Quality of experience in multicast hybrid networks: avoiding bandwidth wasting with a double-stage FEC Scheme

P. Barsocchi  G. Olicer
ISTI-CNR, Pisa Research Area, Via G. Moruzzi 1, 56124 Pisa, Italy
E-mail: gabriele.oligeri@isti.cnr.it

Abstract: Quality of experience is becoming an important parameter for estimating the end user perceived video quality. Video coding algorithms are currently increasing the compression performances by exploiting the temporal and spatial correlations of multimedia information. Such a trend is self-defeating in hybrid networks, due to the frequent channel impairments experienced. Here, the authors present a double-stage forward error correction (FEC) scheme to reduce the channel impairments that a multimedia communication undergoes when broadcasting a video stream through an hybrid infrastructure constituted by satellite and terrestrial wireless links. The authors present a detailed statistical description of the terrestrial wireless channel and exploit it to design the parameters for tuning the algorithm. Simulations results show that this approach not only performs better than the error recovery techniques currently used in the literature, but it also experiences a significant reduction in the bandwidth overhead.

1 Introduction

In last years, hybrid networks based on wireless LANs linked together by satellite have been widely considered in the literature [1–3]. In particular, multimedia communication is becoming more and more a hot topic in such networks due to their broadcast nature. Siller and Woods [4] enlightened how quality of service (QoS) is not a sufficient metric to assess the perceived quality by the end user, and they proposed a framework for estimating the quality of experience (QoE), based on the hypothesis that a better QoE can be achieved when the QoS interactions of the network and application layers are considered as a whole rather than a single entity. QoE is a critical parameter in multimedia communications; Greengrass et al. [5, 6] have shown that 'Not All Packets Are Equal' by enlightening that even a short duration of channel impairments can result in significant visual impairments that last for long time. Error recovery techniques become crucial due to the fact that redundancy increases the perceived quality at the end user but decreases the available bandwidth. Therefore, in such networks available bandwidth is a critical issue: saving satellite bandwidth becomes a challenge that is dealt with by using dynamic control of allocated resources and by adopting bandwidth-saving network protocols, that is, broadcast. As a matter of fact, the SatNEx community [7, 8] has stressed the importance of using broadcast protocols to avoid the wasting of resources in satellite networks, especially in the context of streaming services. Another critical issue is the overall channel efficiency, which is impaired by multiple effects, such as multipath fading on terrestrial networks and signal fading on satellite links. Traditional approaches for error recovery can be divided into two categories: automatic repeat request (ARQ) and FZC (forward erasure codes) techniques. In ARQ, the receivers return the sequence numbers of the lost packets back to the server, so that the server retransmits those packets to receivers. Therefore such an approach performs well when the loss probability is high, the link latency is small and there are few receivers. In FZC, the sender transmits some amount of redundant frames, which allows the receiver to reconstruct the missing data without further interactions with the transmitter. FZC approach is feedback-free and, hence it avoids long recovery
delays, which is typical in satellite links. Whereas a drawback of FZC is the reduction in the available bandwidth. In a hybrid network, the packet loss significantly fluctuates, and incorporating the optimal amount of FZC in a video streaming application is a difficult task; a too little redundancy cannot effectively protect the video bit stream, and an excessive redundancy unnecessarily consumes too much bandwidth.

In this paper, we propose a set of configuration parameters for a new error recovery technique specifically designed for a hybrid scenario constituted by a satellite and a terrestrial wireless network. We exploit a measurement campaign to draw a statistical description for wrong bits. We show how a double-stage FEC scheme can be used to improve the QoE of a broadcast multimedia content saving bandwidth in the transmission links.

The paper is organised as follows. Section 2 surveys the main error recovery techniques. Section 3 introduces the reference scenario. Section 4 is devoted to the description of the measurement campaign and to its statistical description. Section 5 addresses the design of the proposed error recovery technique. Section 6 analyses the simulation results. Finally, conclusions are offered in Section 7.

2 Related work

FEC techniques have been proved to successfully provide reliability in the Internet, as they avoid the control packet implosion and scalability problems of ARQ-based protocols [9, 10]. Barsocchi et al. [11] has shown the performance in terms of video quality by using a FZC. They showed that QoS is always acceptable when using a satellite bandwidth overhead greater than 30%. Yufeng Shan [12] proposed a two-stage FEC scheme, which combines Reed Solomon codes for packet-level protection and BCH codes for bit-level protection. Simulating the Wi-Fi channel by using a Gilbert error model, they present a performance evaluation by correcting both bit errors at MAC/PHY layers and the packet loss at the application layer. The two-stage FEC approach [12] allows us to reduce the redundancy with respect to the FZC approach proposed in [11]. On the other hand, simulating the wireless channel by using a Gilbert error model cannot be suitable; in fact Barsocchi et al. [13] show that the measured traces exhibit long polynomial tails, a peculiar trait that is not shared with the Gilbert error model and that produces error gap distributions with geometrically decaying tails.

2.1 Contribution

In this paper, we present a double-stage error recovery technique based on a combination of an upper layer FEC (hereafter UL-FEC) and a bit-level FEC (hereafter bL-FEC). The former is used to recover the packets lost for no carrier synchronisation both in the satellite and in the Wi-Fi link, while the latter is used to correct the packet corruptions due to fast fading fluctuations. We show how to improve the QoE of a multimedia content and saving bandwidth on the link used for the broadcast transmission. Also, we present the results of an extensive measurement campaign, and we exploit its statistical description to design the parameters for the proposed technique. As far we know, this is the first time a deep inspection of the 802.11 channel behaviour is proposed and exploited to tune an error recovery technique in an effective and efficient way.

3 Scenario

Fig. 1 shows our reference scenario. A set of clients receives a video stream transmitted by means of a hybrid link.

![Figure 1](image_url)
constituted by both a satellite and a terrestrial wireless link. The video stream is transmitted by the video stream server to the satellite transmitter, which broadcasts it to the satellite network. Each satellite receiver, at its turn, broadcasts the video stream to the terrestrial wireless network. The satellite link is characterised by a low bit error rate and a high round trip time, while the terrestrial wireless link is characterised by high fluctuations in the packet loss due to the multipath fading. The broadcast transmissions prevent the use of the ARQ error recovery approach; furthermore, a FEC error recovery procedure has to be applied in between the video stream server and the end users. The error recovery procedure is implemented in three different nodes of the hybrid network: (i) the video stream server applies an UL-FEC to the original video stream, (ii) the terrestrial wireless access point (in our case embedded in the satellite receiver) applies a bl-FEC to the Wi-Fi data frame, (iii) the end user performs two different error recovery policies: the bl-FEC, to recover errors from the wireless link, and PL-FEC to recover lost packets in the end-to-end link.

4 802.11 Channel: a case study

4.1 Hardware and software configuration

We performed an indoor measurement campaign by using two IBM Thinkpad R40e laptops (Celeron 2 GHz with 256 MB RAM, running Debian Linux with a 2.6.8 kernel), equipped with CNet CNWLC-811 IEEE 802.11b PCMCIA wireless cards and standard drivers. The cards were put in ad hoc mode, so that it was not necessary to depend on an access point, and no management overhead was present except for the periodic beacon. We disabled the fragmentation, RTS/CTS, retransmissions (ARQ) and the dynamic rate switching. The speed was set to 11 Mb/s, with a fixed frame length of 1500 bytes. By disabling ARQ, the MAC layer transmits each packet only once, rather than trying to retransmit a frame up to eight times after a loss. This means that we sampled the channel at a constant rate of 200 frames/s, thus accurately measuring the frame error process in the time domain. The procedure described makes the measurement process independent of the MAC protocol and only dependent on the channel and the hardware used. In order to collect bit error statistics of the received frames, we wrote Vbrsr [14], a pair of programs for sending and receiving 802.11 frames. The measurements have been performed with CRC check disabled, and the receiver was able to keep trace of all corrupted bits in each frame. The considered traces have been obtained in an office building of the authors’ research institute ISTI, located in Pisa (IT). It is a typical office environment with an area of approximately 15 m by 20 m. The walls are made of gasbeton, the floor is wooden and a lightweight dropped ceiling is in place. This environment is harsh for wireless communications due to multipath reflections from walls and the possibility of interference by the electronic devices present in the offices. The traces are collected for different distances with a variable number of walls in between the laptops.

4.2 Deep inspection in 802.11 channel impairments

In this section, we present the statistical description of our indoor Wi-Fi measurement campaign. The receiver keeps track of the received frame status by means of a sequence number embedded in each frame by the transmitter. Moreover, disabling CRC check, receiver is able to collect the corrupted bit positions. The transmitted frame can be: (i) lost, if the receiver observes a gap in the sequence numbers, (ii) corrupted, if the receiver receives the frame but the CRC check fails or finally (iii) received, if the receiver correctly receives the frame. Fig. 2 shows the channel characterisation in terms of lost, corrupted and received frames. The showed measure is 2.5 h long, and each point is evaluated as the mean over 100 samples. The number of correctly received frames is about 90%, but only 2% are lost due to a no carrier synchronisation; the residual 8% just fails the CRC check and can be recovered by using an error recovery technique.

The subsequent analysis aims to statistically describe the positions and the occurrences of the corrupted bits inside the 802.11 frame. Let \( p \) be a 1440B long MAC_80211 frame and \( \{s_0, \ldots, s_b\} \) be the sequence of the \( S \) symbols belonging to the packet \( p \). Each symbol \( s_i \), constituted by \( m = 8 \) bits, can be received with no errors as \( s^g_i \) (good symbol), that is, \( s^g_i = s_i \), or corrupted as \( s^b_i \) (bad symbol), that is, \( s^b_i \neq s_i \). Let us define \( F_X(x) \) the cumulative distribution function, hereafter CDF, such that \( F_X(x) = P[X \leq x] \), where \( X \) is a random variable, and \( x \) is a possible outcome of \( X \). Let \( G[s^g] \rightarrow \mathbb{N} \) be a random variable, hereafter gap length, such that \( g = G(s^g) \), where \( g \in \mathbb{N} \), and \( s^g \) is a sequence of \( g \) correctly received symbols, that is, \( [s^g] = [s^g_1, \ldots, s^g_{g-1}] \). Let \( B[s^b] \rightarrow \mathbb{N} \) be a random variable, hereafter burst length, such that \( b = B([s^b]) \), where \( b \in \mathbb{N} \), and \( [s^b] \) is a sequence of \( b \) corrupted received symbols, that is, \( [s^b] = [s^b_1, \ldots, s^b_{b-1}] \).

![Figure 2 Real measures used for the statistical description of the indoor wireless channel](image-url)
The number of corrupted symbols $C(p)$ in the frame $p$ can be defined as $C(p) = \sum b_j$. An upper bound $C^M$ of the maximum number of corrupted symbols per frame can be computed as $P(C(p) \leq C^M) = 0.9$, that is, $F_{C(p)}(C^M) = 0.9$. Fig. 3 shows the CDF associated to the number of corrupted symbols experimented in each frame, that is $F_{C(p)}$. A feasible value for $C^M$ is 20 symbols, therefore, we observe that 802.11 CRC discards frames that are corrupted for less than the 2% (20/1440) of their payload. The upper bound $B^M$ for burst lengths $b_i$ can be computed as $F_B(B^M) = 0.9$. Fig. 4 shows the CDF associated with the symbol burst lengths $b_i$. We observe that $B^M$ value can be approximated with 3. Finally, the upper bound $G^M$ for gap lengths $g_i$ can be computed as $F_G(G^M) = 0.9$. Fig. 5 shows the CDF associated with the symbol gap lengths $g_i$, observing that the upper bound $G^M$ is given by 200 symbols.

5 Improving QoE in broadcast video streaming

The error recovery technique must take into account the different channel behaviour of both the terrestrial and the satellite channel; we applied an upper level FEC over the original video stream, and a Bl-FEC over the 802.11 frame. Fig. 6 shows the error recovery procedure calibrated on the real error characteristic. We simulated an MPEG-2 video stream transmission between a video server and a set of clients. We set up to 1156 B the PDU (Protocol Data Unit) length, fixing to 6 the number of MPEG cells in the UDP packet, and therefore each UDP packet is constituted by 28 B (header) and 6 MPEG cells (188 B large each one). By this way, the redundancy subsequently introduced by the Bl-FEC does not exceed the maximum data length of 1440 bytes, that is, the Bl-FEC does not impact the number of transmitted frames but it just reduces the available bit rate by a negligible quantity (as we will show in the further sections). Moreover, no changes are needed to the packet headers, but modifications to the driver of the wireless card are necessary: (i) a coding algorithm for the data content of the 802.11 frame at the sender side and (ii) an uncoding algorithm triggered by the CRC check result at receiver side. The original video stream is considered as a sequence of UDP packets and it is coded by means of an FZC algorithm [15]. The UL-FEC works at the transport layer, both in the video stream server and in the end user, by fetching blocks of $k$ information packets from the video stream, and then transmitting $k+1$ UDP packets ($k$ of

![CDF associated to the number of corrupted symbols per frame](image1)

![CDF associated to the symbol burst length](image2)

![CDF associated to the symbol gap length](image3)

![Double-stage FEC scheme: The UL-FEC is applied to the UDP video stream while the Bl-FEC is applied to the MPEG-2 cells](image4)
information + l of redundancy) towards the receiving host. At the receiving host, the end user fetches k of the k+l packets per block and recovers the information, provided that no more than l packets are lost in a single block of packets. The coded video stream is transmitted through the satellite network and received by the satellite receiver that performs a bL-FEC over each MPEG-2 cell and broadcasts the video stream to the wireless network. For this purpose, we used the well-known coding algorithm Reed Solomon, but any other bit error correction code can be used. Using a symbol depth of m bits, a codeword size of n = 2^m − 1 symbols and a data word size of k symbols (thus, the redundancy of the code is r = n − k), the Reed Solomon code RS(n, k) can correct up to r/2 = (n − k)/2 errors.

6 Simulation results

6.1 bL-FEC performance evaluation

In this section, we present the simulation results about the bL-FEC in the Wi-Fi link. We only consider the broadcast transmission between the terrestrial wireless access point, embedded in the satellite receiver, and the end users. In this scenario, the errors experimented in the Wi-Fi link affect the satellite bandwidth, that is, the end-to-end error recovery technique must take into account the worst link in terms of packet loss, and this affects the bandwidth of the overall hybrid network. We simulated an 802.11 noisy link by means of a proprietary software that reads in input the traces constituted by the corrupted symbol sequence experimented during the real measurement campaign, and reproduces the same errors in the simulated channel.

Fig. 7 shows the performance analysis of the bL-FEC in the Wi-Fi link. We only considered the corrupted Wi-Fi frames that failed the CRC check, and we simulated a shortened bL-FEC with three different redundancies: (194, 188, 8), (204, 188, 8) and (220, 188, 8). We used each MPEG-2 cell as the data word of the Reed Solomon code. For each configuration, we show the number of recovered packets by using both the Reed Solomon code (solid line) and an interleaved Reed Solomon code (dashed line). For example, using a redundancy of six symbols (2.3%), the bL-FEC is able to recover the 85% and the 60% of the corrupted frames with and without the interleaver, respectively. Note that the interleaver effectiveness decreases when increasing the redundancy; in fact, the burst length is less than three symbols, and the corrupted symbols per frame are less than 20, in 90% of cases (see Section 4.2). The best configuration is the interleaved bL-FEC (204, 188, 8) that allows to recover about 98% of the lost frames with an overhead of 6%. Increasing the redundancy from 6% to 12% does not significantly increase the number of recovered packets. It is worth noticing that almost all the corrupted packets are recovered using a redundancy of 16 symbols [RS(204, 188, 8)], in fact, the number of corrupted symbols per frame sums up to 20, grouped by up to 3 and spaced by up to 200 corrected symbols.

6.2 Double-stage FEC performance evaluation

In this section, we show the simulation results of a double-stage FEC scheme (UL-FEC + bL-FEC). We considered the overall link as characterised by the combination of two independent loss processes: (i) a Bernoulli-loss process, with a mean bit error rate of 10^{-2} in the satellite link, and (ii) a packet-loss process, based on real measurements in the Wi-Fi link. The lost packets in the Wi-Fi link are due to two different effects: no carrier synchronisation, and no packets recovered by the bL-FEC. Fig. 8 shows the double-stage FEC performance. We used three different UL-FEC configurations: (10, 9), (10, 8), and (10, 7). For each UL-FEC configuration, we considered four different bL-FEC configurations: no bL-FEC (commonly used in the literature), interleaved Reed Solomon (194, 188, 8) interleaved Reed Solomon (204, 188, 8) and interleaved Reed Solomon (220, 188, 8). For each configuration
parameter, in Fig. 8, the dashed lines show the overall redundancy (UL-FEC + bL-FEC), while the bars show the packet loss experimented by the end user with the double-stage FEC scheme. UL-FEC(10, 7) and UL-FEC(10, 9) + RS(194, 188, 8) experiment similar packet loss but in the first case the network overhead is 30%, while in the second case 12% only. We want to highlight that the bandwidth overhead experimented in the satellite link decreases from 30% (simple UL-FEC) to 10% (double-stage FEC scheme): fixing the packet error rate, our proposed scheme saves up to 20% of satellite bandwidth and 18% of Wi-Fi bandwidth. Moreover, fixing the network overhead, the packet loss in our technique is considerably less than in the commonly used UL-FEC [see the performance of UL-FEC(10, 7) and UL-FEC(10, 8) + RS(204, 188, 8)].

6.3 Video quality evaluation

In this section, we present the performance of the double-stage FEC scheme in terms of video quality estimation. We considered the well-known video samples Akiyo, Coastguard, Miss America, Stefan and Foreman [16], evaluating the video quality at the end user against the network overhead. For this purpose, we compared the video samples received by the end user with the original video, as transmitted; for this comparison, we used the standard PSNR metric [17]. All videos are available in [18]. The PSNR of a picture $P$ is expressed as

$$PSNR = 10 \log \frac{(2^n - 1)^2}{MSE(P)}$$

where $n$ is the number of bits used to represent each pixel, and $MSE(P)$ is

$$MSE(P) = \frac{1}{w \times h} \sum_{i=1}^{N} (P_{oi} - P_{ci})^2$$

where $[w, h]$ are the picture dimensions, while $P_{oi}$ and $P_{ci}$ are the original and the corrupted video pictures, respectively.

Fig. 9 shows the video quality estimation at the end user versus the code redundancy. We used the same three UL-FEC configurations described in Section 6.2. For each configuration, the bars show the redundancy, while the lines show the PSNR experienced by the end user for the mentioned well-known video sequences. The configuration parameters of the double-stage FEC scheme are ordered with increasing redundancy, once the UL-FEC redundancy is fixed. In all cases, increasing redundancy decreases the packet loss and increases the PSNR value. The commonly used UL-FECs (white bars) reach a video quality performance (41 ≤ PSNR ≤ 44) can be reached by using the proposed FEC scheme UL-FEC(10,9) + IntRS(204, 188, 8), with a network overhead equal to 15%.

7 Conclusions

In this paper, we presented a novel approach to broadcast video streaming in hybrid networks. We proposed a double-stage FEC scheme constituted by a bL-FEC for correcting symbol corruptions, and an UL-FEC for recovering lost packets. We presented the statistical results of an extensive measurement campaign performed in an indoor wireless scenario. We exploited this statistical description to design the parameters of the double-stage FEC scheme. We showed the performance improvements due to the double-stage FEC scheme, in terms of percentage of recovered packets against network overhead. We also presented the simulation results relevant to the video quality estimation performed over real video samples. Future work addresses the theoretical analysis of the optimal FEC parameters and the study of the symbol depth influence on the bL-FEC.

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9 References


