.4 m/s) [8]. In order to limit the zapping delay, the latency T_{lat} caused by protecting the video packets against erasures should not exceed 150 ms [9]. The HDTV performance target is a maximum of 1 GOP with unrecoverable packets in 12 hours.

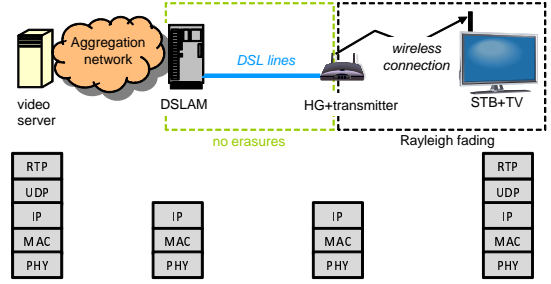


Figure 3: Concatenation of DSL connection and wireless connection (DSLAM = Digital Subscriber Line Access Multiplexer, HG = Home Gateway, STB = Set-Top Box).

	GOP = {IBBPBBPBBPBB}, 25 frames/s, 7.5 Mbit/s video bitrate		
	size (kbit)	# MPEG-2 TS packets	# IP packets
one I-frame	1080	714	102
one P-frame	360	238	34
one B-frame	180	119	17
one GOP	3600	2380	340

Table 1: Average sizes of I-frame, P-frame, B-frame and GOP

When protecting the video packets by means of a RS packet codeword, we consider transmission overheads of 10%, 20% and 40%.

When using SR ARQ, we consider two distinct scenarios as far as the location of the retransmission buffer is concerned.

- When the retransmission buffer is located at the HG, $T_{retr,min}$ is limited to about 5 ms. As 5 ms is less than the 20 ms channel coherence time, the transmitter will defer the retransmission of a packet until 20 ms have elapsed since the previous (re)transmission of the considered packet; hence, this yields $T_{retr} = 20$ ms.
- In the case of a low-cost HG, the retransmission buffer is not located at the HG but further upstream, at the DSLAM. The resulting $T_{retr,min}$ is on the order of 45 ms [8], which exceeds the 20 ms channel coherence time. In this case, we have $T_{retr} = 45$ ms.

Assuming that the average sizes of an I-frame and a P-frame are 6 times and 2 times the average size of a B-frame, Table 1 shows the average sizes of the different types of frames and of the GOP consisting of the frame sequence IBBPBBPBBPBBP. Note that each type of frame gives rise to multiple IP packets. As the IP packet rate is about 700 packets/s and the channel coherence time is 20 ms, about 14 IP packets fit within the channel coherence time (assuming IP packets are transmitted at constant regular intervals). Taking into account the propagation of errors from an I- or P-frame to other frames in the GOP, unrecoverable packet loss in an I- or P-frame is very likely to give rise to a visual distortion. Considering that the I- and P-frames in a GOP constitute on average 60% of the IP video packets, and packet losses tend to occur in bursts with sizes comparable to the channel coherence time (14 IP packets in our scenario), it follows that when a GOP is affected by unrecoverable packet loss, the probability that the packet losses occur in I- or P-frames is about 60%. Assuming that packet losses in B-frames are unnoticed but losses in I- or P-frames yield visible distortions, the probability that a GOP affected by unrecoverable packet loss yields a visual distortion is about 60%. Moreover, some of the IP packets contain other information (audio, data) related to the HDTV program, that is multiplexed with the video information. The loss of packets containing a multiplex of B-frame information and other HDTV related information reduces the QoE (because of audible clicks, ...), although

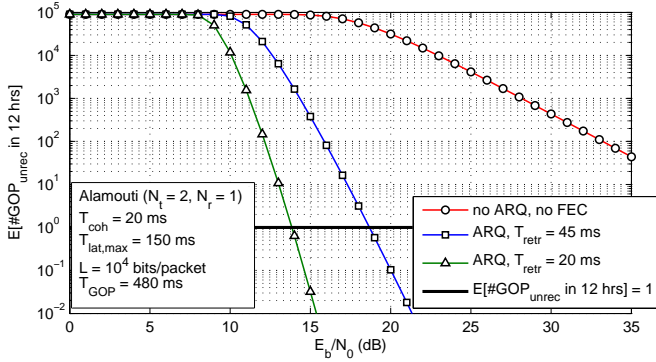


Figure 4: Average number of GOPs affected by unrecoverable packet loss in 12 hrs (Alamouti, $N_r = 1$, ARQ).

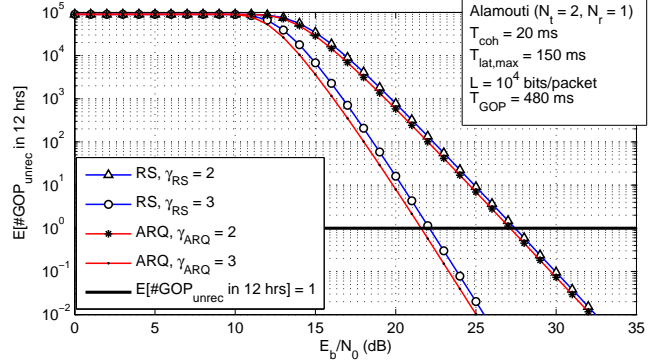


Figure 6: Average number of GOPs affected by unrecoverable packet loss in 12 hrs, RS versus ARQ (Alamouti, $N_r = 1$).

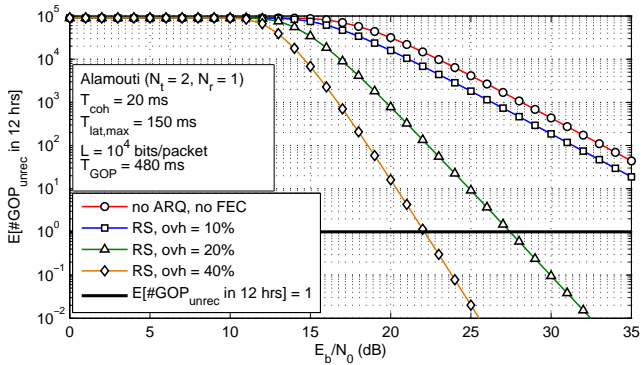


Figure 5: Average number of GOPs affected by unrecoverable packet loss in 12 hrs (Alamouti, $N_r = 1$, RS).

the errors in the B-frame do not propagate and could be concealed. Therefore, the average number of GOPs that is affected by unrecoverable packet loss in 12 hours is a meaningful indicator of the QoE.

When conducting the performance analysis, we assumed that the erasure probability on the DSL link is negligibly small as compared to that on the wireless link between the HG and the STB.

Figures 4-6 show the average number of GOPs with unrecoverable packet loss in 12 hours as a function of E_b/N_0 , for Alamouti with 1 receive antenna and for the different packet protection strategies (SR ARQ, RS erasure coding, none). When using SR ARQ, the cases $T_{retr} = 45$ ms and $T_{retr} = 20$ ms correspond to diversity gains γ_{ARQ} of 4 (max. 3 retransmission) and 8 (max. 7 retransmissions), respectively. In the case of RS erasure coding, overheads of 10%, 20% and 40% yield diversity gains γ_{RS} of 1 (i.e., no diversity gain), 2 and 3, respectively.

- The highest possible diversity gain is $\lceil T_{lat}/T_{coh} \rceil = 8$. This diversity gain is achieved for SR ARQ with $T_{retr} = T_{coh}$, i.e. when the retransmission buffer is at the HG.
- Because of their larger diversity gain, the systems with SR ARQ outperform the systems with RS coding. In order to achieve a diversity gain of 4, the transmission overhead of the systems with RS coding should be increased to about 70%. A diversity gain of 2 is obtained for the systems with SR ARQ when T_{retr} is between 50 ms and 75 ms.
- Figure 6 compares RS coding and SR ARQ in terms of $E[\#GOP_{unrec} \text{ in 12 hrs}]$ for Alamouti with 1 receive antenna, where the system parameters have been selected such that RS coding and SR ARQ yield the same diversity. We observe that the RS code performs worse than SR ARQ. This is because for the RS code the number of dominant erasure patterns yielding

irrecoverable packet loss is larger than for SR ARQ.

6. CONCLUSIONS AND REMARKS

We have pointed out that SR ARQ and RS erasure coding on the application layer give rise to a diversity gain yielding improved error performance, and have presented simple analytical expressions for this gain. For both SR ARQ and RS erasure coding, the maximum possible diversity gain equals $\lceil T_{lat}/T_{coh} \rceil$. However, when using RS erasure coding this maximum diversity gain cannot be achieved because of practical limitations on the allowed transmission overhead. SR ARQ yields the maximum diversity gain provided that $T_{retr,min} < T_{coh}$; otherwise, the actual diversity gain is less.

The RS erasure coding gives rise to a fixed overhead and latency, that are determined by the parameters of the RS code. In the case of SR ARQ, the instantaneous overhead and latency are random; their maximum values are determined by the maximum number of retransmissions, while their averages decrease with increasing E_b/N_0 and are considerably less than the corresponding values for RS erasure coding.

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