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ORIGINAL RESEARCH

Adaptive FEC algorithm based on prediction of video quality and bandwidth utilization ratio

Jiao Feng · Chi Xuefen · Peng Li · Wang Yining · Lin Guan · Xingang Wang

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Abstract In this paper, a channel adaptive FEC algorithm is proposed which balances the trade-off between the QoS of video transmission and the bandwidth utilization ratio in wireless IP networks. Our algorithm can dynamically adjust to a suboptimal number of FEC redundant packets to cater to the time-varying wireless channel. For the sake of obtaining the suboptimal amount of FEC redundant packets, we derive two analytical models, one is the playable frame rate in MPEG video stream, another is the effective utilization ratio of FEC. Based on these analytical models, a suboptimal value of redundant packets, which makes both the quality of video stream and the effective utilization ratio of FEC approximate their maximum, is calculated by predicting the quality of video stream and effective utilization ratio of FEC under different network conditions (characterized by packet loss probability in this paper). The simulation results indicate that the QoS of wireless video transmission and the bandwidth utilization ratio are improved by employing the proposed algorithm.

Keywords Adaptive FEC · Error control · Playable frame rate · Wireless · Video

1 Introduction

The unpredictable nature of packet losses due to time-varying fading, interference, and mobility, means that video transmission over wireless IP networks is faced with a great challenge, since any data loss can heavily damage the quality of the received video. Many video decoders have the ability to conceal slight errors caused by random packet loss, however, damage in video quality caused by heavy burst losses are hard to cover up. In recent years, error control schemes based on Automatic Repeat-reQuest (ARQ) and Forward Error Correction (FEC) have been designed to correct video errors (Le and Hossain 2008; Weng et al. 2008; Anantha et al. 2007; Choi and Shin 2007). Recent literature has revealed that employing FEC on corrupted packets yields better bandwidth utilization and lower delay than with ARQ, and thus FEC has been extensively used to increase error resilience in multimedia communications (Yu et al. 2008; Ha et al. 2007; Khayam et al. 2007; Moltchanov et al. 2006). However, FEC introduces extra bandwidth overhead, therefore the trade-off between bandwidth utilization and the wireless video Quality of Service (QoS) has become an inevitable and important issue.

J. Feng
School of Electronics and Computer Science, University of Southampton, Southampton, UK

C. Xuefen (✉)
Department of Communication Engineering, Jilin University, Changchun City, China
e-mail: chixf@jlu.edu.cn

P. Li
Department of Electronics, University of York, York, UK

W. Yining
School of Media Science, North-East Normal University, Changchun City, China

L. Guan (✉)
Department of Computer Science, Loughborough University, Loughborough, UK
e-mail: L.Guan@lboro.ac.uk

X. Wang
Department of Computing and the Digital Environment, Coventry University, Coventry, UK

Recently, error-resilient wireless video communication has generated significant interest, and a variety of algorithms have been reported in the literature. We summarize some of the key findings as follows. Nafaa developed a reliable media streaming system for use in wireless networks by inspecting channel fluctuations and exploiting FEC to deal them at the application layer (Abdelhamid et al. 2008). Chakareski introduced an adaptive FEC scheme which combats the effects of both packet loss and bit errors in an end-to-end manner. For minimizing the average end-to-end distortion, the sender implements an adaptive FEC scheme to decide which packets will be sent to meet an average transmission rate constraint (Chakareski and Chou 2004). Eckhardt utilized an error control adaptive algorithm based on the low-level packet traces of Wave LAN. Considering the characteristic of the error environment, the algorithm adjusts the FEC redundancy level and packet size to compensate for the deficiencies of FEC coding and to enhance the throughput of the wireless network (Eckhardt and Steenkiste 1999). However, the error control schemes discussed in these references only consider their impact on bandwidth utilization and do not take into account their impact on video playback quality at the receiver.

Kang and Loguinov (2007) proposed an adaptive FEC algorithm for scalable video services in wireless networks. The authors developed a utility metric for FEC-protected video streams and proposed an algorithm for FEC packet distribution. An effective feedback-free loss recovery scheme for layered video was proposed, which combined FEC with flow replication technology (Chan et al. 2006). The server sends video packets in parallel with FEC packets and a number of replicated video packets. The receivers would then exploit the FEC and replicated video stream to make up for data losses. By considering the connection with TCP, Wu et al. (2005) proposed an adaptive FEC algorithm to repair packet losses for MPEG video streaming. In this algorithm, a model was developed to describe the relationship between the video quality of the MPEG video stream, distortion rate of video coding parameters and the amount of FEC redundant packets, which then facilitates an optimal choice of FEC. The models proposed in these three references established the link between the video playback quality at the receiver and the amount of FEC redundant packets from different perspectives. On the other hand, the utilization ratio of wireless bandwidth was not dealt with.

Based on these discussions, we propose a novel channel adaptive FEC algorithm and evaluate it within the NS-2 simulation platform. The algorithm aims at ascertaining the optimal amount of FEC redundant packets to balance the trade-off between the utilization ratio of the wireless channel and the QoS of video transmission. Our research is inspired by and developed from the work of Wu et al. (2005) and Feng et al. (2007). Based on their works, we develop an analytical model of the playable frame rate for MPEG stream with a maximum sending rate constraint. According to the relationship between the number of FEC redundant packets and the wireless channel packet loss probability, we derive another analytical model of the effective utilization ratio of the FEC scheme, which reflects the utilization of wireless bandwidth. Based on these models, we predict the quality of FEC-protected video stream and the effective utilization ratio of FEC under different packet loss probabilities. We then calculate and decide a suboptimal number of FEC redundant packets which causes the quality of the video stream and the effective utilization ratio of FEC approximate their maximum. Based on theoretical analysis, a WLAN environment is set up in NS-2, where the packet loss probability of the wireless channel is detected in the MAC layer of the wireless video transmitter, and, according to the outputs of these analytical models, FEC protection is added into the video stream at this layer.

The rest of paper is organized as follows: in Sect. 2, the analytical model of the adaptive FEC algorithm is described in detail. Following this, Sect. 3 discusses the design and implementation of the channel adaptive FEC algorithm. Simulation results are presented and the FEC algorithm is evaluated in Sect. 4, before several conclusions are given in Sect. 5.

2 Analytical model of the channel adaptive FEC algorithm

In this section, we derive the two analytical models of the adaptive FEC algorithm proposed in this paper. An analytical model is used to formulate the effective utilization ratio of FEC for each video frame. Then an analytical model of the playable frame rate for the MPEG stream is used to calculate the playable frame rate of the FEC-protected MPEG stream.

2.1 Analytical model of the effective utilization ratio of FEC

For a given loss probability, increasing the amount of FEC redundant packets is beneficial to improve the playback quality of the video stream. However, excessive FEC redundant packets may lead to waste of wireless bandwidth. Hence, we need to investigate the relationship between the amount of FEC redundant packets and the effective utilization ratio of FEC when it is employed in wireless video transmission. To illustrate this relationship, we introduce the effective utilization ratio of FEC to characterize the utilization of wireless bandwidth.

Firstly, when FEC is used in video transmission on an error-prone channel, the successful frame transmission probability is (Wu et al. 2003):

$$P(N,K,p) = \sum_{i=K}^{N} \left[\binom{N}{i} * (1-p)^i * p^{(N-i)} \right]. \tag{1}$$

where K is amount of data packets, $N-K$ is the amount of FEC redundant packets, and p is the probability of packet loss. N is the amount of total packets yielded by FEC encoding.

Based on Eq. 1, the effective utilization ratio of FEC may be calculated as:

$$\eta = \frac{K}{N} P(N,K,p) = \frac{K}{N} \sum_{i=K}^{N} \left[\binom{N}{i} * (1-p)^i * p^{(N-i)} \right]. \tag{2}$$

The effective utilization ratio of FEC characterizes the interaction between coding rate and successful frame transmission probability. Under a certain packet loss probability and a fixed amount of user data packets K, the value of $N-K$ which makes η reach a maximum value may be considered as the optimal number of FEC redundant packets.

Figure 1 presents the convex relationship between the amount of FEC redundant packets and the effective utilization ratio of FEC, parameterized by the packet loss probability of the wireless system. As shown in Fig. 1, there is a fixed amount of FEC redundant packets which makes the effective utilization ratio of FEC reach its maximum value. When the quantity of FEC packets further increases, the effective utilization ratio of FEC decreases gradually, and this suggests that an oversupply of FEC redundant packets will use excess wireless bandwidth.

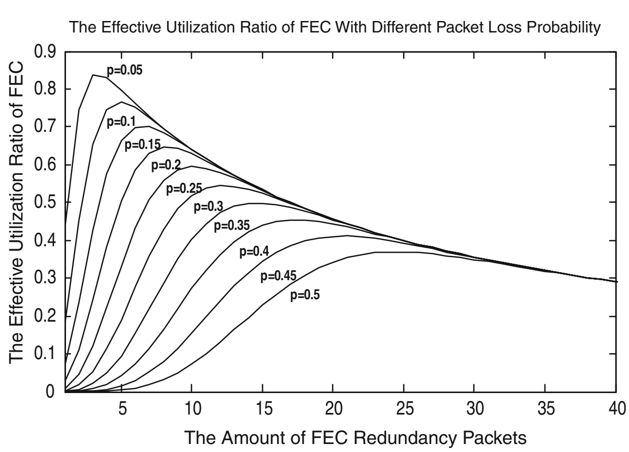

Fig. 1 The effective utilization ratio of FEC

According to Eq. 2, the effective utilization ratio of FEC for I, P and B frame can be derived as follows:

$$\begin{aligned}
\eta_{\mathrm{I}} &= \frac{S_{\mathrm{I}}}{N_{\mathrm{I}}} \sum_{i=S_{\mathrm{I}}}^{N_{\mathrm{I}}} \left[\binom{N_{\mathrm{I}}}{i} * (1-p)^i * p^{(N_{\mathrm{I}}-i)} \right] \\
\eta_{\mathrm{P}} &= \frac{S_{\mathrm{P}}}{N_{\mathrm{P}}} \sum_{i=S_{\mathrm{P}}}^{N_{\mathrm{P}}} \left[\binom{N_{\mathrm{P}}}{i} * (1-p)^i * p^{(N_{\mathrm{P}}-i)} \right] \\
\eta_{\mathrm{B}} &= \frac{S_{\mathrm{B}}}{N_{\mathrm{B}}} \sum_{i=S_{\mathrm{B}}}^{N_{\mathrm{B}}} \left[\binom{N_{\mathrm{B}}}{i} * (1-p)^i * p^{(N_{\mathrm{B}}-i)} \right]
\end{aligned} \tag{3}$$

$$\begin{cases} N_{\mathrm{I}} = S_{\mathrm{I}} + \mathrm{SR}_{\mathrm{IF}} \\ N_{\mathrm{P}} = S_{\mathrm{P}} + \mathrm{SR}_{\mathrm{PF}} \\ N_{\mathrm{B}} = S_{\mathrm{B}} + \mathrm{SR}_{\mathrm{BF}}. \end{cases} \tag{4}$$

2.2 Analytical model of the playable frame rate for MPEG video stream

We assume that each group of pictures (GOP) has the same structure. A GOP contains one I frame and several P and B frames. For a video stream with this GOP structure, all I frames are of equal size, P frames and B frames also have their own fixed size, respectively. In terms of the dependency among I, P and B frames, the analytical model of the playable frame rate for MPEG stream calculates a total playable frame rate with the constraint of maximum sending rate.

2.2.1 *The successful frame transmission probability of I, P and B frame*

For a given GOP pattern, we divide each frame into several fixed size packets. We allocate the FEC redundant packets for each type of video frame according to their relative significance. Considering the size of the frame and the number of redundant packets added to each type of frame, the successful transmission probabilities for each I, P and B frame may be computed by using Eq. 1 to give:

$$\begin{cases} P_{\mathrm{I}} = P(S_{\mathrm{I}} + \mathrm{SR}_{\mathrm{IF}}, S_{\mathrm{I}}, p) \\ P_{\mathrm{P}} = P(S_{\mathrm{P}} + \mathrm{SR}_{\mathrm{PF}}, S_{\mathrm{P}}, p) \\ P_{\mathrm{B}} = P(S_{\mathrm{B}} + \mathrm{SR}_{\mathrm{BF}}, S_{\mathrm{B}}, p)\,. \end{cases} \tag{5}$$

where S_{I}, S_{P} and S_{B} are the sizes of an I, P and B frame in a packet, respectively. Also, $\mathrm{SR}_{\mathrm{IF}}$, $\mathrm{SR}_{\mathrm{PF}}$ and $\mathrm{SR}_{\mathrm{BF}}$ are the amounts of FEC redundant packets allocated to I, P and B frames, respectively.

2.2.2 *Rate of GOP*

We define SM as the maximum sending rate the wireless terminal can acheive. The GOP rate (GOPs per second) can be calculated as:

$$\begin{aligned}
\mathrm{GR} &= \frac{\mathrm{SM}}{(S_\mathrm{I} * s + \mathrm{SR}_\mathrm{IF} * s') + N_\mathrm{P} * (S_\mathrm{P} * s + \mathrm{SR}_\mathrm{PF} * s') + N_\mathrm{B}(S_\mathrm{B} * s + \mathrm{SR}_\mathrm{BF} * s')} \\
&= \frac{\mathrm{SM}}{(S_\mathrm{I} + N_\mathrm{P} * S_\mathrm{P} + N_\mathrm{B} * S_\mathrm{B}) * s + (\mathrm{SR}_\mathrm{IF} + N_\mathrm{P} * \mathrm{SR}_\mathrm{PF} + N_\mathrm{B} * \mathrm{SR}_\mathrm{BF}) * s'} \\
&= \mathrm{SM} * \mathrm{GR}'. \qquad (6)
\end{aligned}$$

Where N_P and N_B are the amounts of P frames and B frames per GOP, respectively. s is the video packet size, and s' is size of each FEC redundant packet (both in bytes).

2.2.3 The playable frame rate for FEC-protected MPEG stream

According to previous works by Wu et al., the total playable frame rate for FEC-Protected MPEG video steam can be derived as (Wu et al. 2003):

$$\begin{aligned}
F &= F_\mathrm{I} + F_\mathrm{P} + F_\mathrm{B} \\
&= \mathrm{GR} * P_\mathrm{I} + \mathrm{GR} * P_\mathrm{I} * \frac{P_\mathrm{P} - P_\mathrm{P}^{(N_\mathrm{P}+1)}}{1 - P_\mathrm{P}} \\
&\quad + N_\mathrm{BP} * \mathrm{GR} * P_\mathrm{I} * P_\mathrm{B} * \left(\frac{P_\mathrm{P} - P_\mathrm{P}^{(N_\mathrm{P}+1)}}{1 - P_\mathrm{P}} + P_\mathrm{I} * P_\mathrm{P}^{N_\mathrm{P}} \right) \\
&= \mathrm{GR} * P_\mathrm{I} * \left[1 + \frac{P_\mathrm{P} - P_\mathrm{P}^{(N_\mathrm{P}+1)}}{1 - P_\mathrm{P}} \right. \\
&\quad \left. + N_\mathrm{BP} * P_\mathrm{B} * \left(\frac{P_\mathrm{P} - P_\mathrm{P}^{(N_\mathrm{P}+1)}}{1 - P_\mathrm{P}} + P_\mathrm{I} * P_\mathrm{P}^{N_\mathrm{P}} \right) \right] \\
&= \mathrm{SM} * \mathrm{GR}' * P_\mathrm{I} * \left[1 + \frac{P_\mathrm{P} - P_\mathrm{P}^{(N_\mathrm{P}+1)}}{1 - P_\mathrm{P}} \right. \\
&\quad \left. + N_\mathrm{BP} * P_\mathrm{B} * \left(\frac{P_\mathrm{P} - P_\mathrm{P}^{(N_\mathrm{P}+1)}}{1 - P_\mathrm{P}} + P_\mathrm{I} * P_\mathrm{P}^{N_\mathrm{P}} \right) \right]. \qquad (7)
\end{aligned}$$

where, again, SM is the maximum sending rate of the wireless terminal. N_BP is the number of B frames ranked between an I and P frame. $N_\mathrm{B} = (1 + N_\mathrm{P}) * N_\mathrm{BP}$.

2.2.4 Maximum sending rate

We assume that the number of wireless terminals in a Basic Service Set (BSS) is k and all the wireless terminals in the same BSS share one wireless channel. The previous works completed by Feng et al. defined the normalized channel throughput as (Feng et al. 2007):

$$T = \frac{P_\mathrm{S} E[P]}{E[\mathrm{slot}]} = \frac{P_\mathrm{S} E[P]}{P_\mathrm{i}\sigma + P_\mathrm{S} T_\mathrm{S} + (1 - P_\mathrm{i} - P_\mathrm{S}) * T_\mathrm{C}}. \qquad (8)$$

where $E[P]$ is the mean length of a transmission packet. $E[\mathrm{slot}]$ is the average slot time duration. T_s is the average time duration that the channel is sensed as busy due to a successful transmission. T_c is the average time duration that a channel is sensed as busy due to a collision. σ is the duration of an empty slot. P_i is the idle probability of the channel in a slot. P_S is the probability of a successful transmission in a slot.

The above derivation process relates to two significant variables ε_1 and ε_2, which describe the transmission probabilities in a time slot for an Access Point (AP) and a station (STA) separately. Also, they relate to the probability of a collision occuring during transmission and the number of retransmissions. When we only exploit FEC to protect the video stream, ε_1 and ε_2 are only related to the probability of a collision during transmission. We define C_1 and C_2 as the probabilities of collision in transmission of an AP and a STA separately:

$$\begin{cases} C_1 = 1 - (1 - \varepsilon_2)^k \\ C_2 = 1 - (1 - \varepsilon_1) * (1 - \varepsilon_2)^{(k-1)}. \end{cases} \qquad (9)$$

Given the number of wireless terminals and assuming constant C_1 and C_2, ε_1 and ε_2 have their own fixed values, respectively. Neglecting hardware constraints, the maximum sending rate of a wireless terminal approximately equals its maximum transmission rate, hence the maximum sending rate of wireless terminal may be approximated by:

$$\mathrm{SM} = T = \frac{P_\mathrm{S} E[P]}{E[\mathrm{slot}]} = \frac{P_\mathrm{S} E[P]}{P_\mathrm{i}\sigma + P_\mathrm{S} T_\mathrm{S} + (1 - P_\mathrm{i} - P_\mathrm{S}) * T_\mathrm{C}}. \qquad (10)$$

By analyzing Eqs. 10 and 7, we eliminate the influence of FEC redundant packets on the mean length of transmission packets when FEC redundant packet and the video packet are of equal size. We may deduce that the maximum sending rate is only dependent on the probability of a collision in transmission when the packet size is fixed. Therefore, SM is a coefficient which does not influence the value of SR_IF, SR_PF and SR_BF when the total playable frame rate reaches its maximum.

3 Design and implementation of the channel adaptive FEC algorithm

In this section, we describe the design of the proposed adaptive FEC algorithm. With a given packet loss probability and taking the matrix of the amount of FEC redundant packets as input, the algorithm predicts the playable frame rate and the effective utilization of FEC for each set of input data. A set of data corresponds to a row of the input matrix. Then, a suboptimal amount of FEC redundant packets for the next time period is selected, which causes both the total playable frame rate and the effective utilization ratio of FEC approximate their maximum values. The description begins with an overview of our adaptive FEC algorithm and is followed by a detailed discussion of the implementation issues.

3.1 Design of the channel adaptive FEC algorithm

3.1.1 Mathmatical design of the channel adaptive FEC algorithm

With the packet loss probability detected by the wireless sender, the derived analytical models can calculate the optimal values of SR_{IF}, SR_{PF} and SR_{BF} which are the number of FEC redundant packets allocated to I, P and B frames respectively. Hence, the design of our adaptive algorithm is expressed as follows:

$$\begin{cases} F' = \max\{F\} = \max\left\{G * P_{\mathrm{I}} * \left[1 + \frac{P_{\mathrm{P}} - P_{\mathrm{P}}^{(N_{\mathrm{P}}+1)}}{1-P_{\mathrm{P}}} + N_{\mathrm{BP}} * P_{\mathrm{B}} * \left(\frac{P_{\mathrm{P}} - P_{\mathrm{P}}^{(N_{\mathrm{P}}+1)}}{1-P_{\mathrm{P}}} + P_{\mathrm{I}} * P_{\mathrm{P}}^{N_{\mathrm{P}}}\right)\right]\right\} \\ \eta_{\mathrm{I}}' = \max\{\eta_{\mathrm{I}}\} = \max\left\{\frac{S_{\mathrm{I}}}{N_{\mathrm{I}}}\sum_{i=S_{\mathrm{I}}}^{N_{\mathrm{I}}}\left[\binom{N_{\mathrm{I}}}{i} * (1-p)^{i} * p^{(N_{\mathrm{I}}-i)}\right]\right\} \\ \eta_{\mathrm{P}}' = \max\{\eta_{\mathrm{P}}\} = \max\left\{\frac{S_{\mathrm{P}}}{N_{\mathrm{P}}}\sum_{i=S_{P}}^{N_{P}}\left[\binom{N_{\mathrm{P}}}{i} * (1-p)^{i} * p^{(N_{\mathrm{P}}-i)}\right]\right\} \\ \eta_{\mathrm{B}}' = \max\{\eta_{\mathrm{B}}\} = \max\left\{\frac{S_{\mathrm{B}}}{N_{\mathrm{B}}}\sum_{i=S_{\mathrm{B}}}^{N_{\mathrm{B}}}\left[\binom{N_{\mathrm{B}}}{i} * (1-p)^{i} * p^{(N_{\mathrm{B}}-i)}\right]\right\} \end{cases} \tag{11}$$

where F' is the maximum total playable frame rate. η_{I}', η_P' and η_B' are the maximum effective utilization ratios of FEC applied to I, P and B frames respectively.

For a given packet loss probability, we use Eq. 11 to calculate the optimal values of SR_{IF}, SR_{PF} and SR_{BF} which makes both the total playable frame rate and the effective utilization ratio of FEC reach their maximum.

3.1.2 Suboptimal scheme of the channel adaptive FEC algorithm

Even with a mass of computational effort, we cannot find such optimal values of SR_{IF}, SR_{PF} and SR_{BF}. We instead propose an alternate suboptimal scheme for guaranteeing video playback quality. A set of the most appropriate values of SR_{IF}, SR_{PF} and SR_{BF} are selected, which jointly allows the total playable frame rate and the effective utilization ratio of FEC to closely approximate their maximum values.

Based on these discussions, we note that the total playable frame rate, F, is a function of the channel packet loss probability and the amount of FEC redundant packet allocated to I, P and B frames (SR_{IF}, SR_{PF} and SR_{BF}). For covering the most probable values of FEC packets, we use H_{in} to denote a matrix of SR_{IF}, SR_{PF} and SR_{BF}, which can be formulated as:

$$H_{in} = [SR_{IF}, SR_{PF}, SR_{BF}]_{n\times 3} \quad (SR_{IF} > SR_{PF} > SR_{BF})$$

The size of H_{in} is denoted as $n \times 3$, which means there are n sets of data as the input parameters of Eq. 10. The value of n lies on the value range of SR_{IF}, SR_{PF} and SR_{BF}, which are upper bounded by the number of video packets of each I, P and B frame respectively. Using the constraint of $SR_{IF} > SR_{PF} > SR_{BF}$, we provide unequal error protection (UEP) to video transmission in accordance to the degree of significance of each I, P and B frame.

Based on the input matrix, H_{in}, and the channel packet loss probability, m sets of values of SR_{IF}, SR_{PF} and SR_{BF} are selected which make the total playable frame rate approach the maximum value. We denote W_{in} to be the matrix which consists of these m sets of data. As the input parameters of Eq. 3, W_{in} may be formulated as:

$$W_{in} = [SR_{IF}, SR_{PF}, SR_{BF}]_{m\times 3} \quad (SR_{IF} > SR_{PF} > SR_{BF})$$

Given a current channel packet loss probability, we can get a pool of utilization ratio of FEC with W_{in} and Eq. 3. The set of W_{in} which obtains the highest utilization ratio of FEC is determined as the suboptimal set of SR_{IF}, SR_{PF} and SR_{BF} values.

3.1.3 Threshold strategy of the channel adaptive FEC algorithm

The suboptimal scheme of the channel adaptive FEC algorithm operates normally when the packet loss probability is lower than the preset threshold which was computed by analyzing many preliminary simulation results. Otherwise, SR_{IF}, SR_{PF} and SR_{BF} are each set to zero. The reasoning is that, when the wireless channel conditions become extremely severe, the reconstructed video quality is unacceptable even if FEC redundant packets are added, and these redundant packets lead to a waste of wireless bandwidth.

3.2 Implementation of the channel adaptive FEC algorithm

We implement the proposed adaptive FEC algorithm on the MAC layer of the wireless terminal by detecting the packet loss probability of the wireless channel and then finding the corresponding suboptimal values of SR_{IF}, SR_{PF} and SR_{BF}. Then, we allocate FEC redundant packets to video packets based on these values.

3.2.1 Dynamic detection of the packet loss probability of the wireless channel

Since we mainly focus on the effect of wireless channel errors, the congestion losses are neglected in our research. In unicast transmission, the FEC redundancy is usually added adaptively on the basis of feedback of the loss pattern. However, the sender cannot collect the state parameter of the wireless channel if the feedback packets with this channel state information are lost. Considering that feedback will introduce more additional delay and lost channel state information due to the feature of the wireless channel, we design a network estimator at the sender to estimate the wireless channel conditions based on the number of received ACK packets. This allows the proposed adaptive algorithm to adapt to the operating parameters of the observed network conditions dynamically. Since the proposed adaptive FEC algorithm takes one GOP format as the object of study, the packet loss probability is calculated after all the video packets in one GOP are transmitted by the wireless terminal. Figure 2 shows the data collecting process of the packet loss probability.

As a sender, the wireless terminal not only accumulates the number of ACK packets, but also calculates the wireless channel packet loss probability. Compared with the feedback scheme, this method is more accurate results with a lower delay.

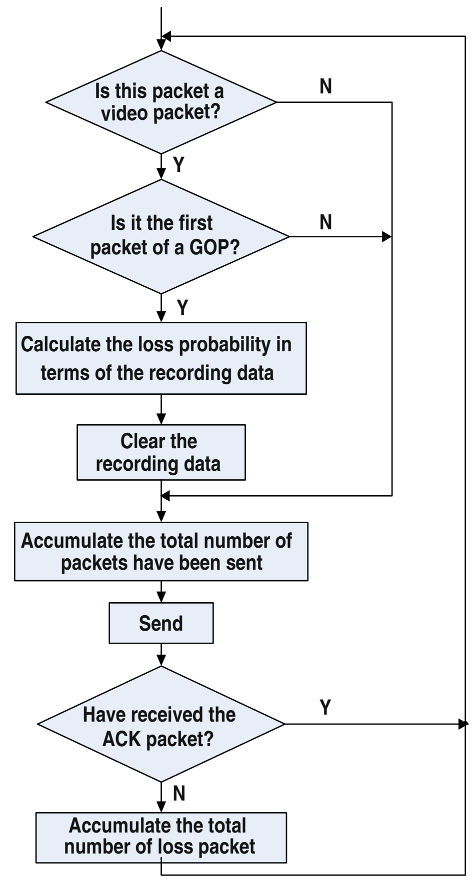

Fig. 2 Flow chart of collecting packet loss probability

3.2.2 Concrete implementation of channel adaptive FEC algorithm

In terms of the channel loss probability collected by our network estimator, the proposed channel adaptive FEC algorithm calculates suboptimal values of SR_{IF}, SR_{PF} and SR_{BF}. Then, the FEC redundant packets corresponding to these values are employed to protect video frames. The concrete implementation is shown in Fig. 3.

Once the link layer of the wireless terminal detects that the packet to be sent is the first packet of a new GOP, our scheme will calculate the packet loss probability observed in the previous transmission period. Then, our adaptive algorithm will find the suboptimal values of SR_{IF}, SR_{PF} and SR_{BF} for this packet loss probability. During the whole period of this GOP, the FEC coding is adaptively applied to each frame in terms of the above output results of the proposed channel adaptive FEC algorithm and the current video frame type.

4 Simulation results and analysis

For evaluating the proposed adaptive FEC algorithm, we set up a WLAN environment in the network simulation

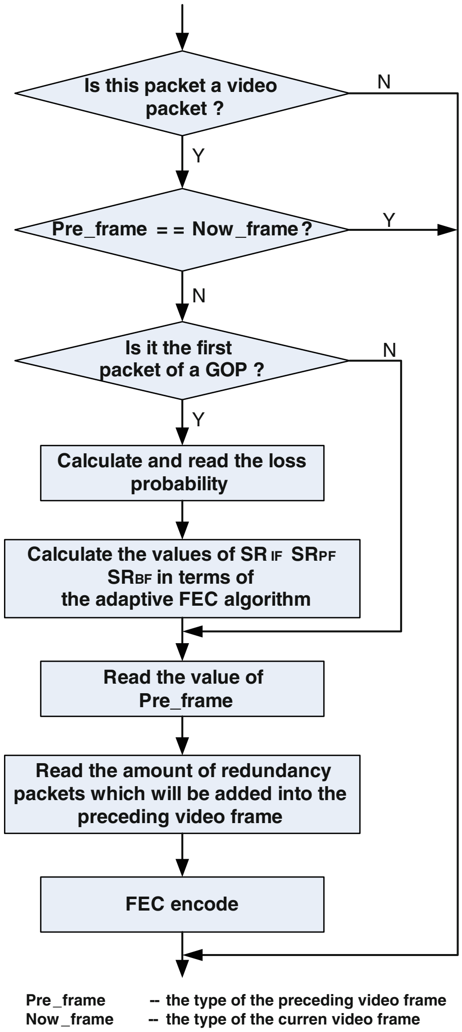

Fig. 3 Adaptive FEC algorithm concrete implementation scheme

(NS) version 2. The designated video-transmitting, wireless terminal implements the 802.11b protocol on the MAC layer. Its transport layer embeds the timestamp and sequence number fields for a video packet according to the Real-time Transport Protocol (RTP). The Bernoulli model is used to model the packet loss pattern for wireless channel. The real-time video data are transmitted from the wireless terminal to a wired terminal by AP and intermediate routers. As previously mentioned, the wireless channel is the only factor that contributes to packet loss in our simulation. A MPEG GOP pattern, 'IBPBPBPB…', and a typical full motion frame rate of 30 frames per second are used. Each GOP is composed of 30 video frames. The parameters that the adaptive FEC algorithm adopts are shown in Table 1.

Since the adaptive FEC algorithm is implemented in MAC layer of the wireless terminal, we set the value of s' to be 1,052 bytes to meet the constraints of the design.

Table 1 The simulation parameters of channel adaptive FEC algorithm

Parameter	S_I	S_P	S_B	s	N_P	N_{BP}
Value	16	4	1	1,024	14	1

Based on the above parameters, we present and discuss the results obtained by simulating the algorithms described in Sect. 2 and implementing the scheme described in Sect. 3. We evaluate the proposed algorithm (named as PFR_FEC for convenience) by comparing our algorithm with the algorithm which only considers the effective utilization ratio of FEC (Only_FEC), and the algorithm which only considers the playable frame rate (Only_PFR), in terms of the Peak Signal to Noise Ratio (PSNR) of the video frame which reflects the integrated system performance. If the sender applies no FEC coding to video transmissions, we name this method as NON_FEC.

Figure 4 illustrates the number of FEC redundant packets allocated to I, P and B frame respectively versus the packet loss rate p. The proposed FEC adaptive algorithm is able to adapt the amount of FEC packets to packet loss probability, which is demonstrated by the fluctuations of the three simulation curves. When $p < 50\%$, the I frame is assigned the most FEC-redundant packets, B frames are assigned the least FEC packets, and P frames are assigned a medium number of FEC packets. This follows the fact that our adaptive FEC algorithm adopts unequal error protection for the video data based on the different significance of I, P and B frames. Since the number of packets for a video frame is taken as the maximum number of FEC redundant packets distributed to this video frame in our algorithm, all three simulation curves have a maximum value. When the packet loss rate is higher than 50%, the PSNR is too low to guarantee acceptable video quality as previously discussed,

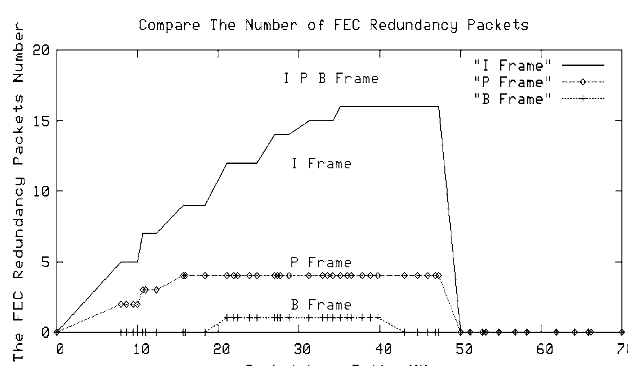

Fig. 4 Amount of FEC redundant packets allocated to I, P and B frames under different packet loss probabilities

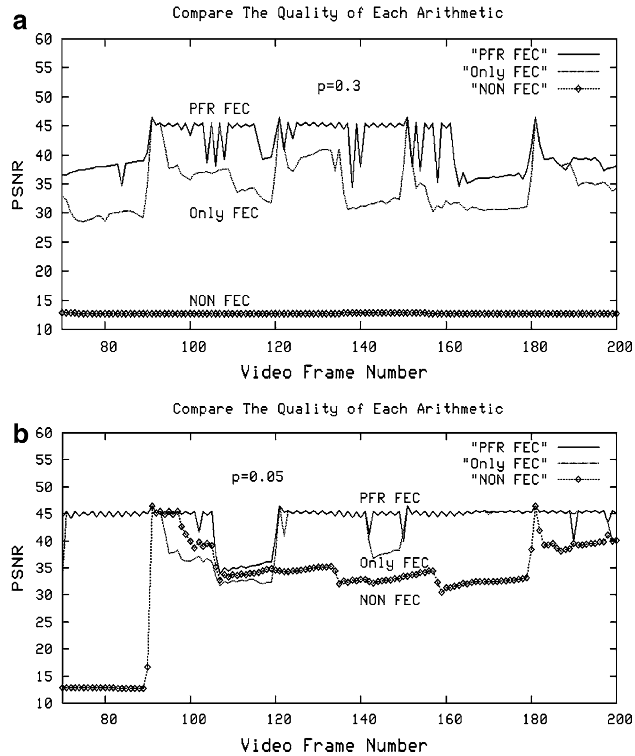

Fig. 5 **a** Comparison of PSNR when the packet loss probability is 0.3. **b** Comparison of PSNR when the packet loss probability is 0.05

and in order to improve bandwidth utilization, FEC coding is not applied to video frames, therefore the number of FEC redundant packets for I, P and B frames are set to zero.

Figure 5 shows the performance of PFR_FEC, Only_FEC and NON_FEC schemes on recovering video packets in terms of PSNR of each video frame. Two averages wireless channel packet loss probability were used, which were 0.3 and 0.05. Figure 5a compares the above three algorithms when the average packet loss probability is 0.3. It can be seen that PFR_FEC outperforms Only_FEC except for several specific points. In fact, these points coincide with the instances when the special B frames (following I frame) are transmitted. This shows that, only for some special cases, the algorithm that merely considers the effective utilization ratio of FEC can perform as well as our adaptive algorithm.

Upon degrading the average channel packet loss probability to 0.05, we obtain different PSNR curves as portrayed in Fig. 5b. Since the state of wireless channel is better than the one in the Fig. 5a, the performance of PFR_FEC and Only_FEC is largely similar. However, PFR_FEC exhibits a superior performance when the wireless environment is slightly worse. By implementing the proposed analytical model of the playable frame rate, our adaptive FEC algorithm achieves a better performance in terms of PSNR.

Table 2 Comparison of average PSNRs under different packet loss probability

PSNR	p					
	0.05	0.1	0.2	0.3	0.4	0.5
PFR_FEC	41.33	40.77	40.68	39.66	33.28	24.41
Only_FEC	39.57	38.52	37.90	37.38	30.04	24.38

In order to investigate the effectiveness of our adaptive FEC algorithm, the average PSNRs for different algorithms under different packet loss probabilities are compared and organized in Table 2. It is evident that PFR_FEC can outperform Only_FEC, especially when the packet loss probability is low; however, when the packet loss rate increases, PFR_FEC is only slightly better than Only_FEC. This derives from the fact that as the channel condition becomes worse, the proposed adaptive algorithm decreases the amount of FEC redundant packets gradually to reduce the burden on the network.

Figure 6 illustrates effective utilization ratio of FEC for each video frame corresponding to three FEC algorithms, where the packet loss probability is set to 0.3. PFR_FEC and Only_PFR have nearly equivalent performances, while Only_FEC achieves a much better performance than either. Only_FEC truly guarantees effective FEC utilization, but this is only one aspect of Only_FEC. In fact, Only_FEC does not consider video playable quality, so its PSNR cannot exceed PFR_FEC. When the effective utilization ratio of FEC reaches its maximum value, the video playback quality is much lower than its maximum value. In order to guarantee the video playback quality, the proposed adaptive FEC algorithm selects the suboptimal number of FEC redundant packets which significantly enhances the video playback quality, while concurrently provisioning a reasonable FEC utilization ratio, which is not as optimal as the one for Only_FEC.

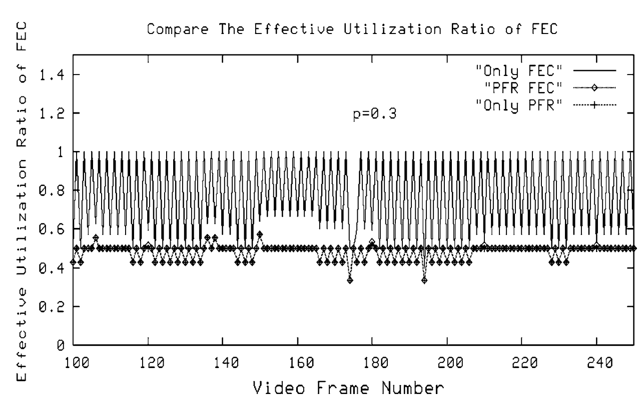

Fig. 6 Comparison of the effective FEC utilization ratio when the packet loss probability is 0.3

Figure 7 shows results of the effective FEC utilization ratio versus the packet loss rate p for I, P and B frames respectively. Comparisons with Only_PFR demonstrate an improved utilization ratio performance of our algorithm (PFR_FEC). It should be noted that Fig. 7a–c show similar trends when $p > 40\%$ as the curves of PFR_FEC approach those of Only_FEC. It follows the fact that our algorithm focuses on effective FEC utilization ratio instead of video playback quality when the wireless channel is degraded. However, when $p < 10\%$, the curves of PFR_FEC approach those of Only_PFR as explained previously. Taking into account the different sizes of I, P, B frames and the quantity constraint of FEC redundant packet allocated to each video frame, the distinction of effective FEC utilization ratio curves for I, P and B frame can be further understood. According to these three figures, the comparison of the three algorithms suggests that the effective FEC utilization ratios of I, P and B frames are slightly improved with our algorithm.

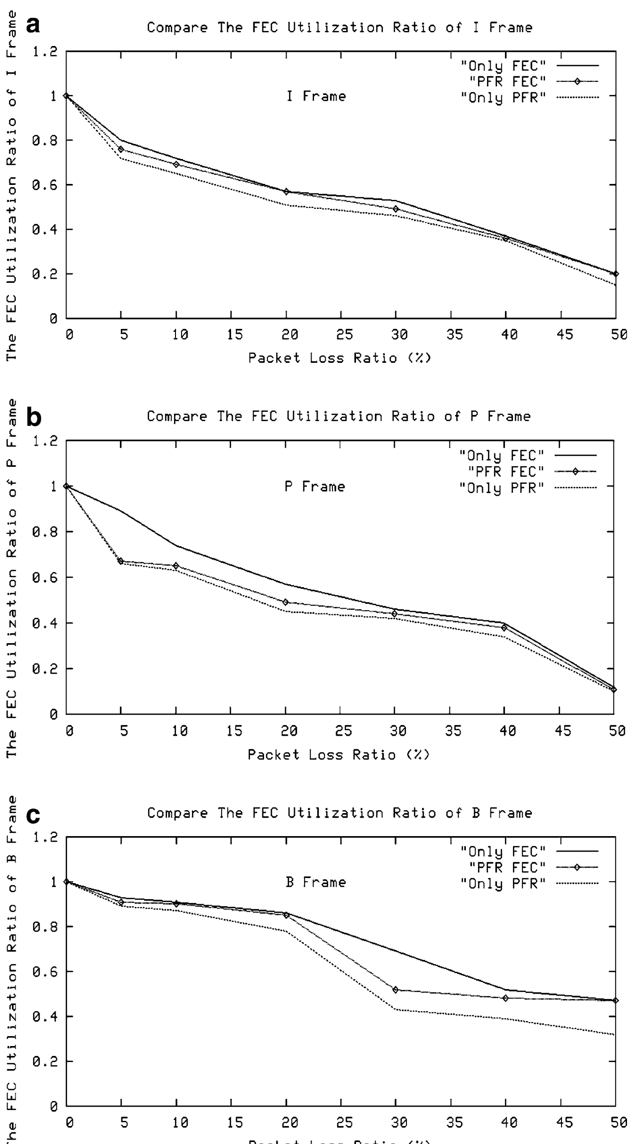

Fig. 7 **a** Comparison of the effective FEC utilization ratio of the I-frame under different packet loss probabilities. **b** Comparison of the effective FEC utilization ratio of the P-frame under different packet loss probabilities. **c** Comparison of the effective FEC utilization ratio of the B-frame under different packet loss probabilities

A comparison of end-to-end delay between our algorithm (PFR_FEC) and NON_FEC is demonstrated in Table 3. This comparison is relevant and necessary, since it is not obvious as to whether our algorithm introduces excessive delay into the wireless video transmission. As seen in Table 3, the maximum end-to-end delay when employing our algorithm is 14.66 ms, which is in excess of 7.65 ms over NON_FEC. Compared with the acceptable maximum of end-to-end delay in wireless video transmissions, which is typically 100 ms, the maximum delay introduced by PFR_FEC is not high enough to influence the wireless video QoS. However, variations in delay over the range of channel packet loss probabilities from 0.05 to 0.5 are able to generate delay jitter, which will adversely affect the QoS. In general, the maximum delay jitter of a wireless video transmission cannot exceed 50 ms. Under this constraint, the effect of delay jitter yielded by our algorithm can not be neglected. Clearly, this should be investigated in our future research.

In order to investigate the impact of collisions caused by a multiplicity of wireless terminals on the proposed adaptive FEC algorithm, we gradually increase the number of wireless terminals to a total of 32, which is the maximum number that can be linked to an AP in WLAN. Figure 8 outlines the average PSNR with different numbers of wireless terminals in the system, where the packet loss probability is set to 0.3. As illustrated in Fig. 8, when the number of wireless terminals increases, there is a gradual downward trend in the average PSNR, which is caused by a rising probability of collision. When the number of wireless terminals falls between 5 and 10, the average PSNR increases slightly due to the increasing number of available FEC redundant packets that contribute to restore video quality. It is worth noting that the PSNR is always greater than 30 dB, which means that clients are unlikely to detect changes in the video playback quality. Although the collisions caused by multiple-user have exerted a negative

Table 3 End to end delay under different packet loss probability

Delay (ms)	p					
	0.05	0.1	0.2	0.3	0.4	0.5
PFR_FEC	10.41	11.92	13.86	14.66	13.85	9.48
NON_FEC	6.79	6.86	6.97	7.01	6.85	6.64
Difference	3.62	5.06	6.89	7.65	7.00	2.84

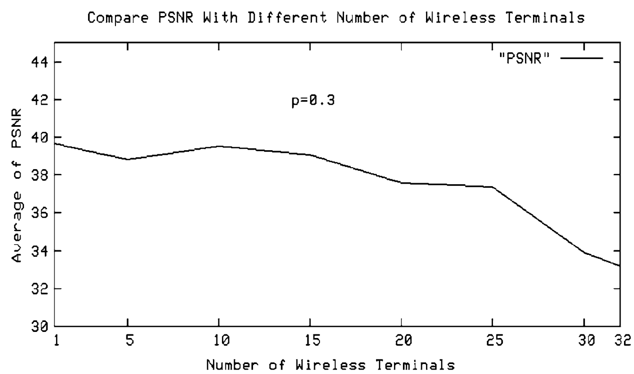

Fig. 8 Average PSNR under different sum of wireless terminals

impact on the proposed adaptive FEC algorithm, the effects are trivial, and thus difficult for clients to perceive.

5 Conclusions

In this paper, we proposed a novel channel adaptive FEC algorithm for real-time video transmission over error-prone and bandwidth-constrained wireless IP networks. As discussed in detail herein, the proposed algorithm can adaptively respond to the time-varying dynamics of packet loss probability of the wireless channel by adjusting the optimal amount of FEC redundant packets to strike a balance between the QoS of video transmission and the utilization ratio of the wireless bandwidth. For a given packet loss probability, the proposed algorithm predicts the total playable frame rate and the effective utilization ratio of FEC. A suboptimal amount of FEC redundant packets that makes both the quality of video stream and the utilization ratio of FEC approximate the maximum is selected. The major contributions given in this paper are: (1) Under the constraint of wireless bandwidth, an analytical model of playable frame rate for FEC-protected MPEG stream is developed; (2) Effective utilization ratio of FEC is derived, which describes the relationship between packet loss probability and the utilization ratio of FEC which reflects the utilization of wireless bandwidth; (3) The effects of FEC coding on both the video playback quality and the utilization ratio of wireless bandwidth are considered in the proposed algorithm. The simulation results show that, compared to the algorithm which only considers the playable frame rate, the proposed channel error rate adaptive FEC algorithm slightly improves the utilization ratio of wireless bandwidth. However, our algorithm provides a better QoS guarantee for wireless video transmission than the algorithms that only consider the utilization ratio of FEC without too much end-to-end delay, nevertheless the delay jitter yielded by our algorithm is unsatisfactory.

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