The Utility of Hybrid Error-Erasure LDPC (HEEL) Codes for Wireless Multimedia

Invited Paper

S. S. Karande, H. Radha
Michigan State University, Department of Electrical and Computer Engineering
East Lansing MI, 48824 {karandes, radha}@egr.msu.edu

Abstract—**Traditional wireless communication protocols do not relay corrupted packets towards the application layer and neither do they forward such packets over multiple hops. Such an approach can lead to a significant number of packet drops and thus a severe deterioration in performance of high bandwidth applications. Cross-layer protocols which do relay and forward corrupted packets have exhibited substantial promise to mitigate the above problem and thus their utility for wireless multimedia needs to be explored further. Moreover, there is a need to identify efficient channel coding methods for the cross-layer channel. Unlike the traditional schemes, where the channel observed at the application layer is a pure erasure channel, in the cross-layer schemes the application layer channel exhibits hybrid erasure-error impairments. Thus in this paper, we use a rather abstract link-layer model on the basis of which we compare the performance of cross-layer and conventional schemes. We identify the modifications required to be made to RS and LDPC based FEC schemes in order to use them over hybrid erasure-error channels. Finally we compare the considered schemes in terms of video quality using the emerging H.264 video standard. Our video analysis is based on employing a hybrid error-erasure channel coding FEC for the cross-layer schemes versus employing erasure recovery FEC for the traditional protocols. We show that cross-layer schemes can lead to a significant improvement in video quality.**

Keywords- Cross-layer, FEC, Video;

I. INTRODUCTION

In recent years the demand for real-time video applications over wireless networks has increased significantly. As the wireless medium is susceptible to channel impairments, the packet drops, on account of symmetric errors at the link-layer, can be large. Thus in this paper we provide an argument in favor of using Hybrid Erasure-Error Correcting FEC schemes in conjunction with cross-layer protocols that permit the relay of corrupted packets to the application layer. Larzon et al. [1] were the first to highlight the utility of such cross-layer protocols by proposing the UDP-lite protocol. Since then “lite” protocols have been extended to various other communication architectures (e.g. [2] for cellular video, [3] for 802.11b WLANs). However in order to keep the discussion generic and not dependent on a particular implementation (or standard), in this paper we consider three abstract communication schemes (a) transmission over erasure channels, which represents the conventional protocols like UDP (CON) (b) transmission in presence of erasures and errors using a cross-layer design (CLD), which is representative of cross-layer schemes like UDP-lite (c) side-information enhanced transmission in presence of erasures and errors using a cross-layer design (CLDS). Detailed description of these schemes is provided in section II.

Though cross-layer protocols increase the packet throughput, they lead to the existence of errors at the application layer. Previous studies, [1]-[3] have assumed that the probability of bit-error in the corrupted packets is always low enough to render the performance of a cross-layer approach to be better than a conventional one. Such an assumption need not always be valid. Moreover most of the previous studies have not extended the cross-layer approach of allowing the relay of corrupted packets to a multi-hop scenario. The level of corruption in a packet increases as it iteratively undergoes impairments when relayed over multiple wireless hops. Thus the above-mentioned tradeoff needs to be analyzed and studied in greater detail. Thus in [4] we studied the above tradeoff in terms of the application layer channel capacity. In section III, we provide a brief description of some of the relevant analysis.

Forward Error Correction scheme (FEC) used in conjunction with the cross-layer protocols must be capable of hybrid erasure and error recovery. Though algorithms capable of hybrid erasure-error decoding of Reed Solomon (RS) codes have existed for a long time [5], their utility at the application layer especially in a cross-layer scenario is under explored. Similarly, though graph codes and in particular LDPC codes have recently received a lot of attention and have been shown to be capacity achieving over a variety of channels with only symmetric errors [6] and for channels with only erasures [6], the design and performance of these codes in presence of erasures as well as errors is substantially unexplored

Thus as a part of the presented work:

In section IV, we identify suitable channel coding schemes that can be employed in conjunction with the cross-layer protocols. In particular we identify the modification required to RS based FEC so that it can provide efficient performance over the hybrid channel and we also investigate the modifications required to be made to the LDPC decoding algorithms in order to enable them to perform hybrid erasure and error correction.

In section V we use the emerging H.264 standard to compare the performance of the three schemes in terms of the video quality.

Finally we summarize our conclusions in section VI.

II. CHANNEL CHARACTERIZATION

The three communication schemes considered in this paper can be explained by considering a generic Logic Transmission Unit (LTU) as shown in Figure 1. The general packet structure can be segregated into two parts:

1) The header information[1] and 2) The data payload.

In addition to traditional header information (e.g., node addresses), the LTU header contains two sets of check sums CHK-HDR and CHK-DATA. The CHK-HDR checksum is applied to and dependent on the header information only; while the CHK-DATA check sum is applied to and dependent on the data payload only. Hence, under this generic LTU model:

- The conventional (non-cross layer) protocols drop a packet if either of the checksums CHK-HDR, or CHK-DATA is not satisfied. Thus if δ represents the probability that at least a single bit is in error in the header and/or the data payload, then probability of a packet being dropped in a conventional (non-cross layer) protocol because at least one of the check sums, CHK-HDR and/or CHK-DATA, was not satisfied is also given by δ.

- CLD, which represents protocols like UDP-lite [1]-[2], turns the CHK-DATA checksum off and drops the packet only if CHK-HDR is not satisfied. Therefore, a CLD channel exhibits both erasures (due to CHK-HDR violations) and possible errors in some of the delivered packets. It is important to note that (without further information or additional parity bits) the CLD channel receiver does not know which delivered packets are error-free and which packets are corrupted. It only distinguishes between erasures and delivered packets.

Thus if λ represents the probability that at least a single bit is in error in the header, then probability of a packet being dropped in a cross-layer scheme because the check CHK-HDR was not satisfied is also λ. Thus $\delta-\lambda$ represents the probability of a corrupted packet being delivered to a CLD/CLDS channel receiver. Moreover, given a corrupted packet at a CLD/CLDS receiver, let ε represent the probability of having a random bit selected from that packet to be in error. Thus the probability of bit error is given by $(\delta-\lambda)\cdot\varepsilon$. Let p be the conditional probability that a bit in an unerased packet is in error. By definition of the above parameters we can deduce that $p=\dfrac{(\delta-\lambda)\cdot\varepsilon}{(1-\lambda)}$.

- Similar to CLD, a CLDS channel drops a packet only if CHK-HDR is not satisfied. However, in CLDS the CRC-DATA is not turned off but neither is the decision to drop a packet dependent on this checksum. Moreover CHK-DATA and information about the success or failure of this check-sum is made available to the application layer as side information. Therefore, and unlike a CLD receiver, the CLDS receiver can distinguish corrupted packets from error-free packets.

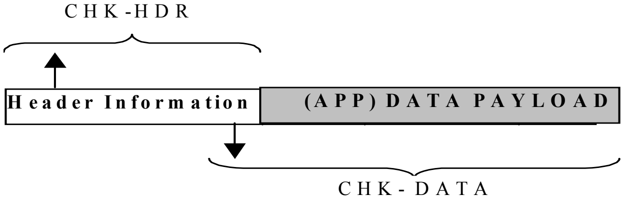


Figure 1. A single Logic Transmission Unit (*LTU*).

Hence, for a cross-layer protocol with side-information (CLDS) let Z be a discrete random variable that takes on three possible outcomes: $S_z=\{0,1,?\}$. Where,

- ***Z*** = ? if the header contains at least single bit error and CLDS drops the packet. Thus $p(Z=?)=\lambda$
- ***Z*** = 0 if a packet contains no errors in the header but contains at least a single bit error in the data
- ***Z*** = 1 if neither the header nor the data payload contain even a single erroneous bit. Thus $p(Z=1)=(1-\delta)$.

III. CAPACITY EVALUATION

A multi-hop wireless channel can be represented as a cascade of channels. For example, a cascade of BEC channels can represent the conventional scheme, where a distinct BEC channel in the cascade represents each link. Similar cascades of BSEC channels can be made for the cross-layer schemes too. However, in case of CLDS it should be noted that the side information Z shall depend on the cumulative errors encountered over all the hops. Thus expressions for capacities over multiple hops are given by equations (1), (2), (3).

The following substitutions in equations (1), (2), (3) convert them into capacity expressions for single wireless link characterized by $\delta,\ \lambda,\ p,\ \varepsilon$.

$$\delta=\delta_1+\sum_{i=2}^{n}\left(\delta_i\cdot\prod_{j=1}^{n-1}\delta_j\right),\quad \lambda=\lambda_1+\sum_{i=2}^{n}\left(\lambda_i\cdot\prod_{j=1}^{i-1}\lambda_j\right)\ \text{and}$$

$$p=\left(\overset{n}{\underset{i=1}{*}}p_i\right),\ \text{(these substitutions imply } \varepsilon=\left(\frac{1-\lambda}{\delta-\lambda}\right)\cdot p\text{)}$$

Thus for most of the remaining paper we find it sufficient to maintain the discussion in terms of $\delta,\ \lambda,\ p,\ \varepsilon$. Transmission over multiple-hops can be represented by higher error/erasure values. Figure 1. shows a comparison of the channel capacities offered by the three protocols considered above. It can be clearly seen that the cross-layer protocols can provide dramatic improvements in capacity when the corruption level in packets is low.

---

[1] In practical implementations the header and CRCHK-HDR might be further partitioned into multiple headers and checksums. In addition, it is noteworthy that we assume that the total number of bits in the header and the total number of bits in the data payload remain exactly identical for all the three communication schemes outlined above.

$C_{CON(n-hop)} = \prod_{i=1}^{n}(1-\delta_i)$	(1)
$C_{CLD(n-hop)} = \left(\prod_{i=1}^{n}(1-\lambda_i)\right)\cdot\left(1-h_b\left(\mathop{*}_{i=1}^{n} p_i\right)\right)$ Note: $a * b = a\cdot(1-b)+b\cdot(1-a)$ by definition	(2)
$C_{CLDS(n-hop)} = \left(\prod_{i=1}^{n}(1-\delta_i)\right)+\left(\prod_{i=1}^{n}(1-\lambda_i)\right)\cdot \left(1-h_b\left(\left(\frac{1-\left(\prod_{i=1}^{n}(1-\lambda_i)\right)}{\left(\prod_{i=1}^{n}(1-\delta_i)\right)-\left(\prod_{i=1}^{n}(1-\lambda_i)\right)}\right)\cdot\left(\mathop{*}_{i=1}^{n} p_i\right)\right)\right)$	(3)

IV. FEC PERFROMANCE AND DESIGN

For all FEC simulations in this section we use a packet block-length of 30, packet size of 500 bytes and coding rate of 0.66 (i.e. 20 message packets in each block). It is worth noting that all the results in this section are expressed in terms of message packet throughput. Thus for all the figures in this section

$$throughput = \frac{(total\ msg.\ pkts.\ recd.\ after\ channel\ decoding)}{(total\ msg.\ pkts.\ transmitted)}$$

As many current deployments of forward error correction schemes for low-delay applications employ Reed Solomon codes it is important to establish the gains of using a cross-layer protocol with an RS based FEC scheme. Traditionally RS codes are employed on packet-based schemes on the basis of a simple interleaving, where an entire block of packets is broken down into multiple code words. In FEC systems designed for channel failures consisting only of packet drops, the length of the codeword is not an important parameter. However for FEC schemes meant to correct erasures and errors the performance improves as the code-length is increased. On account of brevity of space we present only the results of breaking down the packet block into 100 codewords. The RS code is based on $GF(2^8)$ and each codeword consists of 150 symbols. Moreover, each packet contributes 5 symbols to each codeword. The results for the conventional scheme are based on employing RS based erasure recovery. The CLD scheme when employed with RS based FEC always uses an algorithm capable of hybrid erasure-error decoding. The CLDS scheme uses the hybrid-decoding algorithm only when the number of packets affected by channel impairments is greater the number of redundant packets. Else it treats all corrupted/dropped packets equally and employs an erasure-decoding algorithm.

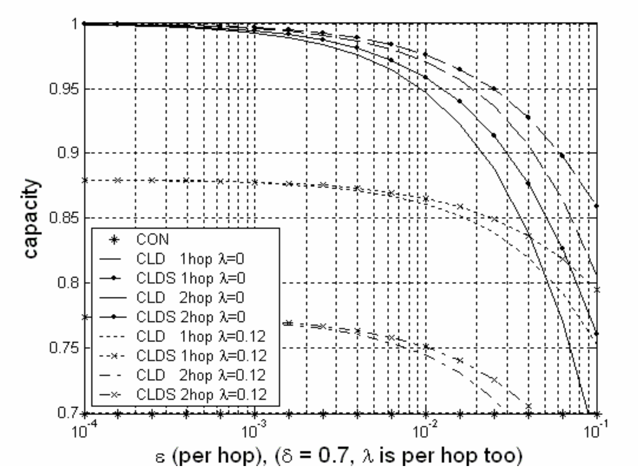


Figure 2. Comparison of channel capacity

Though LDPC (and other similar graph codes) codes have been extensively employed for a variety of channels, their usage at the application layer has been limited. The current erasure correcting LDPC based FEC schemes treat an entire packet as a single symbol. Since an efficient design of a sparse graph code requires the length of the codeword to be large, FEC blocks at the application layer also have to consist of a large number of packets to provide good performance. Thus the research at the application layer has primarily concentrated on design of efficient codes for transfer of bulk data [6]. The advantage of using a symbol of size smaller than the entire packet is minimal, if the channel failures consist only of burst erasures on account of packet drops. However, in a cross-layer scenario a significant advantage can be gained by employing a code based on a smaller symbol size. Thus in all the LDPC based FEC simulations we use a code based on GF(2) and split a packet block into 4 codewords. Each codeword consists 1000 bits from each packet. Thus each codeword is a (30000, 20000) regular LDPC code with degree distribution (3,6).

The LDPC decoding algorithm used in conjunction with the cross-layer protocols is required to handle simultaneous decoding of errors and erasures. The LDEE codes presented in [7] is the only study that we are aware of, that has analyzed the problem of LDPC decoding for errors and erasures. However, as the messages passed in the LDEE decoding algorithm can take only three possible values; the decoding capability of these codes is compromised. Thus we use a decoding algorithm which is based on the soft decoding belief propagation algorithm used in [6] and which does not constrain the messages passed along the graph edges to a few finite discrete values. Thus HEEL decoding is achieved by setting all the erased bits to 0 and setting the apriori probability of the erased bit being in error to 0.5.

The HEEL decoding algorithm used for CLDS is modified to take advantage of the side information provided by CHK-DATA. If the CHK-DATA of a particular packet is satisfied than we set the apriori probability of the bits in this

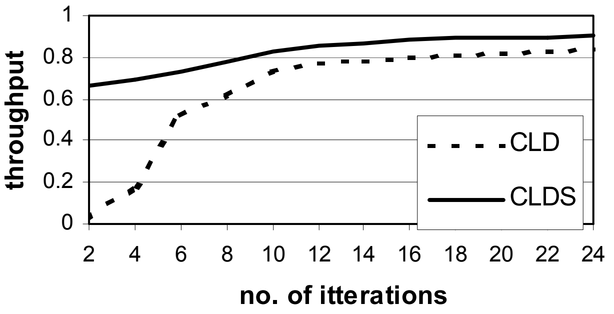


Figure 3. Improvement due to side-information.

packet being in error to 0. Thus the iterative decoding algorithm does not change the value of the bits that have been already received correctly. Even when the decoding algorithm does not converge to a codeword, it is possible for the decoding to correct some errors; and hence we identify the packets that were initially corrupted but are rendered error free after FEC decoding by updating the CRC-DATA checksum. Figure 3. identifies the precise effect of using such side-information.

Finally it should be highlighted that the FEC schemes that we are employing are systematic in nature and thus in the event of a block-decoding failure, message packets that were received without any corruptions can be forwarded to the application. However in a CLD scheme as the CHK-DATA is turned off, in the event of a decoding failure the entire packet block is dropped.

Due to brevity we cannot present all the results for FEC performance, however the key observations were as follows. It was observed that when the value of δ is small then the advantage of using a cross-layer scheme is reduced. The RS based schemes are susceptible to increase in the value of ε, while the LDPC schemes are more susceptible to increase in packet drops due to header corruption. It was observed that for a given δ, λ the utility of side information for HEEL decoding increases as the level of corruption increases. In addition it was observed that under severe channel conditions the penalty for not facilitating CHK-DATA side-information to higher layers can be very severe.

Figure 4. shows that under severe channel conditions the performance of LDPC based FEC schemes is significantly better than RS-based schemes (with conventional or cross-layer protocols). It also demonstrates the severe drop in performance of RS based FEC scheme over CLD due to lack of CHK-DATA side information. In most realistic scenarios the average channel conditions are not so severe and in particular the corruption level of packets when the transmission is over a single hop is not very high. Thus under less severe conditions even RS based cross-layer schemes can provide significant improvement over conventional protocols employing pure erasure recovery. This should be clearly evident from Figure 5.

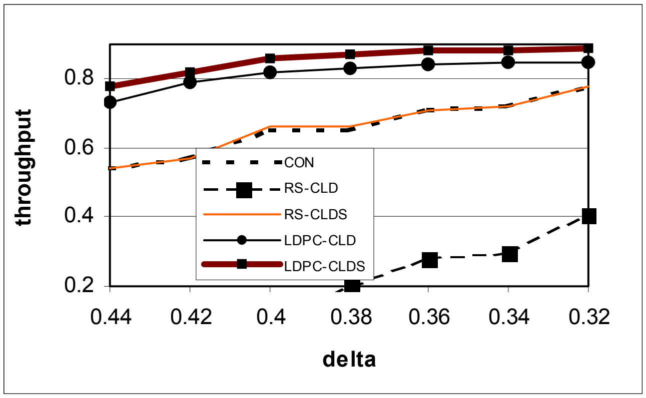


Figure 4. FEC throughput for severe channel conditions i.e. when the channel coding rate is greater than the channel capacity C_{CON} of the conventional scheme ($\lambda = 0.05$, $\varepsilon = 0.05$)

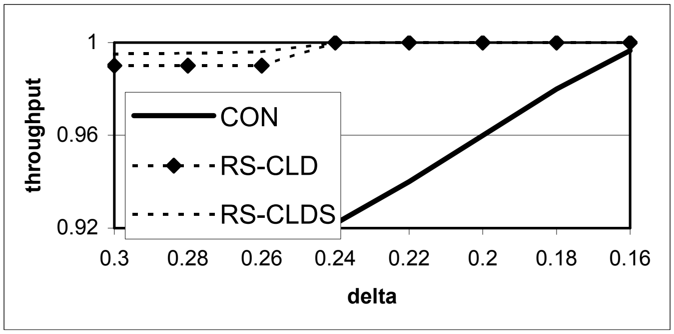


Figure 5. Throughput of RS based FEC for non-severe channel condtions i.e. channel coding rate is lesser than C_{CON} ($\lambda = 0.05$, $\varepsilon = 0.02$)

V. VIDEO SIMULATIONS

Discussions in previous sections have concentrated on exhibiting the capacity and throughput improvements that can be achieved using cross-layer protocols. At this stage, it is necessary to clearly establish the advantage of using the cross-layer approach in terms of the quality of video available at the receivers. We use the emerging H.264/JVT video standard for all the video simulations in this section. The "stefan" test sequence used here has a "cif" frame size and is encoded at a frequency of 30 frames/sec. We used a constant quantization size of QP = 16 to achieve a source encoding of 1.8Mbps. The results presented in this section are a subset of the examples we considered and on account of brevity of space we are unable to provide more detailed results.

Figure 6. shows the results of simulations on a 3-hop scenario using RS based FEC. The FEC packet block consists of 50 packets, of which 20 are message packets. Thus the coding rate 0.4, is maintained at a reasonably low value to ensure that the channel capacity is not lesser than the coding rate for the conventional scheme at least for the first few hops. It can be seen that by the third hop the reduction in capacity of the conventional scheme in comparison to the cross-layer

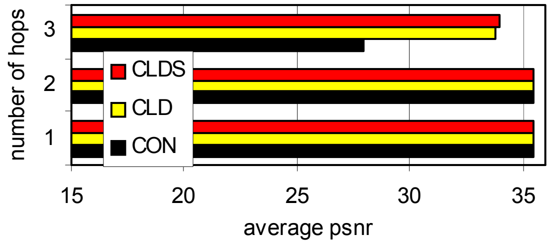


Figure 6. Quality Degradation over multiple hops

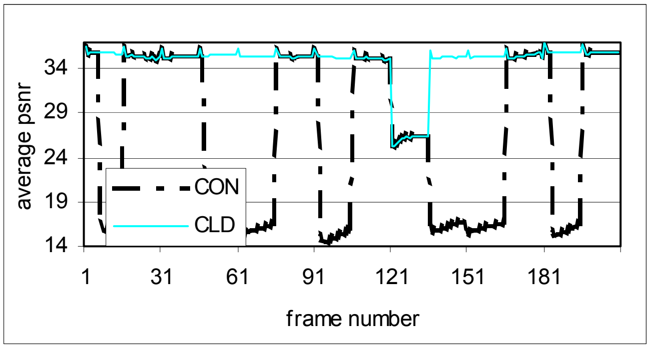
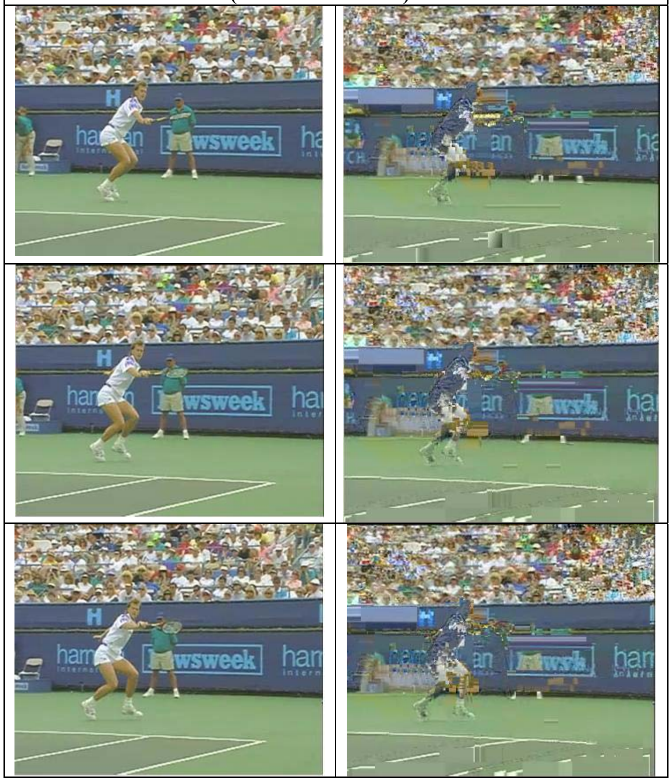


Figure 7. Temporal PSNR based comparison for RS based FEC over 3 Hops. ($\delta = 0.2$, $\lambda = 0.06$, $\varepsilon = 0.02$ per hop)

RIGHT: CLD (FRAMES 191-193) LEFT: CON



schemes is significant. It should be noted that on the first 2 hops the cross-layer schemes could have provided 100% reliability at higher coding rates too and thus a coding rate of 0.4 is limiting the performance of the cross-layer schemes.

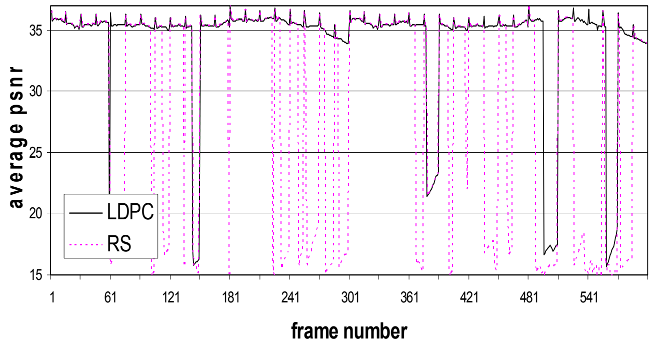


Figure 8. LDPC v/s RS psnr based temporaL comparison for CLD scheme. (N, K) = (30, 20), δ =0.30, λ =0.05 ε =0.05. Average PSNR for a) RS = 28.27dB b) HEEL = 34.09dB

Figure 7. provides a snapshot of the temporal comparison of the video quality provided by CON and CLD at hop-3. Corresponding picture frames have been included to underline the difference in distortion and facilitate subjective evaluation. All the standard error-resilience features are activated during the source encoding, thus on account of a complete picture frame being lost, we repeat the previous picture frame, thus in high loss scenarios 'block-distortion' is often converted into 'motion jerkiness'.

It should again be highlighted that the results based on RS can be improved upon by HEEL, Figure 8. clearly establishes the comparative performance of LDPC v/s RS in terms of video quality.

VI. CONCLUSION

The LDPC and RS decoding algorithm were modified to provide hybrid decoding and also to take advantage of side-information. It was shown that the combination of HEEL with a cross-layer approach provides the best option among the considered schemes. Finally H.264 based video simulations were used to clearly establish that cross-layer schemes could provide significant improvement in video quality.

REFERENCES

[1] L. Larzon, M. Degermark, and S. Pink, "UDP Lite for Real Time Multimedia Applications," ICC, Vancouver, June 1999.

[2] A. Singh, A. Konrad, A. D. Joseph, "Performance Evaluation of UDP Lite for Cellular Video," NOSSDAV, 2001.

[3] S. A. Khayam, S. S. Karande, H. Radha and D. Loguinov, "Performance Analysis and Modeling of Error and Losses over 802.11b LANS for High-Bitrate Real-Time Multimedia," Signal Processing: Image Communication, vol. 18, Aug 2003.

[4] Shirish Karande and Hayder Radha, "Does Relay of Corrupted Packets Lead to Capacity Improvement?," IEEE Wireless Communications and Networking Conference (WCNC), March 2005.

[5] S. A. Vanstone and P. C. van Oorschot, "An Introduction to Error Correcting Codes with Applications," Kluwer Academic Publishers.

[6] IEEE Tran. on information theory, Special Issue on codes on graphs and iterative algorithms, vol. 47, Issue 2, Feb 2001.

[7] M. Mitzenmacher, "A Note on Low Density Parity Check Codes for Erasures and Errors," SRC Tech. Note 1998-017, COMPAQ, 1998.