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14. ABSTRACT
This final report is divided into two parts. In the first part, we present the generalization of our joint source-network coding scheme FGA-FEC to wireless video communications. We consider the in-net adaptation of video resolution, frame-rate, and quality to match the network link parameters of bandwidth, packet-loss probability, and bit-error rate, as well as the specific requests/needs of the end-users. This algorithm assumes a high-rate network backbone that is relatively lossless. In the second part of this report, we extend this FGA-FEC method to work in a distributed fashion on internal network nodes, thus making it suitable for peer-to-peer networks. We assume the nodes possess some computational ability in addition to

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Final Report on Joint-Source Network Coding for Wireless

ABSTRACT

This final report is divided into two parts. In the first part, we present the generalization of our joint source-network coding scheme FGA-FEC to wireless video communications. We consider the in-net adaptation of video resolution, frame-rate, and quality to match the network link parameters of bandwidth, packet-loss probability, and bit-error rate, as well as the specific requests/needs of the end-users. This algorithm assumes a high-rate network backbone that is relatively lossless. In the second part of this report, we extend this FGA-FEC method to work in a distributed fashion on internal network nodes, thus making it suitable for peer-to-peer networks. We assume the nodes possess some computational ability in addition to forwarding and routing capability, not unlike a PC.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1. Y. Shan, I. V. Bajic, S. Kalyanaraman, and J. W. Woods, "Overlay Multi-Hop FEC Scheme for Video Streaming," Signal Processing: Image Communication, vol. 20, p. 710-727, Sept. 2005. (Special Issue on Video Networking, Invited)

2. I. V. Bajic and J. W. Woods, "Error Concealment for Scalable Motion-Compensated Subband/Wavelet Video Coders," IEEE Trans. Video Technology, vol. 17, p. April 2007.

3. Y. Shan, I. V. Bajic, J. W. Woods, and S. Kalyanaraman, "Scalable Video Streaming with Fine Grain Adaptive Forward Error Correction," IEEE Trans. Video Technology, accepted for publication, 1/7/2009.

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1. Y. Shan, J. W. Woods, and S. Kalyanaraman, "Fine Grain Adaptive FEC (FGA-FEC) Over Wireless Networks," Proc. IEEE ICIP, San Antonio, TX, Sept. 2007.

2. Y. Shan, J. W. Woods, and S. Kalyanaraman, "Distributed Fine Grain Adaptive FEC Scheme for Scalable Video Streaming," Proc. SPIE VCIP, San Jose, CA, Jan. 2008.

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Graduate Students

NAME	PERCENT_SUPPORTED
Yufeng Shan	1.00
FTE Equivalent:	**1.00**
Total Number:	**1**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
John Woods	0.15	No
Shivkumar Kalyanaraman	0.15	No
FTE Equivalent:	**0.30**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
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Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

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Names of Personnel receiving masters degrees

NAME

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8 January 2009

1. INTRODUCTION

In this attachment we cover work on two aspects of the research. In the first part, we investigate a two-stage FEC scheme for video streaming on wireless networks, that operates at both the MAC/PHY layer and application layer. We employ header CRC and FEC at the MAC/PHY layer, and make a slight change so that packets with bit errors are forwarded up rather than being discarded there. In the application layer, we employ packet level FEC to recover dropped packets. We also present work on a distributed extension of our FGA-FEC that can work when there is no high-speed backbone, i.e. peer-to-peer and *ad hoc* networks.

2. FGA-FEC FOR WIRELESS NETWORKS

Current IEEE 802.11 wireless LANs are designed for reliable data transmission. They treat classical data and multimedia flows alike, even though these two kinds of flows have different requirements. The wireless physical (PHY) and media access control (MAC) layers [5] 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. 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 our work, 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. We enhance the MAC/PHY layers to efficiently support multimedia flows by using both header CRC and FEC. We also slightly modify 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.

Our proposed scheme has the following characteristics: *network efficiency* through enhanced MAC protocol using header CRC and FEC to improve application layer effective throughput and *protection efficiency* through unequal error protection that 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.

2.1 System Overview

The proposed system diagram is shown in Fig. 1.

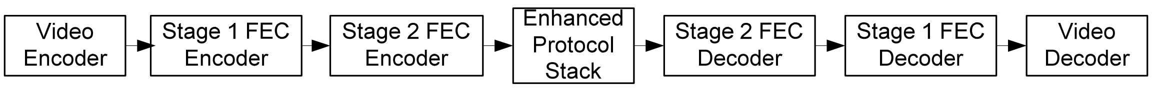


Figure 1. System diagram of the proposed two-stage protection scheme

At the application layer, two-stage FEC is applied to the encoded video bitstream 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, where a small amount of bit-level FEC is added to recover bit errors from the MAC/PHY layers for each packet. At the receiver side, we first process the bit-level FEC, so 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 our work, we chose Reed-Solomon (RS) codes for packet-level protection (stage 1) and BCH codes for bit-level protection (stage 2).

2.1.1 Enhanced Protocol Stack

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 [6] protocol should be used at transport layer to match the enhanced MAC protocol. To ensure better delivery and to improve the effective application layer throughput, we enhanced 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.

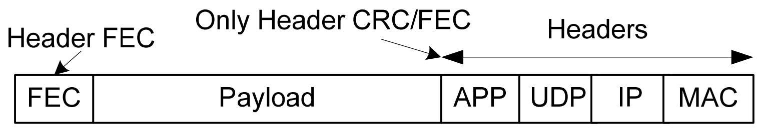


Figure 2. Enhanced MAC/PHY layer with Header CRC and Header FEC

The header part of each protocol layer is crucial, because if the 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. 2. The whole packet is dropped if the header CRC or FEC fails.

2.1.2 Two-stage FEC Scheme

Packet losses in a wireless channel can be roughly categorized into two types: (a) packets dropped due to routing disruption or congestion at the intermediate nodes, and (b) packets discarded at the MAC/PHY layers due to internal bit errors. A two-stage FEC scheme is shown in Fig. 3.

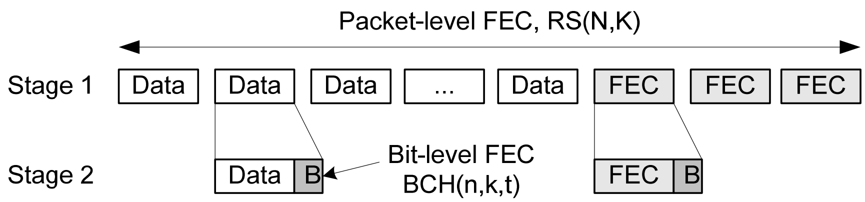


Figure 3. Detail of the proposed two-stage FEC scheme

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

2.1.3 Residual packet loss probability

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. The number of MAC-layer retransmission times is set to one for all three schemes. Any bit error in a packet after FEC correction will 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 payload and packet header size are 1000 bytes and 60 bytes, respectively. For RS only, we add FEC using an RS code across packets with code rate 239/255. For IEEE 802.11, we follow 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 for header CRC, but uses BCH(511, 502, 1) as a protection method for the header part as shown in Fig. 2. The proposed two-stage FEC scheme significantly outperforms conventional 802.11 plus application-only protection strategy as shown in Fig. 4.

Protection Method	FEC codes	Code rate
802.11	SW-ARQ	1 retransmission
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 comparison of several protection schemes

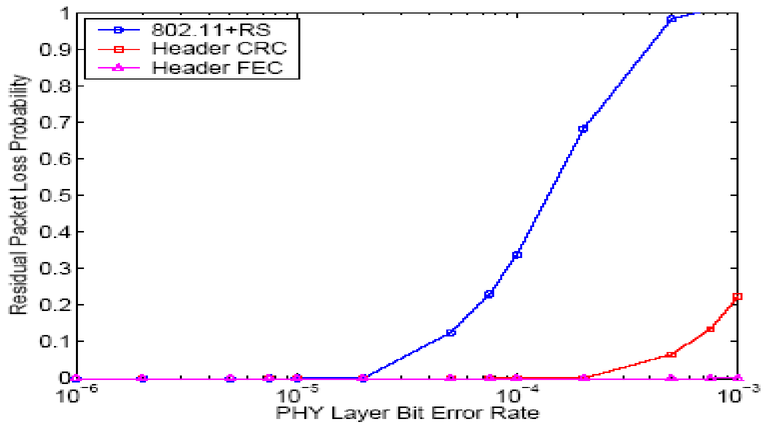


Figure 4. Residual packet-loss probability of several FEC schemes vs. BER

2.2 Simulations

To evaluate the performance of our proposed schemes 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 [7] wireless module is used in this section and the simulation topology is shown at Fig. 5. Two types of simulations are performed, single hop and multihop (2 hops here). In the single hop simulation, node1 works is the sender, node2 is the receiver, and node3 is idle. There is no contention in this scenario. For the multihop simulation, node1 works as sender, node3 is the receiver, and node2 is an 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 averaged over many trials and the average bit-error burst length on the Gilbert channel is 2. In order to reduce delay variation, we set the maximum number of MAC-layer retransmissions to 2. The retransmission is based on standard 802.11 SW-ARQ. Both RTS and CTS packets are exchanged before a packet transmission.

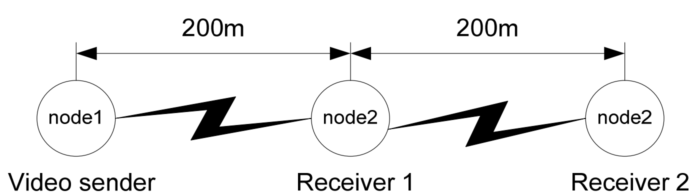
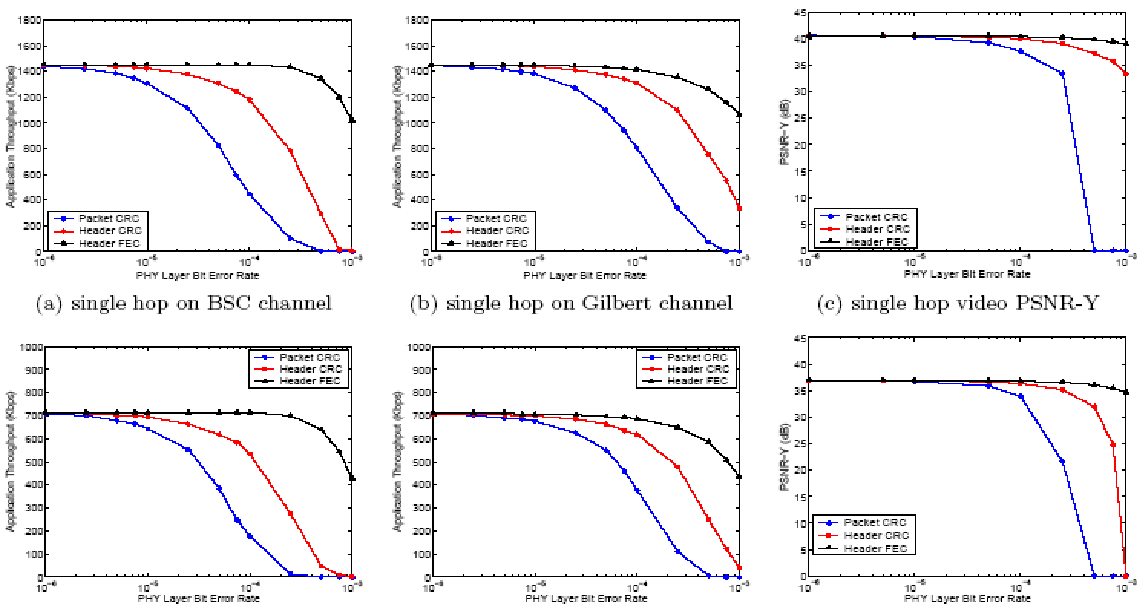


Figure 5. our ns-2 video simulation topology

3.2.1 Application layer effective throughput

To get the maximum *effective throughput* (i.e. error-free throughput) in the application layer, the application layer CBR traffic is set to 2 Mbps from sender to receiver in the single hop simulations, to saturate the channel. The packet and header sizes are set to the same size as in Section 2.1.3. To combat channel bit errors, a BCH(8191, 8000, 14) code is applied to each packet in header CRC and header FEC. The packets are dropped upon BCH decoder failure. For the 802.11 packet CRC scheme, we directly follow the standard and a packet CRC is performed at the receiver. Any bit error must result in the whole packet being dropped and triggers retransmissions until the maximum retransmission time. 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, then a retransmission is triggered. In the multihop simulations, since there are contentions among the three nodes, we reduce the application layer CBR traffic to 1.2 Mbps.



(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 6: Effective application layer throughput on BSC and Gilbert channel for different physical layer BER and corresponding video PSNR-Y

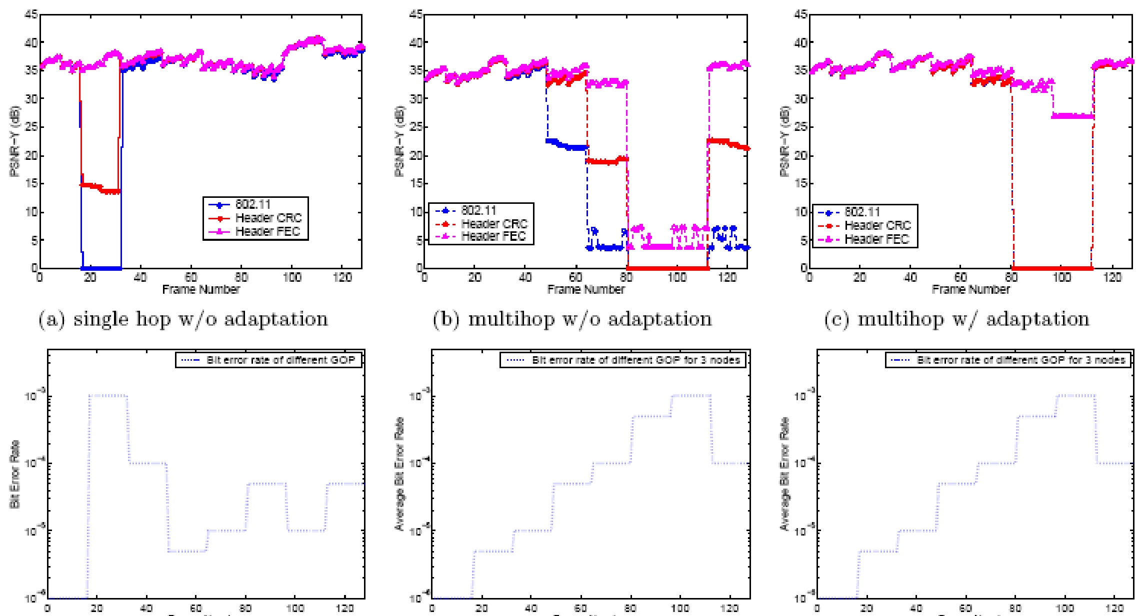
Fig. 6 shows the effective application-layer throughput of the single hop simulation for the BSC (Fig. 6(a)) and Gilbert (Fig. 6(b)) channels, and multihop simulation on the BSC (Fig. 6(d)), Gilbert (Fig. 6(e)) channels. We see that standard IEEE 802.11 performs very poorly at high bit-error rates, because of the error free delivery design requirement. The header CRC scheme performs better than 802.11 due to its smaller CRC check size. 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.

Given the effective application layer throughput in Fig. 6(b) and Fig. 6(e), we test the objective video performance. We assume an MC-EZBC [3] 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. 6(c) and Fig. 6(f) are the average of the first 100 frames from the single hop and multihop simulations, respectively. 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 coded video 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.

2.2.2 Video Performance with MD-FEC

We further tested the video performance of our proposed scheme using MD-FEC [1,2]. We use the same FEC bit allocation scheme proposed in [1]. Three kinds of simulations were performed: single hop, multihop without FEC adaptation, and multihop simulation with FEC adaptation (FEC can adapt to network conditions). The MC-EZBC video bitstream was first encoded with MD-FEC at the 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 shown in Figs. 7(d), 7(e) and 7(f) for the Gilbert channel. The corresponding PSNR of each GOP is shown above each BER graph in Fig. 7. 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 the single hop simulation, the packet loss is most likely caused by bit errors in the wireless channel. We see a dramatic performance drop in the 802.11 and header CRC schemes at severe bit-error rate (1×10^{-3}) in Fig. 7(a). This matches very well with the trend in Fig. 6(b), where 802.11 has less bandwidth even than required for the video base layer, and the header CRC scheme can only accept the video base layer. In the multihop simulation without FEC adaptation, node2 works as an intermediate node to forward packets to node3, both node1 and node2 are senders, and further node2 is also a receiver. In Fig. 7(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 a 10% packet-loss rate and average error-burst length of 2 packets, for better protection.



(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 7: Video PSNR-Y vs. frame number at different channel conditions of each GOP

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 ($1{\times}10^{-3}$), 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. 7(b) also matches very well with Fig. 6(f). In Fig. 7(c) multihop simulation with FEC adaptation, 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 match the condition of the channel. Therefore, comparing to Fig. 7(b), all curves in Fig. 7(c) have better performance in terms of video PSNR, especially two-stage FEC with header FEC, which performs very well even in the face of severe channel conditions (1×10^{-3}).

3. DISTRIBUTED VERSION OF FGA-FEC ALGORITHM

In this section, we investigate a distributed FGA-FEC scheme for scalable video streaming to heterogeneous users over a congested multihop network, where we do FGA-FEC decode/re-code at selected intermediate overlay nodes, and do FGA-FEC adaptation at remaining nodes. In order to reduce the overall computational burden, we propose two methods: (1) coordination between optimization processes running at adjacent nodes to reduce the optimization computation, and (2) extension of our overlay multihop FEC (OMFEC [8,9]) to reduce the number of FGA-FEC decode/recode nodes. Simulations show that the proposed scheme can greatly reduce computation, and can provide near best possible video quality to diverse users.

Our FGA-FEC can encode scalable video in such a way that both the embedded bitstream and the error correction codes can be easily and precisely adapted in a multidimensional way to satisfy diverse users without complex transcoding at intermediate nodes. The server first encoded the scalable video based on the highest user request and aggregated network conditions, then it sent the encoded bitstream into the network. Inside the network, the DSNs adapted the FGA-FEC encoded bitstream to satisfy heterogeneous users by shortening and/or dropping packets. We assumed that there was no congestion in the network backbone, i.e. that the backbone available bandwidth was large enough to accommodate all user requirements. This assumption is for service provider based structured networks, where the congestion and packet loss mainly happen at the edge of network or at the last mile connection. One problem still remains: in a multihop network, congestion could be anywhere inside the network, especially in an ad hoc wireless network. How should we modify FGA-FEC to work with a congested back-bone? Here, a congested link is defined as a link whose available bandwidth is less than the minimum required bandwidth to accommodate a user's video request. One solution to address this problem is a hop-by-hop based solution. We can optimize FEC protection for each individual link and apply FGA-FEC decode/re-code at each DSN for each user. By FGA-FEC decode/re-code, we mean that a DSN decodes FGA-FEC of the received GOP, re-optimize the multiple descriptions and then re-codes the GOP with new designed FGA-FEC for its downlinks. This would be a heavyweight hop-by-hop computationally intensive method if done at every overlay node. Here, we argue it may not be necessary to do FEC decode/re-code at each DSN.

We need to identify the congested links in the backbone and apply the appropriate transformation at each DSN. Still, running the full FGA-FEC optimization at even some DSN nodes may be computationally demanding. So, here we describe a distributed algorithm, where we do FGA-FEC decode/re-code at the selected DSNs. The proposed distributed FGA-FEC scheme includes two parts: (1) a coordination method between FGA-FEC optimization processes running at nearby nodes to reduce the optimization computation, and (2) we apply OM-FEC [8,9] to reduce the number of FGA-FEC decode/re-code nodes, i.e. we use FGA-FEC adaptation where permitted and perform FGA-FEC decode/re-code only at certain key DSNs. This design thus lies between the end-to-end and hop-by-hop paradigms. If there is no congestion over the backbone, we choose end-to-end FGA-FEC scheme, no FEC decode/re-code is needed at intermediate nodes, but efficient adaptation. If each backbone link is congested, it is a heavyweight hop-by-hop FEC decode/re-code scheme. For this more advanced distributed algorithm, we only focus on SNR scalability, and leave extension to resolution and frame-rate scalability as a topic of future work.

3.1. DISTRIBUTED FGA-FEC

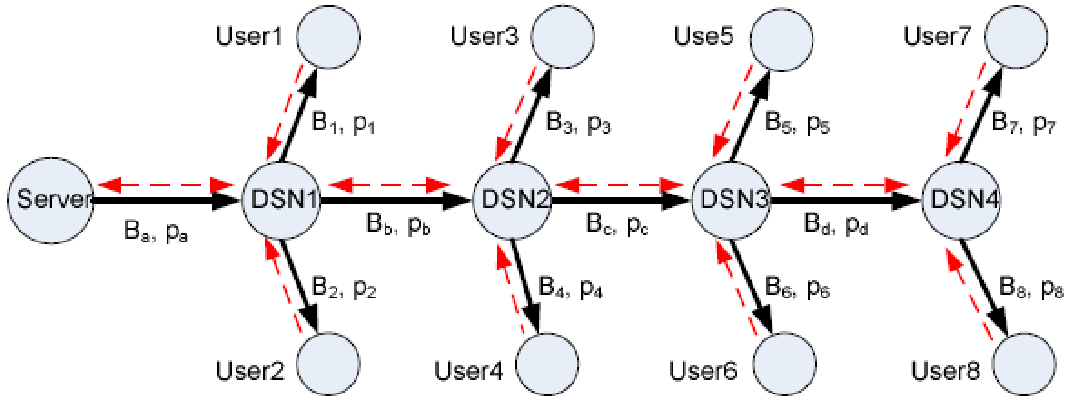


Figure 8. Streaming video from server to users through DSNs, red-dotted arrows are overhead information flows, black solid arrows are video flows.

We outline our idea in a simplified example as shown in Fig. 8, where a server streams video to 8 diverse users through DSNs over a congested backbone. Before the streaming session, each end user sends its ideal video request (*Dmin* in terms of distortion) and maximum tolerable distortion (*Dmax*) to its directly connected DSN. During the streaming, at each time interval (1 GOP or multiple GOPs), edge DSNs (DSN4, whose downlinks have only end users) initialize optimization processes for each child to figure out what kind of bitstream it needs to request from its parent DSN (DSN3). This request is based on its children's link conditions and their video requests. The combined video request of its child nodes along with the optimization result is sent to DSN3 as overhead information. DSN3 then runs optimizations for its own children, including DSN4 (DSN3 treats DSN4 as one ordinary user), and generates the requested information to its parent DSN2. This process is repeated until we arrive back at the server. The server then runs the same algorithms as DSNs to determine the amount of FEC that should be applied to the video and then sends the encoded video into network. Inside the network, some selected DSNs will decode, redo the FGA-FEC design and recode FEC for some users, the other DSNs are only adaptation nodes. There are two kinds of flows in the distributed algorithm, upstream overhead information flow (shown via red-dotted arrows at Fig. 8) and downstream video data flow (shown via black arrows). Each DSN only exchanges optimization information with its direct parent or children, generating only local overhead information traffic. The DSNs use this information to coordinate optimization processes running at nearby nodes to reduce the computational burden, as well as to decide which nodes that will be involved in the FGA-FEC decode/re-code. We apply the idea of OM-FEC to minimize the number of involved FGA-FEC decode/re-code nodes while still maintaining the near optimal

The FGA-FEC optimization algorithm is run at both DSNs and video server. A DSN runs optimization for its children to figure out what kind of bitstream it needs to request from its parent DSN or server. The server runs optimization to design the FEC and to encode a GOP. The only difference in the optimization algorithms running at DSNs and server are the input parameters. In this study, the optimization time interval is one GOP. We defer details to our published VCIP 2008 paper [10].

The motivation of coordination typically is from the following: (1) video statistical information between adjacent GOPs does not usually change rapidly, and (2) the server and parent DSNs have the optimization information from their child DSNs of the same GOP, with only different available bandwidth B and packet-loss probability p. Therefore, the problem can be simplified into how to utilize the previous optimization information as network conditions and video statistics change. We will use two coordination methods: (1) search with previous GOP results at this DSN, and (2) search with current GOP result from child node. The edge DSNs (DSNs whose children are all end users) initialize optimization for a new GOP. There, we can use optimization information from the previous GOP, we call this method "search with previous GOP." Intermediate DSNs and the server have local information not only of the same GOP from child DSNs but also have their previous GOP optimization result. Thus, they can use information of either of these GOPs to initialize their optimization search. Using the optimization information from child DSN, will be called "search with neighbor." We also consider a full search method, where each node runs the optimization algorithm independently. There, the upstream communication between nodes is only the video request. The optimization information to be shared between nodes are the λ's and rate break points R_i 's.

3.2. Coordination to Reduce Number of FGA-FEC Decode/re-code Nodes

An extreme case of the distributed FGA-FEC is hop-by-hop FGA-FEC decode/re-code, i.e. do FGA-FEC decode/re-code at each DSN. This method can provide the best possible video quality for diverse users in a congested backbone, since the protection is specifically optimized for each individual user. One may argue that it is not necessary to do the FGA-FEC decode/re-code at each DSN, if only part of the network is congested. For example, we already have shown that if the network backbone is not congested, our simpler FGA-FEC adaptation can also provide a near optimal solution if the user diversity is not too great. Combining these two ideas together, we do FGA-FEC decode/re-code at some selected nodes, while still providing similar video quality to hop-by-hop FGA-FEC decode/re-code. So here, we apply our OM-FEC concept to the network backbone to divide the network into segments and hence minimize the number of FGA-FEC decode/re-code nodes. We use the topology of Fig. 8 to illustrate the idea. In Fig. 8, if there is no congestion in the backbone, we can directly encode a video using FGA-FEC only at the server and then use the simpler FGA-FEC adaptation inside the network. If some links in the backbone are congested, we need to identify them and apply FGA-FEC decode/re-code functions at the boundary nodes of these congested links. We still use local information to decide upon the congested links.

3.3 EXPERIMENTS AND SIMULATIONS

We did experiments and simulations to show the efficiency of our proposed distributed FGA-FEC scheme using videos *Foreman* CIF, 18 GOPs, *Mobile*, SIF, 8 GOPs and *Football*, SIF, 7 GOPs, with 16 frames/GOP in all three sequences. The source encoder is MC-EZBC, $N = 64$. The proposed scheme includes two approaches (1) a coordination method between optimization processes running at adjacent nodes to reduce computation, (2) using the OM-FEC concept to reduce the number of FGA-FEC decode/re-code nodes while still maintain near optimal video quality, measured in terms of PSNR. Regarding the first approach, we compare the number of iterations need to reach the optimization stop point using "full search," "search with previous GOP," and "search with neighbor." For the later approach, we compare with hop-by-hop FEC decode/re-code scheme and show that we can get similar video quality, but use fewer node involved in FEC decode/re-code. Finally, we measured the CPU time of using the distributed FGA-FEC algorithm to show the efficiency.

3.1. Optimization Performance

We solve the optimization problem using a bisection search to find the best λ value. We need find a stopping criteria. We use $| R_{total} - B| < 1/N \times B$ and $|\lambda - \lambda\text{previous}| < \varepsilon$, i.e. the total rate should be close to the available bandwidth and λ is not changing much, where ε is a threshold. Intuitively, a larger threshold should correspond to coarser precision. After the optimization, $(N - 1/N \times B) < R_{total} < (N + 1/N \times B)$. If $R_{total} < B$, we need to allocate more video data to R_N to satisfy $R_{total} = B$. If $R_{total} > B$, we need to remove some video data from R_N to satisfy $R_{total} = B$. Experiments show that $\varepsilon = 1\times 10^{-5}$ is a very good choice in that the quality loss is almost negligible.

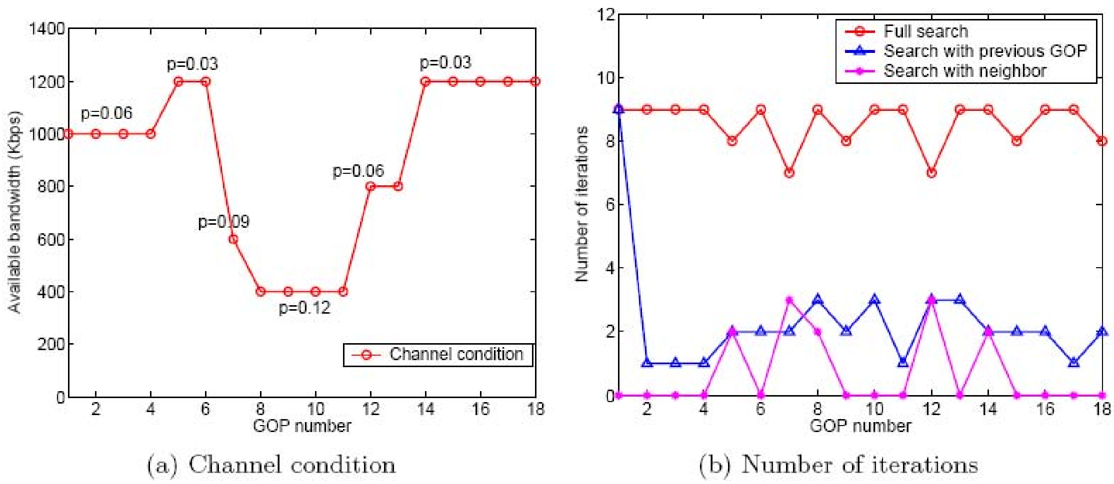


Figure 9. Dynamic Channel Conditions: full search algorithm vs. our our proposed “search with previous GOP” and“search with neighbor,” in terms of number of iterations at a dynamic channel, (a) channel conditions varying over GOP number, (b) the number of iterations to reach optimal stopping point.

In Fig. 9, we compare the full search algorithm with our proposed “search with previous GOP” and “search with neighbor” methods on a dynamic channel, where the channel condition changes over the GOPs as in Fig. 9(a). The corresponding number of iterations to reach the stopping point for the three methods are shown in Fig. 9(b). Here one iteration is defined as one λ step calculation. Initially, we set $\lambda = 1\times 10^{-3}$ in the “full search” method. For full search optimization, the bisection search starts from the initial λ to the optimization stopping point. In the “search with previous GOP” method, the first GOP is the same as full search, we start from an initial λ value 1×10^{-3} and search to the optimization stopping point. After the first GOP, we use the previous GOP final λ (optimal point value) as our starting point to optimize the current GOP for the current network condition. In ”search with neighbor,” we use the same GOP information in previous network conditions from child DSN. For “search with neighbor” method, if the network condition does not change, the optimization value can be used directly without optimization. From Fig. 9, we see that if the channel condition changes, both “search with previous GOP” and “search with neighbor” have similar performance, but when channel condition is statistically consistent, using “search with neighbor” gains over “search with previous GOP,” saving about 2 iterations on average. The results in this section show that the coordination between adjacent nodes can greatly reduce the optimization computation. Full comparisons are given in the VCIP paper [10].

4. CONCLUSIONS

We proposed a two-stage FEC scheme with an enhanced MAC protocol to efficiently support multimedia data transmission over wireless LANs. 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. 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.

In this project, we also devised a distributed FGA-FEC algorithm for video streaming to diverse users on a congested network. We proposed a distributed approach to greatly reduce the computational burden of optimization by exchanging overhead information between adjacent nodes. We extended the idea of OM-FEC to determine the congested links and hence to reduce the number of needed FGA-FEC decode/encode nodes. Here we apply FGA-FEC adaptation whenever permitted and do FGA-FEC decode/re-code only at the edge of congested links. Simulations have shown the performance of the proposed scheme.

REFERENCES

[1] I. V. Bajic and J. W. Woods, "EZBC video streaming with channel coding and error concealment," in *Proc. SPIE VCIP* 2003, Lugano, Switzerland, July 2003.

[2] R. Puri and K. Ramchandran, "Multiple description source coding using forward error correction codes," Proc. 33rd ACSSC, Pacific Groove, CA, October 1999.

[3] S.-T. Hsiang and J. W. Woods, "Embedded video coding using invertible motion compensated 3-D subband filter bank," *Signal Processing: Image Commun.*, pp. 705-724, May 2001.

[4] http://www.hpl.hp.com/research/ssm (not active)

[5] IEEE Computer Society LAN MAN Standard Committee, *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, IEEE Std. 802.11, New York, 1999.

[6] IETF, "RFC 3828: The lightweight user datagram protocol (udp-lite)," July 2004.

[7] network simulator- ns-2; http://www.isi.edu/nsnam/ns/

[8] Y. Shan, I. V. Bajic, S. Kalyanaraman, and J. W. Woods, "Overlay multi-hop fec scheme for video streaming," *Signal Processing: Image Commun.* Vol. 16, pp. 710–727, September 2005.

[9] Y. Shan, I. Bajic, S. Kalyanaraman, and J. Woods, "Overlay multi-hop fec scheme for video streaming over peer-to-peer networks," in *International Conference on Image Processing*, pp. 3133 – 3136, IEEE, Oct. 2004.

[10] Y. Shan, J. W. Woods, and S. Kalyanaraman, "Distributed Fine Grain Adaptive-FEC Scheme for Scalable Video Streaming," Proc. SPIE VCIP, San Jose, CA, Jan. 2008.