A Self-Regulated Redundancy Control Scheme for Wireless Video Transmission

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Abstract

This paper presents a self-regulated redundancy control scheme for high-bit-rate video transmission using packet-level forward-error-correction (FEC) codes over error-prone wireless networks. The effectiveness of FEC on video is obtained by regulating its redundancy cost to balance that tradeoff of bandwidth utilization and FEC efficiency based on channel status, temporal dependency of video frames, and network congestion level. Experimental results show the proposed scheme maintains the desired quality-of-service (QoS) control over unloaded networks with the realistically measured wireless loss trace in 802.11b WLAN and over loaded networks, the adverse effect of FEC efficiency due to blindly increasing redundancy can be reduced to achieve the better video quality.

Keywords: Wireless channels, FEC, Video transmission

1. Introduction

The error handling mechanism has the potential impact on the ultimate quality evaluation in order to support the high-bit-rate video transmission over the error-prone wireless networks. Motivated by the characteristic of video applications that a certain level of loss tolerance would be acceptable to end users, both applications and transport layer take the advantage of the appropriate error handling mechanism to achieve a higher throughput of the processing data. For the transport layer in conjunction with MAC layer, the newly-developed protocol, known as UDP-Lite, intends to forward the corrupted packets due to wireless error to the upper video application [7]. The video application uses the error resilience tool, such as reversible variable-length coding (RVLC) and data partitioning in MPEG-4 video standard [8], to retrieve useful data section from those corrupted packets. Therefore, the network performance and also video quality are improved without lost data retransmission. However, the benefit of higher throughput in network level can not be equally shifted to the video quality in the application level due to the bursty nature of wireless error [1]. The performance enhancement hence can be done by the error control schemes such as forward-error-correction (FEC).

The deployment of FEC, however, introduces the additional redundancy cost that causes the bandwidth sharing problem and also self-induced congestion to adversely affect the effectiveness of FEC [2]. By grouping source data packets into blocks of size $k$, FEC encodes $n = k + h$ packets for network transmission where $h \geq 0$ is the degree of redundancy. If any $k$ or more packets are successively received, the block can be completely reconstructed. The used bandwidth is hence increased by a factor of $n/k$. For robust transmission in wireless channels, FEC obtains the adequate information about channel status to determine the value of $h$ by loss differentiation algorithms (LDA) which differentiate wireless losses from congestion losses [5].

Unfortunately, the effectiveness of FEC decreases since the redundancy could reinforce the network congestion, which causes congestion losses and even longer end-to-end delay to impede timely recovery in receiver. This is significant to VBR compressed video sources since it usually exhibits long-range dependence (LRD) with larger losses and/or delay [3]. Therefore, higher redundancy degree for loss protection does not necessarily result in better FEC efficiency. Once the FEC
application is unresponsive to the self-induced congestion, increased redundancy degree and severe congestion would interact to form a vicious circle with the expensive bandwidth cost. This makes the potential danger of congestion collapse from undelivered packets, stating that the bandwidth is wasted by delivering packets through the network that are dropped before reaching the receiver, to even degrade the overall network performance [4].

In this paper, we primarily focus on applying FEC scheme based on LDA to support the high-bit-rate video transmission over wireless networks. In order to achieve the good tradeoff between the redundancy cost and FEC efficiency, the proposed self-regulated scheme controls the redundancy by three fundamental factors: channel status, temporal dependency of video, and network congestion level. There are two components involved: cost-constrained FEC (CC-FEC) and self-induced congestion regulation. We firstly analyze the FEC efficiency while the amount of redundant packets is required not to exceed the amount of source packets so that the total transmission rate is bound to the double of the original rate for a video flow (that is, $1 \leq n/k \leq 2$). With this requirement, CC-FEC chooses the redundancy to unequally protect video packets, which have different importance levels due to their temporal dependencies, by measuring loss statistics to approximate the target recovery rate. According to the results of loss differentiation, the redundancy degree assigned by CC-FEC can be further regulated to avoid the self-induced congestion. When congestion is dominant, the regulation is done by lowering the QoS control level with less redundancy to reduce the adverse effect on performance degradation of both FEC and overall network utility.

The remaining of this paper is organized as follows. In section 2, the overall structure of the proposed redundancy control is presented. Then in section 3, the self-regulated redundancy control is developed. Experiments and related results are given in section 4. At the end of this paper, conclusions are summarized in section 5.

2. Overview of wireless video systems

Fig. 1 depicts the overall structure of the wireless video system with redundancy control in an end-to-end network environment. There exist several components of the self-regulated redundancy control including the FEC encoder, redundancy controller RC in sender side, FEC decoder and loss differentiation controller LDC in receiver side. On the sender side, the FEC encoder segments the video packet stream generated by the video encoder into blocks of fixed size $k$. According to the redundancy level $h$ passed from RC, the FEC encoder forwards total $n=k+h$ packets for each block to the transport layer for network transmission.

During the traverse of network path, packets could be either dropped due to resource contention or corrupted to due to wireless error. These corrupted packets might be regarded as lost or received through the specific transport layer for further handling of the upper application. On the receiver side, upon receiving packets from transport layer, LDC performs the loss differentiation algorithm (LDA) to discriminate wireless losses from congestion losses by treating all incoming packets including video and redundant packets equally. Then LDC returns a feedback message about the network state to the sender-side RC.

The receiver-side FEC decoder would checks whether packets belonging to the same block have arrived and the loss recovery for original $k$ video packets might proceed if not sufficient amount of complete packets is available. After the FEC processing, the reconstructed $k$ video packets would be forwarded to the video player. Otherwise, those remaining complete packets and possibly the corrupted packets are also forwarded for video decoding to take advantage of error resilience feature of video coding standard.
3. Self-regulated redundancy control

3.1. Cost-constrained FEC
3.1.1. FEC model

To analyze the effects of FEC for simplicity, the sending of packets is regarded as a series of independent Bernoulli trials. Therefore, the loss recovery function of the FEC scheme can be modeled as

\[ F(n, k, p) = \sum_{i=0}^{n} \binom{n}{i} (1-p)^i \times p^{n-i} \]  \hspace{1cm} (1)

where \( p \) is the packet loss rate. The recovery rate \( R \) can be thus attained by calculating the probability that more than \( k \) packets out of \( n \) are successfully received while given the degree of redundancy \( h \). Depending on the selection of \( h \), the FEC model could achieve the desired QoS level for robust data transmission.

Given the target recovery rate \( R \), the cost of the FEC scheme to achieve \( R \) for a \( k \)-packet block can be showed as \( C_{th} = (h/k) \) where \( h \) is the number of redundant packets. The redundancy cost \( Ct > 1 \) implies the FEC scheme needs to inject more redundant packets than source packets into networks at the risk of increasing delay. According to Eq. (1) with the constraint on \( Ct \leq 1 \), the total output traffic of the data flow adopting the redundancy control for the target \( R \) is no more than the double of the amount of the source data.

Although the Eq. (1) gives an approach to control the degree of redundancy, it is often not possible to know the packet loss rate \( p \), which is non-stationary in general networks, in advance. Instead of tracking instantaneous \( p \), the recovery scheme can derive the probability distribution of the amount of lost packets within a block. Based on the similar independence assumption of \( p \) as the FEC model, the cumulative probability of the amount of lost packets \( l, 0 \leq l \leq k \), in a block of size \( k \) is

\[ B_{od}(l; k, p) = \sum_{i=0}^{l} \binom{k}{i} p^i \times (1-p)^{k-i} \]  \hspace{1cm} (2)

Therefore, Eq. (2) is binomially distributed with parameters \( k \) and \( p \). It is reasonable to associate the number of lost packets with the number of redundant packets since the value of \( h \) determines the maximum \( l \) that can be tolerant in a block. If all redundant packets are assumed to be loss-free, \( l \) redundant packets would achieve the recovery rate that equals the loss probability of \( l \) lost packets. Assume that \( h=l \) and \( n=k+h \), it’s not difficult to prove that the property of \( F(n, k, p) \leq B(h; k, p) \) holds. Remind that the purpose of the redundancy control protocol is to choose a value of \( h \) to achieve the target \( R \). Since the loss probability distribution is easily available from the loss statistics of receiver’s feedback messages, given the cost constraint of FEC \( (Ct \leq 1) \), it’s possible that the recovery rate of Eq. (1) could be approximated by the loss probability of Eq. (2) with \( h=l \). This can be done by selecting an appropriate \( l \) through the recovery rate approximation as \( h \) fed into the FEC scheme.

3.1.2. Explicit and implicit approximation

The recovery rate approximation can be achieved in the explicit and implicit way. For the explicit approximation, the target recovery rate \( R \) is specified by user. The objective is finding the appropriate redundancy \( h \) for blocks of predetermined size \( k \) to meet target \( R \) through the following approximation algorithm:

\[ B(h; k, p) \geq R + \alpha_c, \hspace{1cm} R < 1, \]
\[ B(h; k, p) \geq R - \alpha_c, \hspace{1cm} R = 1. \]  \hspace{1cm} (3)

\( \alpha_c \) is the compensation factor for approximation difference. It is practical to assume high recovery rate for most users and applications, and thus \( \alpha_c \) can be properly allocated by a small value. Given the desired \( k \), the appropriate value of \( \alpha_c \) could be chosen by the analytic result of large \( p \) since the QoS control should provide at least no worse recovery service than the user-specific one. Additionally, as the target \( R \) approaches to one, the hyperbolic shape of the recovery-redundancy binomial relation presents the characteristic of the near heavy tail which results in the increase of redundancy to achieve full recovery only with a little improvement in recovery rate. \( \alpha_c \) is hence the tolerance factor to relax the bandwidth cost when the full recovery is required. However, the value of \( \alpha_c \) should be much smaller than the value of \( \alpha_c \) to prevent the excessive quality degradation.

The implicit approximation provides class-based loss recovery to support the relative QoS control. For \( m \) recovery classes, class \( c \) has higher or at least no lower recovery rate than class \( c-1 \) where \( 1 \geq c \geq m \). The recovery rate of class \( c \) is expressed as \( R(c) = c/m \) and the approximation algorithm of the implicit recovery follows

\[ B(h; k, p) \geq R(c) + \alpha_c, \hspace{1cm} c < m, \]
\[ B(h; k, p) \geq R(c) - \alpha_c, \hspace{1cm} c = m. \]  \hspace{1cm} (4)

Although the class with larger \( c \) receives higher recovery rate, the difference between adjacent classes may not be perfectly classified by \( 1/m \) due to the indivisibility of the redundant packet. Additionally, less than \( m \) classes could be functioned as larger \( m \) is assigned. That is, several contiguous classes share a similar redundancy \( h \), and they
will all receive the same recovery rate. Therefore, we denote the effective number of class as $m^*$, and $m^* \leq m$.

3.1.3. Unequal loss protection

The idea of unequal loss protection is used in CC-FEC to improve recovery efficiency by explicitly assigning different redundancy degree based on the temporal dependency of MPEG video. For MPEG video, the raw video data are encoded as intra-coded (I), predictive (P), and bidirectional (B) video frame. Due to the coding dependency, the three frame types-I, P, B-have descending importance in order to video player. Take an example of group-of-picture (GOP) size 12, the frame sequence is showed as $I_0, B_{01}, B_{02}, P_1, B_{11}, B_{12}, B_{13}, B_{21}, B_{22}, B_{31}, B_{32}$. Each frame might be segmented into packets in a maximum size MTU for network transmission. Given a target recovery rate $R$, the $k$-packet block carrying any I-frame packets receives the full protection that recovery rate is set to 1 since a corrupted I-frame will make all the following P- and B-frame in the GOP undecodable. For a series of P-frame, the former P-frames are used as reference by subsequent P-frames in one GOP. Therefore, P-frames that are closer to I-frame should be assigned to the higher protection to ensure that the prediction of subsequent frames is based on referenced frames with better quality. As showed in Fig. 2, the protection level of blocks carrying latter P-frame packets is linearly decreased between the recovery rate 1 and $R$. Finally, blocks carrying B-frame packets receive the protection level $R$. Since the value of $k$ could be varied such that a block might carry packets that belong to different frame types, the assignment would be made by the highest protection level observed within the $k$-packet block.

3.2. Self-induced congestion regulation

To prevent the self-induced congestion from reducing the effectiveness of FEC scheme and the global network performance, the redundancy degree used to recover losses should be appropriately regulated when congestion losses are detected. We design a block-counting transition model for the purpose of redundancy regulation as shown in Fig. 3. Based on the implicit recovery rate approximation described in 3.1.2, there are $m$ classes for the relative recovery control and thus $m^*$ effective classes are available. The target recovery rate $R$ would map to the effective class $c$ when $R(c-1) < R \leq R(c)$ holds. In Fig. 3, each state is labeled by its corresponding effective recovery class and class 0 is created as a virtual class representing no redundancy exists. Initially, the network is assumed as non-congested and the state is in class $c$. Once the recovery rate of the currently visited class can’t be attained along with congestion losses detected by LDA for $d$ consecutive blocks, the performance degradation of FEC stems from the higher congestion level which may be induced by redundancy. Then the redundancy control protocol transits the current state to one lower effective class, so fewer redundant packets are transmitted for loss recovery. Until $c=0$, no redundant packets are generated to be transmitted along with source packets, and the persistent congestion thus excludes the self-induced effect of FEC. The corresponding state transitions are defined in Table 1. On the contrary, the redundancy control protocol operates in the similar way to react the non-congested network state. For contiguous $d$ blocks without congestion signal to achieve the recovery rate of the visited class, the current state would transit to higher class by one until initial class $c$ is reached.

4. Performance results

4.1. Experimental set-up

Fig. 4 shows the experimental setup. The wireless network employed an 802.11b access point (AP) operating in distributed coordination function (DCF) to connect
the decodable frame rate, where
\[ \text{Decodable frame rate (Q)} = \frac{\text{Number of correctly decodable frames}}{\text{Number of total frames}} \]
and 0\( \leq \)Q\( \leq \)1 [9]. A frame is considered decodable at the video player when at least a fixed portion \( DT \) (decodable threshold) of the data in each frame must be received and also all the frames it depends on are considered decodable. If the value of \( DT \) is set to 1 for all video frames, then the video player is completely intolerant to data losses. Fig. 6 (top, middle) shows the corresponding performance measurement for the application-level quality. There exists a little gap between network-level and application-level quality since the final decodable frame rate of 0.94 is attained for the case of \( DT=1.0 \). This quality gap is primarily induced from partially received frames or from frames that can not be decoded because they depend on other undecodable frames. Taking the advantage of better resilience features in transport protocol such as UDP-Lite and in MPEG-4 video standard such as RVLC, however, the video player could relax the loss intolerance with the value of \( DT<1 \). For \( DT=0.75 \) and 0.5, the final decodable frame rate is 0.95 and 0.96, respectively.

4.3. CC-FEC with congestion regulation

Fig. 6 (bottom) shows the experimental results of the proposed self-regulated redundancy control with regulation parameter \( d=3 \) when the Poison traffic is joined. The number of recovery class \( m=10 \). Other configurations remain unchanged. In Fig. 6 (bottom, left) and (bottom, middle), a static FEC with redundancy \( h \) set from 0 to 8 presents the self-induced congestion problem in wireless networks. Although increasing redundancy degree can achieve higher recovery rate to protect both wireless and congestion losses, the decodable frame rate the user concerns is much lower than the measured recovery rate and beyond a certain \( h \) value, would drop sharply due to the longer end-to-end delay that adversely

![Figure 4. Experiment set-up](image-url)

![Figure 5. Packet loss pattern (left) and traffic trace of “Jurassic Park I” movie clip (right).](image-url)
affects video transmission with the real-time constraint. For the wireless video system, loss differentiation of wireless and congestion losses can be done for loss recovery schemes. If CC-FEC without regulation only aims at the recovery of wireless losses, the congestion losses will impede the attainable recovery rate 0.93 to achieve the target 0.95 and the decodable frame rate observed is 0.54. When CC-FEC with regulation is applied to the same video source, the achieved decodable frame rate 0.64 is higher and also close to the optimal value 0.7 of a static FEC even if the measured recovery rate is lower. Fig. 6 (bottom, right) shows the continued changes in ratio of the redundant packets to the source packets during the entire run to indicate CC-FEC with regulation is well-behaved to control the redundancy according to the network contention level.

5. Conclusions

This paper presents the self-regulated redundancy control scheme using packet-level FEC to support the high-speed video transmission in wireless networks. Based on the appropriate loss differentiation for video applications, the proposed scheme not only protects video streams from wireless losses according to the temporal dependency of video frames, but controls the redundancy degree to reduce the adverse effect of FEC efficiency. The self-regulated redundancy is done by complying with the redundancy cost constraint as well as performing the congestion regulation. We first observe that the proposed scheme can preserve the user-specified QoS along with the advantages of error resilience for bursty wireless losses. When the network is loaded, the received video quality can be better because of the good tradeoff between bandwidth utilization and FEC efficiency. The future work is to evaluate the proposed scheme in bandwidth sharing and fairness problems.

References