Two-Stage FEC Scheme for Scalable Video Transmission over Wireless Networks*

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ABSTRACT

In this paper, we propose a two-stage FEC scheme with an enhanced MAC protocol especially for multimedia data transmission over wireless LANs. The proposed scheme enables the joint optimization of protection strategies across the protocol stack, and packets with errors are delivered to the application layer for correction or drop. In stage 1, packet-level FEC is added across packets at the application layer to correct packet losses due to congestion and route disruption. In stage 2, bit-level FEC is processed within both application packets and stage-one FEC packets to recover from bit errors in the MAC/PHY layer. Header CRC/FEC are used to enhance the MAC/PHY layer and to cooperate with the two stage FEC scheme. Thus, we add FEC only at the application layer, but can correct both application layer packet drops and MAC/PHY layer bit errors. We explore both the efficiency of bandwidth utilization and video performance using the scalable video coder MC-EZBC and ns-2 simulations. Simulation results show that the proposed scheme outperforms conventional IEEE 802.11.

Keywords: W ireless, FEC, Video streaming, Cross-Layer, Scalable

1. INTRODUCTION

Current IEEE 802.11 wireless LANs are designed for reliable data transmission. They treat classical data flows and multimedia flows alike, even though these two kinds of flows have different requirements. The wireless physical (PHY) and media access control (MAC)[1] layers are designed to be as reliable as possible, so that one bit error in a packet could result in the whole packet being dropped. However, due to the error resilience features of many state-of-the-art multimedia CODECs and the utilization of error correction strategies at the application layer, packets with errors are still useful for multimedia applications. Therefore, mechanisms are needed to *efficiently* support multimedia data transmission over wireless networks. Packet losses in a wireless channel can be roughly categorized into two: (a) packets are dropped due to routing disruption, interference, and congestion in the intermediate nodes, and (b) packets are discarded in the MAC/PHY layers due to internal bit errors. To efficiently protect data from losses/errors in a wireless environment, two questions occur: At which protocol layer should the protection scheme be located? and How should the protection strategies be deployed? One simple solution is to add protection mechanisms at each protocol layer, as in the current wireless 802.11 protocol. However, we argue that the layered protocol protection strategy does not always result in efficient performance for the delivery of multimedia data, due to the independency of each protocol layer.

In this paper, we propose a two-stage FEC scheme with an enhanced MAC protocol to efficiently support multimedia data transmission over wireless LANs. Since only the application knows the characteristics of the multimedia data, the proposed scheme enables joint optimization of protection strategies across the protocol stack, and packets with errors are delivered to the application layer for correction or drop. The reason we choose to study FEC for video error recovery in this paper is due to the fact that a wireless ad hoc network is usually multihop and multiple re-transmissions would result in unpredictable delay and jitter at the application layer. We enhance the MAC/PHY layers to efficiently support multimedia flows by using both header CRC and FEC. We also slightly modified the protocol stack so that it can deliver packets with errors from the MAC layer to the application layer, instead of just dropping them. For the two-stage FEC, we add FEC only at the application layer, but can correct both application layer packet drops and MAC/PHY layer bit errors. Packet-level FEC (Stage 1) is added across packets at the application layer to correct packet losses due to congestion and route

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disruption. Bit-level FEC (Stage 2) is processed within both application packets and stage 1 FEC packets to recover bit errors from the MAC/PHY layers. Our proposed scheme has the following characteristics: *Network efficiency*: enhanced MAC protocol using header CRC and FEC improves application layer effective throughput; all useful information is delivered to the application. *Protection efficiency*: unequal error protection is easily deployable, since we only process FEC at the application layer. Furthermore, the proposed scheme combines bit-level protection codes (good at random bit error correction) and symbol level codes (powerful at correcting burst losses) to correct both bit errors at MAC/PHY layers and packet losses at the application layer. Since we jointly consider the whole protocol stack, we can also call our proposed scheme cross-layer.

1.1. Related work

In recent years, many papers have proposed cross-layer solutions for wireless video. Li and van der Schaar[2] proposed an error protection method that can provide adaptive quality of service to layered coded video by utilizing priority queueing at the network layer and retry-limit adaptation at the link layer. The video layers are unequally protected over the wireless link by the MAC with different retry limits that are dynamically adapted depending on the wireless channel conditions and traffic characteristics. Krishnamachari *et al*[3] propose an adaptive cross-layer protection strategy for enhancing robustness and efficiency of scalable video transmission where application layer FEC, MAC layer re-transmission strategy and an adaptive video packetization scheme are jointly optimized to maximize visual performance. The proposed scheme focus on wireless links from 802.11a base station to mobile users. Manshaei *et al*[4] propose a simple and efficient cross-layer mechanism for dynamically selecting the transmission mode that considers both the channel conditions and characteristics of the media. The proposed Media-Oriented Rate Selection Algorithm (MORSA) finds the highest possible transmission rate while guaranteeing a specific bit error rate by adjusting the physical layer modulation. Goldsmith *et al*[5] propose a cross-layer approach to support real-time video streaming, where information between different layers of the protocol stack is exchanged and end-to-end performance is optimized by adapting to this information at each protocol layer. Choi *et al*[6] proposed a cross-layer optimizer that interfaces the video streaming application and the radio link layer by means of parameter abstraction to maximize the end-to-end quality of the streaming service jointly for all users while efficiently using the wireless resources. State information is abstracted from selected layers and provided to the cross-layer optimizer.

1.2. Organization

The remainder of the paper is organized as follows: In Section II, we give a detailed description and analysis of our proposed two-stage FEC protection scheme and enhanced MAC protocol by using header CRC and FEC. In Section III, simulation results are provided, followed by conclusions in Section IV.

2. SYSTEM OVERVIEW

Fig. 1 illustrates the 802.11 wireless LAN protocol stack and packet structure associated with each layer, where "H"s represent the header of each protocol layer.

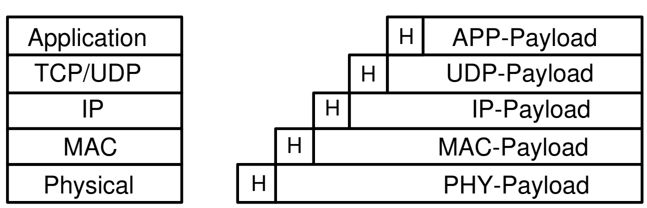


Figure 1. 802.11 protocol stack and associated packet structure

An application packet consists of data payload and application header. Whenever a packet is passed down to the next protocol layer, a header associated with that layer is added, as shown in Fig. 1. In this stack, UDP and IP provide source and destination IP addresses and port numbers of the communication pair to ensure correct delivery. Packets are dropped at the IP layer due to congestion or route disruption. On the other hand, MAC/PHY protocols support adjacent host communications and have to deal with bit errors. Any bit error within a packet could result in the whole packet being dropped, even though the errors could be corrected in the application layer. To efficiently support multimedia applications, we slightly modify the protocol stack so that it can deliver packets with errors to the application layer. This can be achieved by simply turning off the CRC checksum function in the MAC/PHY layers. The UDP-lite[7] protocol should be used at transport layer to match the enhanced MAC protocol. To ensure better delivery, we enhance the MAC/PHY layer by modifying the 802.11 packet CRC mechanism to check only the header part possibly also with bit-level FEC for the header part.

The proposed system diagram is shown at Fig. 2.

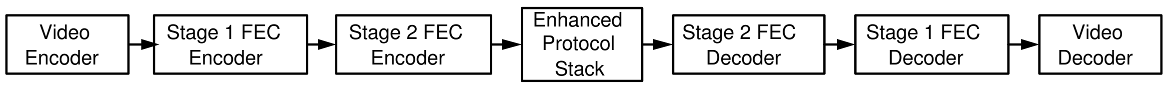


Figure 2. System diagram of the proposed two-stage protection scheme

At the application layer, two-stage FEC is applied to the encoded video bitsteam based on network conditions. In stage 1, packet level FEC is added across application layer packets to correct packet drops due to congestion or route disruption. Stage 2 is processed within each application packet, a small amount of bit level FEC is added to recover bit errors from the MAC/PHY layers at each packet. At the receiver side, we first process the bit-level FEC, the bit errors from the MAC/PHY layers can be recovered. Then we pass the bitstream to the stage 1 FEC decoder for further correction. In this paper, we choose Reed-Solomon (RS) codes for packet-level protection (stage 1) and BCH codes for bit-level protection (stage 2).

2.1. Channel Models and Enhanced MAC Layer

For simplicity, we start from a virtual channel with two nodes, one sender and one receiver. We further assume no contention between these two nodes. The binary symmetric channel (BSC) model and the Gilbert model[8] are used as our channel models. The Gilbert model is the first order binary Markov Channel model. Given two states, good state (G) with error probability P_G and bad state (B) with error probability P_B, the burst length in state G and B are both geometrically distributed with respective means P_{GB}^{-1} and P_{BG}^{-1}, where P_{GB} (P_{BG}) is the transition probability from the good (bad) state to the bad (good) state. The steady state probabilities of being in state G and B are $\pi_G = \frac{P_{BG}}{P_{GB}+P_{BG}}$ and $\pi_B = \frac{P_{GB}}{P_{GB}+P_{BG}}$. The overall average bit error rate p_b produced by the Gilbert model is:

$$p_b = P_G\pi_G + P_B\pi_B = \frac{P_G P_{BG} + P_B P_{GB}}{P_{GB} + P_{BG}} \tag{1}$$

The BSC error model is a memoryless model where bit errors are produced by a sequence of independent trials. Each bit has the probability p_b being flipped and $1 - p_b$ being successfully transmitted, p_b is then the Bit Error Rate (BER) for the wireless link. Given a packet with size L bytes being transmitted over a wireless channel with BER p_b, the probability of packet error $P_e(L)$ can be calculated as:

$$P_e(L) = 1 - (1 - p_b)^{8L} \tag{2}$$

The 802.11 MAC layer defines two medium access coordination functions, basic *distributed coordination function* (DCF) and optional point coordination function (PCF). Since DCF can be used both in ad hoc and infrastructure modes while PCF can only work on infrastructure mode, we will focus on DCF mode in this paper. DCF is a distributed medium access scheme based on the most popular *Carrier Sensing Multiple Access with Collision Avoidance* (CSMA/CA) protocol. The current MAC mechanism of 802.11 LAN uses stop-wait ARQ (SW-ARQ) to transmit a packet. If a packet arrives at a node with an empty queue and the medium has been found idle for an interval of longer than a distributed inter frame space (DIFS), the node can transmit the frame immediately, and the successfull transmission of the packet is confirmed by an ACK packet. Therefore, both the packet itself and the feedback ACK must be successfully transmitted. Assume that the uplink and downlink have the same BER p_b, the probability to successfully transmit a packet P_{suc} is then:

$$P_{suc} = (1 - P_e(L))(1 - P_e(S_{ACK})) = (1 - p_b)^{8(L+S_{ACK})} \tag{3}$$

Where L and S_{ACK} are the size of MAC packet and ACK packet in byte, respectively. Given a physical layer bandwidth B_{PH}, the effective application layer throughput B_{AP} can be estimated as:

$$B_{AP} = B_{PH} * P_{suc} * r \tag{4}$$

where r is the ratio defined as $r = application\_packet\_size/MAC\_packet\_size$

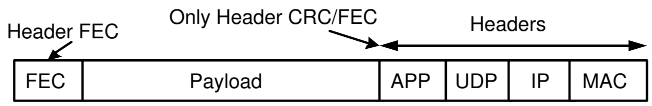


Figure 3. Enhanced MAC/PHY protocol using header CRC and header FEC

The header part of each protocol layer is crucial, because if header has some errors in it, usually the whole packet is useless. We use header CRC and header FEC to enhance the MAC/PHY layers to efficiently support multimedia delivery. We slightly modified the 802.11 MAC/PHY layer packet CRC mechanism to check if there is something wrong within the header part as shown in Fig. 3. The packet is dropped if the header CRC fails. With this header CRC mechanism, the probability of successful transmission of a packet P_{sucH} becomes

$$P_{sucH} = (1 - p_b)^{8(S_{header}+S_{ACK})} \tag{5}$$

Where S_{header} is the size of all the header bytes. Since S_{header} is much smaller than the packet itself, the probability of successful transmission of a packet using header CRC is larger than when using whole-packet CRC. It also results in a larger effective throughput at the application layer according to Equation 4. Similarly to header CRC, a bit-level FEC can be added to the header part to combat bit errors in the header and further reduce the probability of header errors. We performed a MATLAB simulation to compare the application layer bandwidth efficiency of using header CRC, header FEC and packet CRC as shown at Fig 4. Here, we assume that the application layer packet payload size is 1000 bytes, the CRC header size is 60 bytes (UDP 8 bytes, IP 20 bytes, MAC header 24 bytes, application layer header 4 bytes) and the ACK packet size 14 bytes. Physical layer bandwidth is set to 2 Mbps. In all cases, a packet should be dropped if any CRC check fails.

In Fig. 4, we use the same method as the current 802.11 does for MAC layer packet CRC, any bit error inside a packet results in the whole packet being dropped. For header CRC, only the header part (see Fig. 3) is checked at the receiver side, if anything is wrong within the header part, the whole packet is dropped. Even if only the header part is checked, the performance degrades a lot at high bit-error rates, and this is due to the large number of header check errors. So, we further added a $BCH(511, 502, 1)$ code to protect the header part from bit errors. The performance then becomes good even at high bit-error rates and the bandwidth overhead added by the header FEC is only 0.1%. Clearly, the header CRC/FEC results in a better application layer throughput, but the received packet may have errors in it. To protect the packet payload from errors, a $BCH(8191, 8000, 14)$ code is applied to each packet, and therefore, any 14 bit errors out of the 8191 codeword bits can be corrected. While fixed FEC adds overhead at low bit rates, it performs quite well at high bit error rates. In Fig. 4, a plot of header FEC with payload FEC has lower throughput compared with header FEC alone. This is because of the overhead in payload FEC and we also artificially drop the packet if payload FEC cannot correct the errors. This is comparable to 802.11 packet CRC with error free delievery. We will evaluate these schemes under more realistic conditions using the ns-2 simulator later on in this paper. Here, we define a FEC decoding failure if FEC cannot correct all errors in a codeword. To identify a decoding failure is an engineering problem. If combined with CRC, the FEC decoder first decodes the codeword, then makes a CRC check of the decoded codeword, if the CRC is ok, then decode, otherwise, declare a decode failure.

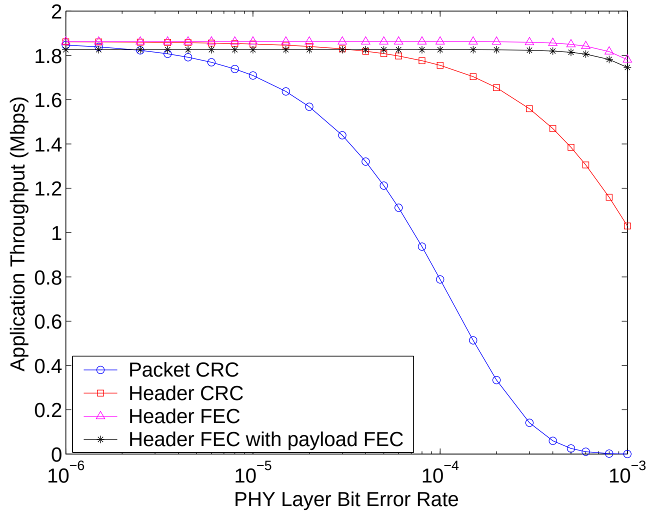


Figure 4. Application layer bandwidth efficiency vs BER

2.2. Two-Stage FEC Scheme

At Fig. 4, even if a BCH code is applied to each packet payload, the curve with payload FEC still drops at high bit-error rate. This is because the whole packet is being dropped due to header FEC decode failure. Bit level in packet FEC protection cannot correct packet losses. Thus, we need to have a scheme to correct both bit errors and packet drops. We propose a two-stage FEC scheme to solve the problem as shown in Fig. 5.

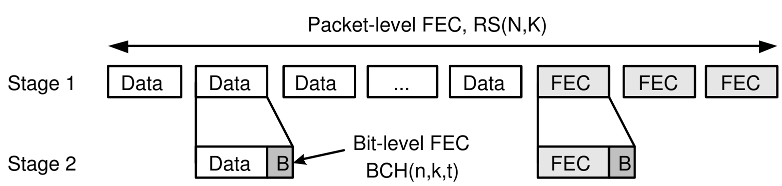


Figure 5. Detail of the proposed two-stage FEC scheme

In stage 1, packet level FEC is added across application layer packets to correct packet drops due to congestion or route disruption. We use RS codes for stage 1 FEC.

In stage 2, FEC is processed within each application packet, and a very small amount of bit-level FEC is added to recover any bit errors from the MAC/PHY layers. We use BCH codes for stage 2 FEC.

We assume a wireless channel with physical bandwidth B_{PH}, bit-error rate p_b, and probability of a packet being dropped at the sender due to congestion p_{drop}. For simplicity, we ignore ACK packet in this section. First we start from header CRC, since any bit error in header part would result in a whole packet being dropped, the probability of a packet loss p_{loss} can be calculated as:

$$p_{loss} = p_{drop} + 1 - (1 - p_b)^{8(S_{header})} \tag{6}$$

Bit-level FEC is added within each packet to correct bit errors. Given a BCH (n,k,t) code, number of bit errors larger than t in a codeword cannot be corrected, so the probability of not correctly decoding the codeword $P_{BCH}(E)$ is

$$P_{BCH}(E) = \sum_{j=t+1}^{n} \binom{n}{j} p_b^j (1 - p_b)^{n-j} \tag{7}$$

All these packets with errors are passed to the packet level FEC RS(N,K)for further correction. After BCH decoder correction, the residual bit-error rate p_{rb} can be estimated as:

$$p_{rb} = p_b P_{BCH}(E) \tag{8}$$

Reed-Solomom codes are Maximum Distance Separable (MDS) codes.[9] They are especially suitable for correcting burst errors. Given the correction results of BCH decoding, to calculate the probability of error on decoding the RS codeword, is a total probability problem. We define $R(E)$ as the event of RS decoder correction failure, B(E) as the event of BCH decoder correction failure and B(C) as the event of BCH decoder successful correction. Therefore the RS correction failure $P_{RS}(E)$ in the proposed two-stage FEC can be calculated as:

$$P_{RS}(E) = P\{R(E)|B(C)\}P_B(C) + P\{R(E)|B(E)\}P_B(E) \tag{9}$$

where $P_B(E)$ and $P_B(C)$ are the probability of BCH decoding error and the probability of BCH decoding success, respectively.

If BCH can successfully correct the bit errors inside packets, the conditional probability of RS error decoding is an erasure correction problem as

$$P\{R(E)|B(C)\} = \sum_{i=d_{min}}^{n} \left(\begin{array}{c} N \\ i \end{array} \right) p_{syc}^i (1 - p_{syc})^{N-i} \tag{10}$$

where the probability of symbol erasure is $p_{syc} = p_{loss}$, and $d_{min} = N - K + 1$.

If the BCH code fails to correct the bit errors inside the packets, then the conditional probability of RS error correction is a mixed erasure and error correction problem and can be calculated as

$$P\{R(E)|B(E)\} = \sum_{i=[(N-K)/2]+1}^{N} \left(\begin{array}{c} N \\ i \end{array} \right) p_{sye}^i (1 - p_{sye})^{N-i} \tag{11}$$

where the probability of symbol error is a combination of packet loss and packet error, can be calculated as

$$p_{sye} = p_{loss} + 1 - (1 - p_b)^m \tag{12}$$

Where m is the symbol size of $RS(N, K)$ code.

After both BCH code correction and RS code correction, the residual bit error rate can be reduced to

$$p_{rsrb} = p_{rb} P_{RS}(E) = p_b P_{BCH}(E) P_{RS}(E) \tag{13}$$

For header FEC, we can have a similar analysis, but using a residual bit-error rate after header FEC decoding to calculate p_{loss} at Equation 6.

We compare the protection performance of our proposed schemes (Two-stage FEC + header CRC/FEC) with conventional application layer FEC (RS only + 802.11) in terms of residual packet error rate. MAC layer re-transmission times are set to one at all three schemes. Any bit error in a packet after FEC correction should result in the packet being dropped, this is comparable to the situation in conventional 802.11 error-free delivery.

The parameter setup is given in Table 1. The packet size is the same as in Fig. 4. For RS only, we add FEC using RS code across packets and the code rate is 239/255. For 802.11, we do the same as in the 802.11 wireless LAN. Regarding two-stage FEC, we use $RS(255, 245)$ as stage 1 FEC and across the application layer packets. The $BCH(8191, 8000, 14)$ code is applied within each application layer packet as stage 2. Two-stage FEC with the header FEC scheme uses the same FEC for stage 1 and stage 2 as header CRC, but uses $BCH(511, 502, 1)$ as a protection method for the header part as shown in Fig. 3. The proposed two-stage FEC scheme significantly outperforms the conventional 802.11 plus application-only protection strategy as shown in Fig. 6

Protection Method	FEC codes	Code rate
802.11	SW-ARQ	retransmission one time
RS only	RS(255,239)	239/255
Two-stage FEC with header CRC	BCH(8191,8000,14) + RS(255,245)	239/255
Two-stage FEC with header FEC	BCH(8191,8000,14) + RS(255,245) BCH(511,502,1)	239/255

Table 1. Parameter setups for compare of several protection schemes

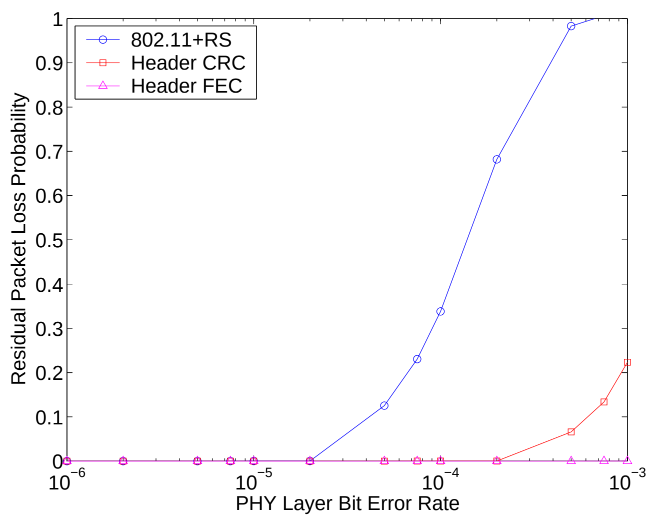


Figure 6. Residual packet loss probability of several FEC schemes vs BER

2.3. Effective Application-Layer Throughput

In this section, we analyze the effective application-layer throughput using different protection methods in a two-node communication topology, without contention. Here, we define the effective throughput as the throughput of error free traffic. Any packets with errors after correction are dropped at the application layer, and is comparable with 802.11 error -free delivery. We compare four protection schemes: 802.11 ARQ, application-layer FEC using Reed-Solomon codes, the proposed two-stage FEC with header CRC, and two-stage FEC with header FEC. We assume the same wireless channel as in Section 2.1.

For 802.11, any bit error in MAC packet should result in a whole packet being dropped. The effective application layer throughput $B_{AP}(802)$ can be estimated as

$$B_{AP}(802) = rB_{PH}(1-p_b)^{8(L+S_{header}+S_{ACK})}(1-p_{loss}) \quad (14)$$

In our application-layer scheme, an $RS(N, K)$ packet-level FEC scheme is applied across packets with code rate $C_{RS} = K/N$. After the RS code correction, the effective application-layer throughput can be estimated as:

$$B_{AP}(RS) = rB_{PH}(1-p_{rbrs})^{8L/C_{RS}}(1-p_{loss})C_{RS} \quad (15)$$

Where p_{rbrs} is the residual bit error rate after RS decoding and $p_{rbrs} = p_b P_{RSO}(E)$. The probability of error decoding the RS codeword $P_{RSO}(E)$ can be calculated using equation 11 and equation 12.

Regarding the two-stage FEC with header CRC/FEC, we combine both the packet-loss correction capability and bit-level protection ability to maximize the overall system performance. We use $BCH(n, k, t)$ for bit-level protection within a packet and $RS(N, K)$ for packet-level protection. C_{our} represents the combined code rate using two-stage FEC scheme.

At receiver side, the BCH decoder first decodes the received packet. No matter whether the BCH decoder can fully correct the bit errors or not, it passes the packets to the RS decoder for further burst-loss correction and also packet-loss correction. The effective throughput can be estimated as

$$B_{AP}(our) = rB_{PH}(1 - p_{rsrb})^{8L/C_{our}}(1 - p_{loss})C_{our} \tag{16}$$

Equation 16 can be used for both header CRC and header FEC, but using different p_{loss}. The value p_{loss} can be calculated directly from equation 6 if header CRC is used. For header FEC, we still use equation 6 but replace of p_b with p_{rb} from equation 8.

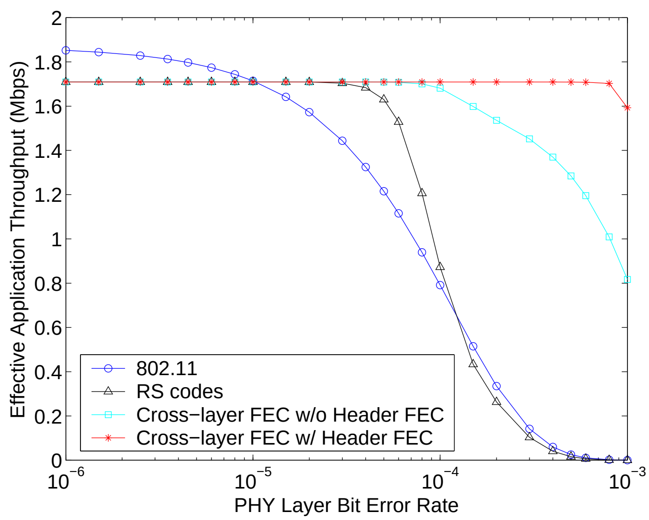


Figure 7. Effective application layer throughput efficiency of several FEC schemes vs physical channel BER

Fig. 7 shows the performance of the above mentioned four protection methods regarding their effective throughput. Except for 802.11, the same amount of FEC is added to data in the three other schemes. The simulation parameter setup is listed in Table 1. The results show that at very low bit-error rate, 802.11 offers the highest effective throughput, since the SW-ARQ requires less overhead than fixed FEC protection. If an adaptive FEC scheme is used, we can expect similar results to those of our proposed scheme at low bit-error rates. As the bit-error rate goes higher, the performance varies dramatically. For 802.11, the probability of retransmission and packet drops goes very high at high bit-error rates, and it quickly reduces the effective throughput to a very low rate. Due to the characteristic of RS codes (if a codeword can correct the bit-errors, it would completely correct it or completely not correct it if errors are beyond its correction capability[9]), the RS-only protection method is even worse than 802.11 at high bit-error rates with the FEC overhead. On the other hand, our proposed two-stage FEC scheme effectively joins the advantages of both bit-level protection and packet-level protection. The performance is better than both 802.11 and RS-only protection schemes. The plot of two-stage FEC with header CRC also drops at higher loss rates, and this is due to the reason that at higher loss rates, the probability of header error goes up and results in a relatively high number of packets being dropped, beyond the correction capability of the RS code in the application layer. Further, we add a small amount of bit level FEC to protect header from errors. Since the added $BCH(511, 502, 1)$ can correct one bit error in a 511 bits codeword, the performance is very good compared to the other three schemes at high BER with less than 0.1% overhead.

2.4. Scalable video coding and FEC design

The wireless channel is time varying, error prone, and usually bandwidth constrained. A distinct characteristic of wireless communications is its large variation in bandwidth and packet loss rate. Compared with the conventional fixed-bit-rate video or multi-layer approach that only supports a discrete number of bitstream layers, scalable video coding is more suitable for wireless communications, since a scalable video bitstream can be almost continuously tailored to the time-varying channel characteristics. In this paper, we use the fully scalable coder MC-EZBC[10] to evaluate our proposed two-stage FEC scheme, in conjunction with an enhanced MAC protocol.

2.4.1. MC-EZBC coding

MC-EZBC is a highly scalable motion-compensated subband/wavelet video coder with high compression performance, rivaling that of the unscalable coding standard H.264. It produces embedded bitstreams supporting a full range of scalabilities. Fig. 8 shows a typical Group-Of-Pictures (GOP) structure of this coder with 16 video frames. The top level represents the video at full frame rate. These incoming frames are subject to motion estimation and the resulting motion vectors (shown as arrows) are used for motion-compensated (MC) temporal filtering (MCTF). In this version of the coder, neighboring frames are decomposed using a motion-compensated Haar filter bank to produce the temporal low frequency bands (solid lines) and temporal high frequency bands (dashed lines) at the next lower level. This process is repeated until we obtain the MC average of all 16 frames in the GOP, which is at the bottom of the temporal pyramid. Video data in this case has five temporal scalability layers, going from full frame rate down to LLLL-level at 1/16 of full frame rate. Temporal subbands are then subject to spatial subband/wavelet analysis and encoded using a version of the EZBC coding algorithm, details of which are given in.[10] The bitstream sequence is organized in an embedded fashion. Each GOP coding unit consists of independent bitstreams $\{Q^{MV}, Q^{YUV}\}$, where Q^{MV} denotes the bitstream for the motion fields, and Q^{YUV} for the subband coefficients of color components Y, U, and V of the video. The motion vector code stream is embedded in frame rate. The remaining bitstream is fully embedded in quality/bit-rate, spatial resolution, and frame rate. Such a scalable bitstream is especially suitable for mid-stream adaptation and can be adapted to different frame rates, SNRs, and resolution according users' requirements. For simplicity, we only consider SNR or bitrate scalability in this paper. Scaling in term of quality is obtained by stopping the extraction process at any point in the bitstream. To achieve a certain bitrate, we simply stop extracting bits when that bitrate is reached.

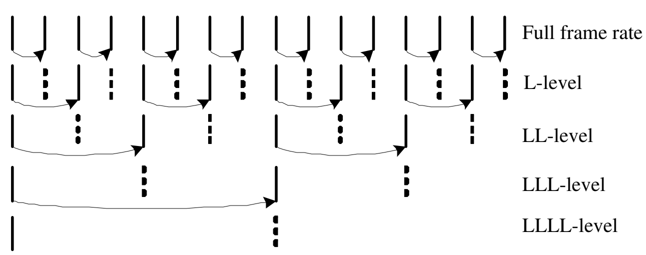


Figure 8. A typical GOP of 16 frames with 5 layers of temporal scalability

2.4.2. FEC design

Since the wireless channel is time varying, the effective video bit rate correctly received at the receiver side is a random variable. The 802.11 wireless LAN MAC layer uses SW-ARQ to ensure packet delivery. Therefore, a sender can easily estimate its sending rate based on the ACKs. A video system is time sensitive, so excessively delayed packets are useless. The advantage of the scalable encoded bit stream is that it can be chopped at any point to match very well with the bandwidth varying channel: the more bits the receiver gets, the better the video quality. In this paper, we use MD-FEC[11] as stage 1 FEC to protect the MC-EZBC video bitstream. MD-FEC transforms this unequally important bitstream into one of equally important descriptions (packets) by using erasure correcting RS codes. First the embedded source bitstream is divided into N sections marked with $R_1, R_2, ..., R_N$ at Fig. 9, where $R_1 \leq R_2 \leq ... \leq R_N$. Section k is further split into k subsections and encoded by a $RS(N, k)$ code.

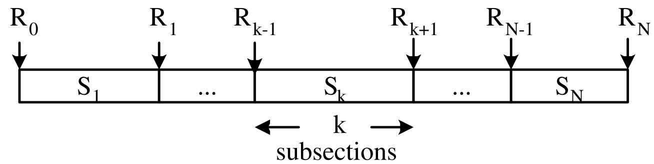


Figure 9. Rate partition of an embedded bitstream into N layers or quality levels

RS codes are applied to each section vertically, the contributions from each of the N levels are then concatenated to form the N descriptions as shown in Fig. 10. This packetization scheme thus provides the property: if n packets are received, decoding is guaranteed up to R_n. MD-FEC can generate a certain rate encoded bitstream in a GOP and send it to the channel. At the receiver, the decoder only needs to decode the received part to R_n. In a conventional FEC method, if the first packet gets lost in a GOP, the whole GOP is useless. The benefit of using MD-FEC as stage 1 is that we can at least decode to a certain rate if any part of the bitstream is received.

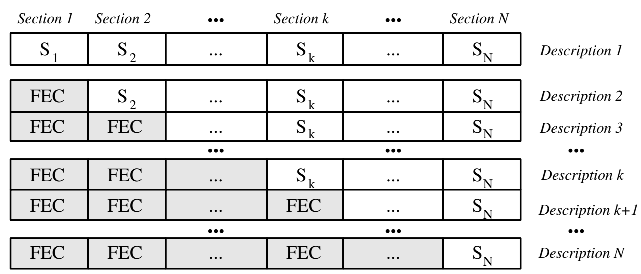


Figure 10. MD-FEC generates N descriptions or quality levels

Let q_i be the probability that any i out of N packets are successfully delivered. To find the optimal rate partition $R = \{R_1, R_2, ..., R_N\}$, which minimizes the end-to-end mean distortion $E[D(R)]$ defined as

$$E[D(R)] = \sum_{i=0}^{N} q_i D(R_i) \tag{17}$$

subject to:

$$\begin{cases} 0 \leq R_1 \leq R_2 \leq ... \leq R_N; \\ R_{total} \leq R_{max}; \\ R_i - R_{i-1} = k_i * i; \qquad k_i \geq 0 \; and \; i = 1, ..., N. \end{cases}$$

Where R_{total} is the total amount of bandwidth for both packet-level FEC and video data. R_{max} is the maximum available bandwidth for the channel. Given a packet loss probability p, q_i can be calculated as $q_i = \begin{pmatrix} N \\ i \end{pmatrix} (1-p)^i p^{N-i}$. According to Equation 2, bit error rate at lower protocol level can dramatically affect the application layer throughput. Therefore the FEC design should try to recover all the random errors at the low protocol levels. Given the needed bit-level FEC bandwidth B_{bit} and available bandwidth B_{avail}, R_{max} can be calculated as $R_{max} = B_{avail} - B_{bit}$. In this paper, we use the method proposed in[12] to allocation optimal stage 1 FEC according to network conditions.

2.4.3. FEC Adaptation

To efficiently protect packets from losses and to match the available sending rate, adaptation is needed for FEC design. The FEC codes cannot only correct errors, but also detect errors. The receiver estimates the loss behavior of the channel and feeds back the result to the sender. Two types of loss information are sent back to the sender. The packet loss information is fed back regarding stage 1 FEC design for each GOP. This loss information does not include packet drops due to FEC correction failure. Since bit errors in the packet can dramatically affect the application layer loss rate, stage 2 bit-level FEC uses a Step-Increase-Step-Decrease (SISD) method. A NACK packet is sent back to sender in the case of FEC decoder failure. Then the sender encodes the bit-level FEC with a step higher FEC code, eg. from $BCH(n, k, t)$ to $BCH(n, k, t+1)$. If errors inside a packet can be corrected, the receiver should also know how many bit errors are inside the packet. If the correction capability is much higher than the bit errors, for instance, the correction capability is twice higher than the number of errors, the receiver also feeds back an ACK for the bit-level FEC to step decrease one level from $BCH(n, k, t)$ to $BCH(n, k, t-1)$.

3. SIMULATIONS

To evaluate the performance of our proposed scheme in terms of effective application layer throughput and video PSNR, we perform several simulations to compare our two-stage FEC plus enhanced MAC protocol with the conventional 802.11 based method. The network simulator ns-2[13] wireless module is used in this section and the simulation topology is shown at Fig. 11.

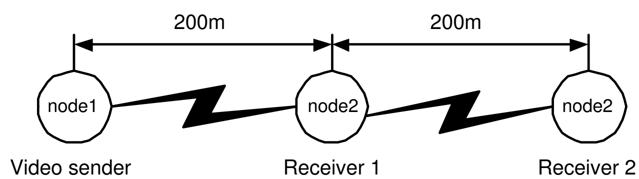


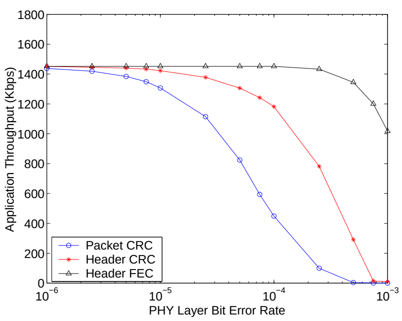
Figure 11. NS-2 video simulation topology

Two types of simulations are performed, single hop and multihop (2 hops in this paper). In the single hop simulation, node1 works as sender, node2 as receiver, and node3 is idle. There is no contention in this scenario. For multihop simulation, node1 works as sender, node3 as receiver, and node2 is the intermediate node that forwards data from sender to receiver2. Contention exists among the three nodes. The wireless physical layer bandwidth is set to 2 Mbps. The bit-error rates in this section are all average and the average bit-error burst length on the Gilbert channel is 2. In order to reduce delay variation, we set the maximum MAC layer retransmission time to 2. The retransmission is based on standard 802.11 SW-ARQ. Both RTS and CTS packets are used before a packet transmission.

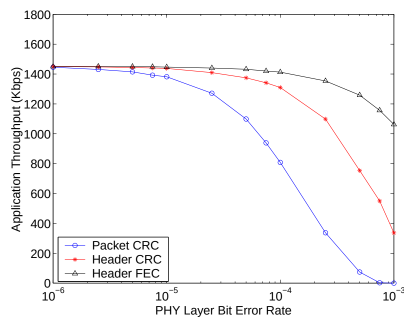
3.1. Effective Application Layer Throughput

To get the maximum effective throughput in the application layer, application layer CBR traffic is set to 2 Mbps from sender to receiver in single hop simulations, to saturate the channel. The packet and header size is set to the same size as in Section 2.1. To combat channel bit errors, a $BCH(8191, 8000, 14)$ code is applied to each packet in header CRC and header FEC. A packet is dropped upon BCH decoder failure. For the 802.11 packet CRC scheme, we directly follow the standard, a packet CRC is performed at receiver. Any bit error must result in the whole packet being dropped and trigger retransmissions until the maximum retransmission times. In the header CRC scheme, the receiver performs a header CRC, and drops a packet if the header CRC fails. In the header FEC scheme, a $BCH(510, 480, 3)$ code is applied to the 60 byte header part, resulting in 2 additional FEC bytes. This code can correct a number of bit errors up to 3 in a 511 bit codeword. If the BCH decoder cannot successfully decode the codeword, the a retransmission is triggered. In multihop simulations, since there are contentions among the three nodes, we reduce the application layer CBR traffic to 1.2 Mbps.

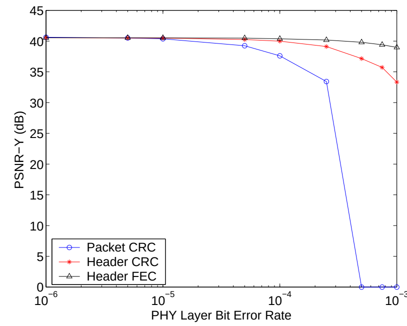
Fig. 12 shows the effective application-layer throughput on single hop simulation on the BSC channel (Fig. 12(a)), Gilbert channel (Fig. 12(b)) and multihop simulation on BSC channel (Fig. 12(d)), Gilbert channel (Fig. 12(e)). Similarly to Section 2.1, IEEE 802.11 performs very poorly at high bit error rates, because of the error-free-delivery design requirement. Compared to results in Section 2.1, the header CRC scheme performs worse than the theoretical simulation, this is because of the additional loss of RTS/CTS packets and ACK packets at higher bit error rates. With the help of header FEC, the probability of header error is greatly reduced. The degradation of the curve is most likely due to the ACK error and RTS/CTS failure at higher bit error rates. For



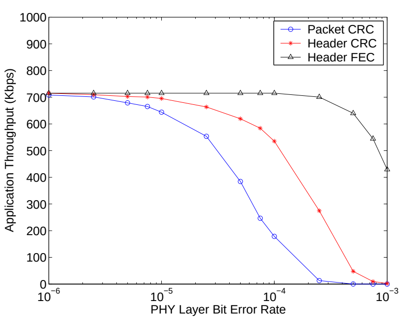
(a) single hop on BSC channel



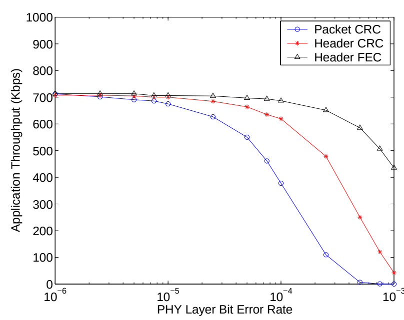
(b) single hop on Gilbert channel



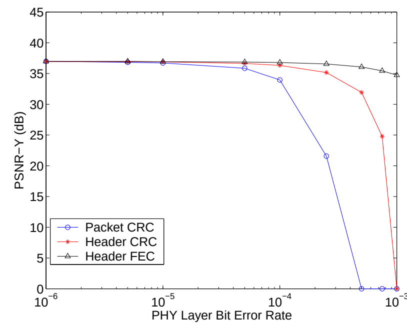
(c) single hop video PSNR-Y



(d) multihop on BSC channel



(e) multihop on Gilbert channel



(f) multihop video PSNR-Y

Figure 12. Effective application layer throughput on BSC and Gilbert channel at different physical layer BER and corresponding Video PSNR_Y

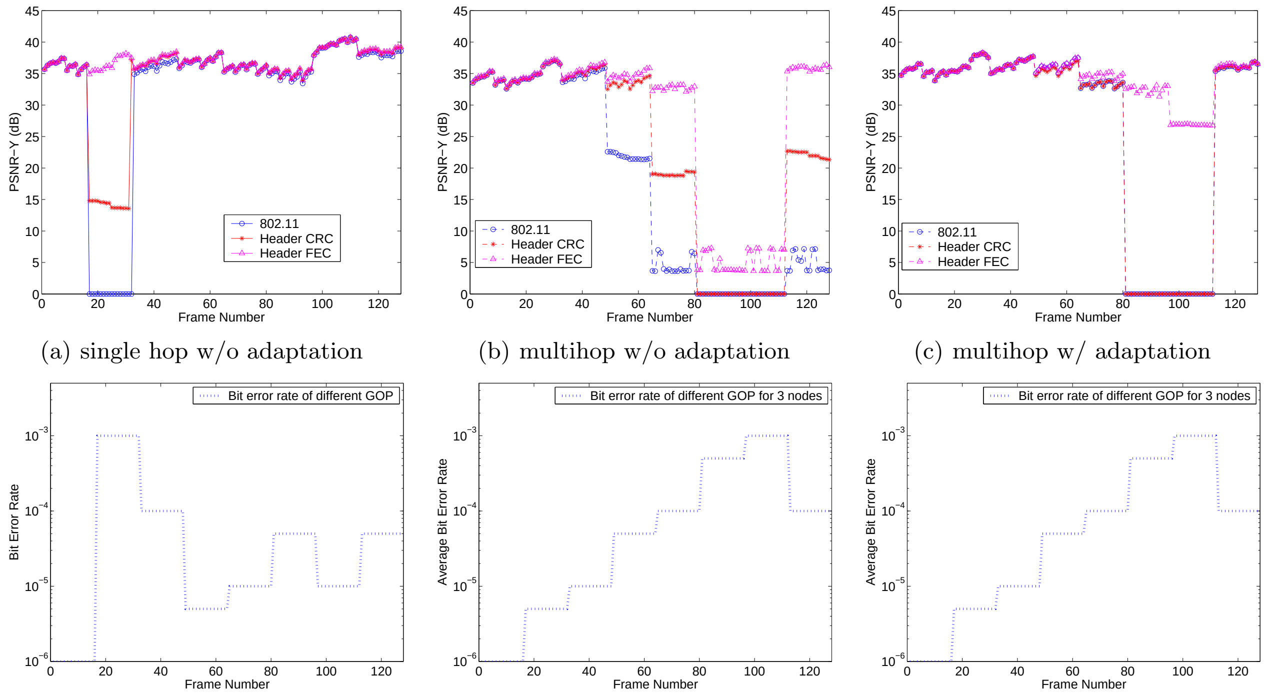
example, at 1×10^{-3} bit error rate, the probability of ACK(14 bytes) error is around 10.6% and the RTS(20 bytes)/CTS(14 bytes) packets error probability is 23.8%.

Given the effective application layer throughput at Fig. 12(b), Fig. 12(e), we further test the performance of the video system. We assume an MC-EZBC encoded video bitstream is sent over a wireless Gilbert channel. The sender can adapt the bitstream based on channel conditions. The video sequence is monochrome *Foreman* CIF, 30 fps. The PSNRs shown in Fig. 12(c) and Fig.12(f) are the average of the first 100 frames from the single hop and multihop simulations. We notice that the PSNR for 802.11 packet CRC reduces to zero at higher loss rates, and this is thought due to there not being enough bandwidth for transmission of even the base layer of the bitstream. Clearly, we see better PSNR using our enhanced MAC protocol (header CRC and header FEC). The contention among the three nodes reduces the performance of the system.

3.2. Video Performance

We further tested the video performance of our proposed scheme using MD-FEC. Three kinds of simulations were performed: single hop simulation, multihop simulation without FEC adaptation, and multihop simulation with FEC adaptation. The MC-EZBC video bitstream was first encoded with MD-FEC at maximum bit rate 1 Mbps. Each GOP was encoded into 128 packets by the MD-FEC encoder for stage 1 FEC and resulted in a packet size of around 500 bytes. All packets are further encoded with bit-level FEC (stage 2), and a $BCH(4195, 4000, 4)$ code is applied in both single hop and multihop simulations. The physical layer average bit error rates for each GOP are set at Fig. 13(d), 13(e) and 13(f), under Gilbert channel. The corresponding PSNR of each GOP is shown above each BER graph in Fig. 13. The protection schemes compared are 802.11 packet CRC, header CRC, and header FEC, all with two-stage FEC.

Since there is almost no contention in single hop simulation, the packet loss is most likely caused by bit errors in the wireless channel. We see dramatic performance drop in the 802.11 and header CRC schemes at severe bit error rate (1×10^{-3}) in Fig. 13(a). This matches very well with the trend in Fig. 12(b), where 802.11 has less



(a) single hop w/o adaptation
(b) multihop w/o adaptation
(c) multihop w/ adaptation
(d) BER for each GOP, single hop
(e) BER for each GOP, multihop w/o adaptation
(f) BER for each GOP, multihop w/ adaptation

Figure 13. Video PSNR_Y vs. frame number at different channel conditions of each GOP

bandwidth even than required for the video base layer, and the header CRC scheme can only accept the video base layer. In multihop simulation without FEC adaption, node2 works as the intermediate node to forward packets to node3, both node1 and node2 are senders, and further node2 is also a receiver. In Fig. 13(b), the MD-FEC encoded video bitstream is fixed at 1 Mbps. The wireless channel is time varying and error prone, therefore, the stage 1 MD-FEC design is based on 10% packet loss rate and average error burst length is 2 packets, for better protection. Due to the limitation of physical bandwidth and high number of retransmissions at high bit-error rates, a large number of contentions and packet drops reduces the effective throughput greatly, and that results in a large video PSNR drop. Though MD-FEC is very powerful, as the channel BER goes high (1×10^{-3}), the probability of retransmission goes very high, and none of the three protection schemes work well. But still the proposed header FEC scheme can transmit part of the base layer at 1×10^{-3} BER. Fig. 13(b) also matches very well with Fig. 12(f). In Fig. 13(c) multihop simulation with FEC adaption, the FEC design is based on the feedback from the receiver and the actual sending rate. At high bit error rates, the sending rate goes down and FEC can be designed based on the available sending rate. The sender can truncate the scalable video bitstream to suite the channel. Therefore, comparing to Fig. 13(b), all curves in Fig. 13(c) have better performance in terms of video PSNR, especially two-stage FEC with header FEC, which performs very good even in the face of severe channel conditions ((1×10^{-3})). Video clips related to Fig. 13 can be found at my website.[14]

4. CONCLUSIONS

In this paper, we propose a two-stage FEC scheme with an enhanced MAC protocol (header CRC/FEC) to efficiently support multimedia data transmission over wireless LANs. The proposed scheme enables the joint optimization of protection strategies across the the protocol stack. Two-stage FEC combines bit-level protection codes (good at random bit error correction) and symbol level codes (powerful at correcting burst losses) to correct both bit errors in the MAC/PHY layers and packet losses in the application layer. Simulations show that the proposed scheme outperforms conventional IEEE 802.11. Future work will focus on joint source and network coding for video streaming over a mobile multihop network.

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