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Optimal Bit Allocation for Hybrid Scalable/Multiple-Description Video Transmission Over Wireless Channels

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ABSTRACT

In this paper, we consider the problem of optimal bit allocation for wireless video transmission over fading channels. We use a newly developed hybrid scalable/multiple-description codec that combines the functionality of both scalable and multiple-description codecs. It produces a base layer and multiple-description enhancement layers. Any of the enhancement layers can be decoded (in a non-hierarchical manner) with the base layer to improve the reconstructed video quality. Two different channel coding schemes (Rate-Compatible Punctured Convolutional (RCPC)/Cyclic Redundancy Check (CRC) coding and, product code Reed Solomon (RS)+RCPC/CRC coding) are used for unequal error protection of the layered bitstream. Optimal allocation of the bitrate between source and channel coding is performed for discrete sets of source coding rates and channel coding rates. Experimental results are presented for a wide range of channel conditions. Also, comparisons with classical scalable coding show the effectiveness of using hybrid scalable/multiple-description coding for wireless transmission.

Keywords: Hybrid scalable/multiple-description video coding, Wireless video transmission, Optimal bit allocation, R-D optimization, Unequal error protection

1. INTRODUCTION

With the advent of personal communication services, the diversity in bandwidth availability for users increased, which has also motivated more work to be done in the field of layered video coding combined with joint source-channel coding over wireless systems. In this paper we consider the problem of operational rate-distortion optimal hybrid scalable/multiple-description video transmission over wireless channels.

Layered video coding has been classified into two main categories, Scalable Coding (SC)[1–7] and Multiple Description Coding (MDC).[8–10] The former produces uncorrelated layers of different importance that have a hierarchal structure. The base layer is the most important layer and is required for decoding, while the enhancement layers tend to improve the video quality when decoded along with the base layer. For the latter, layers produced can be decoded independently (using some redundancy between the layers). A combination of SC and MDC has been proposed in Ref. 11, 12. Also, recently a Hybrid Scalable/Multiple-Description Codec (HSMDC) has been proposed in Ref. 13, 14, which is aimed to combine the advantages of both SC and MDC. Using HSMDC, the encoded bitstream consists of a base layer and multiple-description enhancement layers. Here, any of the multiple-description layers can be decoded with the base layer to enhance the decoded video quality. Again, this is due to the added redundancy within the enhancement layers.

In this paper, we propose a wireless transmission system for layered video over a flat-fading Rayleigh channel. HSMDC codec is used for video coding and two different schemes for forward error correction (FEC) coding using, i) Rate-compatible punctured codes (RCPC)[15]/Cyclic redundancy check (CRC) code,[16] and, ii) the product code structure consisting of RCPC/CRC and erasure-correction systematic Reed-Solomon (RS) codes.[17] These

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channel coding methods provide unequal error protection (UEP) among different layers of the encoded video. However, it is important to mention here that in the first scheme proposed here, even a single error (after channel decoding) in the received packet would result in the loss of the corresponding layer of that frame. This will adversely affect the decoded video quality. To address this, in the second scheme we use the erasure-correction capabilities of the RS codes in a product code structure. In this coding scheme, the row code consists of CRC and RCPC code while the column code is an erasure-correction systematic RS code. Each layer (of the corresponding frame) is first divided into packets of equal size and is encoded using RS codes. All packets are subsequently protected using RCPC/CRC code giving unequal protection among all the layers. At the receiver, row-wise Viterbi decoding is done and erroneous video packets after CRC detection are marked as "erased", as opposed to the immediate loss of the corresponding layer as in the previous scheme. After receiving all the packets (for a layer of the corresponding frame), the column-wise RS decoding is performed. If the number of "erased" packets in a layer is more than $2t = n - k$, the layer is dropped. The decoded bitstream is then source decoded to get the reconstructed video sequence.

The problem of video transmission over wireless channels under a bandwidth constraint is challenging due to the inherent multipath fading characteristics. Also, the distortion of the decoded video is a function of both the channel errors and the lossy compression. For all of the above reasons, it is not trivial how to allocate the bit rate between source and channel coding. The problem is even more complex if layered video is considered, where layers are of different importance. Then, besides bit allocation between source and channel coding, bits should be allocated between the video layers for both source coding and channel coding. In this paper, we formulate this problem as a constrained optimization problem and solve it using the Lagrangian multiplier method for a given set of source rates and channel rates and channel conditions.

In related work, joint source-channel coding for motion-compensated DCT-based SNR scalable video is studied in Ref. 18, 19, in which an algorithm is proposed to allocate the available rate between scalable layers, and within layers between source and channel. H263+ is used as the source codec and results are shown for two and three scalable layers. In Ref. 20, it is shown that, in scalable subband coding combined with channel coding, excellent results will be obtained if UEP is applied to different bits in the compressed bitstream. An algorithm for distortion minimization using the universal distortion-rate characteristics is presented in Ref. 21. Different algorithms are proposed in Ref. 22, to allocate bit rate between source and channel coding of scalable video, over a noisy channel. The problem of joint source/channel transmission over lossy channel is studied in Ref. 23 for MPEG-4 video codec. The advantage of decoding any of the multiple-description enhancement layers using HSMDC and its performance as compared to SC is studied in Ref. 13. However in this work, we examine the application of HSMDC for wireless video transmission and propose a joint source-channel coding framework for optimal bit allocation.

The rest of the paper is organized as follows. Section 2 gives an overview of the hybrid scalable/multiple-description video codec used in this work. Section 3 presents an overview of the channel model and channel codes used here. Section 4 discusses the optimal bit allocation for both the channel coding techniques used here and section 5 presents the experimental results. Section 6 concludes the paper.

2. HYBRID SCALABLE/MULTIPLE-DESCRIPTION CODEC

There are two main paradigms for layered video coding: Scalable Coding (SC) and Multiple Description Coding (MDC). A scalable codec produces a bitstream that can be partitioned into layers that form a hierarchy. One of the layers is called the base layer and is required for video reconstruction. The other layers, called enhancement layers, can be decoded along with the base layer and improve the decoded video quality. However, in order for an enhancement layer to be useful in decoding, the base layer and all hierarchically higher enhancement layers are needed at the decoder. In contrast with scalable codecs, multiple-description codecs produce non-hierarchical layers that can be decoded independently and produce a video sequence of a certain quality. Therefore, any layer that is received by the decoder is used in the reconstruction. In order for this to be possible, the multiple description layers need to share some information, thus the layers are correlated. This correlation causes a decrease in coding efficiency.

In this work, we have used a Hybrid Scalable/Multiple-Description Codec (HSMDC) as proposed in Ref. 13. HSMDC combines the advantages of both the SC and MDC paradigms, such that it produces a bitstream

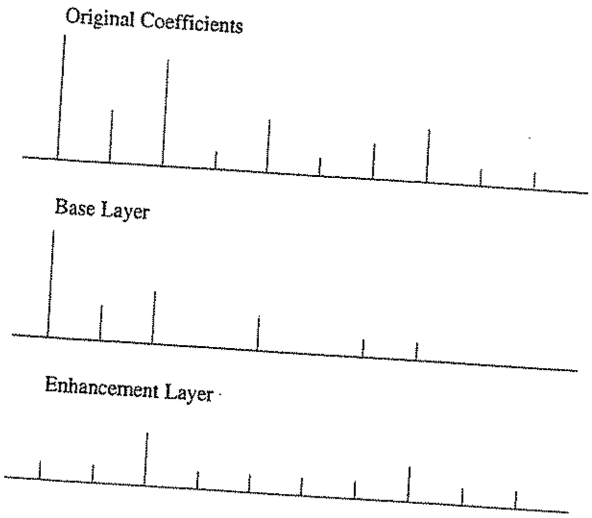

Figure 1. Partitioning of DCT coefficients for SNR scalability

that consists of a base layer and several multiple-description enhancement layers. As in SC, the base layer is required for video reconstruction. In addition to the base layer, one or more received multiple-description enhancement layers can be used in the decoding and improve video quality. Thus, in contrast with SC, here any received enhancement layer is useful in decoding (in a non-hierarchical manner) as long as the base layer has been successfully received. This is due to the added redundancy within the multiple-description enhancement layers which is parameterized by α where $1 \leq \alpha \leq 2$. $\alpha = 1$ corresponds to no added redundancy while $\alpha = 2$ indicates completely redundant (exactly same) enhancement layers. To illustrate clearly, if we consider a video encoded with a base layer and two multiple-description enhancement layers using HSMDC, an increase in the value of α translates in an increase of the PSNR if the base layer and only one of the enhancement layers is decoded. However, decoding all the layers results in the decrease of the PSNR as compared to SC. It is also shown that the compression efficiency of HSMDC is better than that of MDC and is close to that of SC. This is due to the fact that in HSMDC only the enhancement layers need to be correlated and the correlation between enhancement layers doesn't need to be as high as in the case of MDC since base layer needs not be correlated with any other layers. Thus, HSMDC relaxes the hierarchy of SC by only requiring the base layer, containing the most important information to be successfully received and provides non-hierarchical enhancement layers at the expense of a small reduction in compression efficiency. The proposed codec in Ref. 13 is based on the architecture of the H.263 video compression standard. However, any motion-compensated DCT-based codec can be used as a basis.

The Hybrid Scalable/Multiple-Description algorithm operates in two steps. It is first assumed that the DCT of the Displaced Frame Difference (DFD) (or the intensity for intra blocks) is taken and quantized. Then, during the first step, the base layer layer is constructed for each block by subtracting a suitable value from each quantized coefficient (see Fig. 1). The subtracted values then become the enhancement layer. The determination of the subtracted values is optimal in the operational rate-distortion sense. In the second step of the algorithm, the enhancement layer obtained in the first step is converted into two multiple-description enhancement layers by selecting a threshold for each block and duplicating into both descriptions the quantized coefficients with values equal to or greater than the threshold while alternating between descriptions the other coefficients, in a fashion similar to the algorithm in Ref. 9. The experimental results in Ref. 13 clearly demonstrate the functionality of having multiple description enhancement layers that comes at the expense of a slight decrease of the PSNR when using all layers in the decoding. In this work, HSMDC performance over wireless channels is compared with SC.[5]

3. CHANNEL MODEL AND CODING

3.1. Channel Model

Binary phase shift keying (BPSK) is used for signal modulation and a flat-fading Rayleigh channel with additive white gaussian noise (AWGN) and perfect interleaving (i.e., we assume that the samples of the Rayleigh random process ψ_k are independent identically distributed (i.i.d.)) is modeled for the transmission. The discrete-time equivalent model is:

$$r_k = \psi_k s_k + n_k \tag{1}$$

where r_k is the received sample for the kth symbol, s_k is the transmitted symbol $\left\{\sqrt{E_b}, -\sqrt{E_b}\right\}$ where E_b is the transmitted bit energy, ψ_k is a complex Rayleigh distributed random variable and n_k is complex AWGN $N(0, \frac{N_o}{2})$. The SNR of the channel is defined as $\frac{E_b}{N_o}\mathrm{E}\left\{|\psi_k|^2\right\}$, where $\mathrm{E}\{.\}$ is the expectation operator.

3.2. Forward Error Correction

We have used two channel coding techniques employing, i) RCPC codes[15]/CRC code,[16] and, ii) the product code structure consisting of RCPC/CRC and systematic RS code.[17] These coding schemes are used to provide UEP to the layered video bitstream.

3.2.1. RCPC Codes

In both the channel coding schemes mentioned above, RCPC codes[15] are used to provide the UEP to the bitstream. The rate of a convolutional code is defined as k/n where k is the number of input bits and n is the number of output bits. For variable rate coding, a higher rate code can be obtained by *puncturing* the output of a "mother" code of rate $1/n$. For rate compatibility, higher rate codes are chosen to be subsets of the lower rate codes. Decoding of the convolutional codes is carried out by the Viterbi algorithm.

3.2.2. RS Codes

Reed-Solomon[17] codes are a subset of BCH codes and are linear block codes. RS code is specified as $RS(n,k)$ with s-bit symbols. This means that the encoder takes k data symbols of s bits each and adds parity symbols to make an n symbol codeword. There are $n-k$ parity symbols of s bits each. An RS decoder can correct up to t errors and $2t$ erasures, where $2t = n-k$. For the second scheme proposed here, erasure-correction systematic RS codes are used to provide UEP for different layers.

3.2.3. CRC Codes

CRC codes are used in this work for error detection. Details on CRC codes can be obtained from Ref. 16.

4. OPTIMAL BIT ALLOCATION FOR WIRELESS VIDEO TRANSMISSION

4.1. Scheme 1:FEC Using RCPC/CRC

4.1.1. System Setup

Under this scheme, the source codec produces a layered video bitstream with L layers, i.e., a base layer and $L-1$ enhancement layers. Here, each layer (of every frame) is considered as one packet and is then channel coded using RCPC/CRC code with UEP from a given set of channel rates. The packets are transmitted over a flat-fading Rayleigh channel with AWGN. At the receiver, each channel-coded packet is decoded using the Viterbi decoder and any erroneous packets are dropped after CRC detection. The decoded bitstream is then fed to the source decoder to get the reconstructed video sequence.

4.1.2. Optimal Bit Allocation

The problem we address is as follows: Given an overall transmission bitrate R_{budget}, the goal is to optimally allocate R_{budget} between source and channel coding over all scalable layers, such that the overall distortion D_{s+c} is minimized, i.e.,

$$\min D_{s+c} \quad s.t. \quad R_{s+c} \leq R_{budget}, \tag{2}$$

where R_{s+c} is the total bitrate available for both source and channel coding for all layers. The distortion caused by the source coding is due to quantization and is deterministic while the distortion due to channel errors is stochastic. Therefore, the total distortion is also stochastic and the expected value of it is used.

For L layers, R_{s+c} is defined as

$$R_{s+c} = \sum_{l=1}^{L} R_{s+c,l}, \tag{3}$$

where $R_{s+c,l}$ is the combined source and channel rate for layer l and is defined by

$$R_{s+c,l} = \frac{R_{s,l}}{R_{c,l}}, \tag{4}$$

where $R_{s,l}$ and $R_{c,l}$ are the individual source and channel rates for layer l, respectively, taken from a discrete set of admissible rates . It should be emphasized that $R_{s,l}$ is in bits/s and $R_{c,l}$ is dimensionless. Now, (2) can be rewritten as follows

$$\min D_{s+c} \quad s.t. \quad \sum_{l=1}^{L} \frac{R_{s,l}}{R_{c,l}} \leq R_{budget}. \tag{5}$$

For the hybrid codec (HSMDC) used in this work, the total expected distortion D_{s+c} is a function of the total rate allocated to each layer and the parameter α that determines the added redundancy. It can be expressed as

$$D_{s+c} = D_{s+c,B}\left(R_{s+c,B}\right) + D_{s+c,E}\left(R_{s+c,B}, R_{s+c,E}, \alpha\right), \tag{6}$$

where $D_{s+c,B}$ and $R_{s+c,B}$ are the expected distortion and the total rate for the base layer, respectively. $D_{s+c,E}$ is the expected *differential distortion*[18] due to multiple-description enhancement layers which is a function of $R_{s+c,B}$, enhancement layer rates $R_{s+c,E}$ and α. In the absence of channel errors, only the distortion for base layer would be positive and the distortions for all other layers would be negative since inclusion of these layers reduces the mean squared error (MSE).

However, for the scalable codec (SC) used here, the total expected distortion is dependent only on the rates allocated to all the layers and can be written as

$$D_{s+c} = D_{s+c,B}\left(R_{s+c,B}\right) + D_{s+c,E}\left(R_{s+c,B}, R_{s+c,E}\right). \tag{7}$$

The problem in (2) is a constrained optimization problem and is solved as an unconstrained one by using the Lagrangian method as follows

$$J(\lambda) = D_{s+c} + \lambda R_{s+c}, \tag{8}$$

where λ is the Lagrangian multiplier. The solution to this problem, R^*_{s+c} and hence D^*_{s+c}, is also the solution to the constrained problem of (2) if and only if $R^*_{s+c} = R_{budget}$. In practice, since there is only a finite set of choices for source and channel rates, it is not always possible to exactly meet R_{budget}. In this case, the solution is the bit rate that is closest to R_{budget} while being lower than R_{budget}. By varying λ from zero to ∞, the result of (8) will trace out the operational rate-distortion curve for the system. For each combination of available source and channel rates at all layers, a set of operating points are obtained. The convex hull of these operating points is denoted by D^*_{s+c}, that is,

$$D^*_{s+c}\left(R_{s+c,1}, \ldots, R_{s+c,L}\right) = C\left(D_{s+c}\left(R_{s+c,1}, \ldots, R_{s+c,L}\right)\right), \tag{9}$$

where $C(.)$ represents the operational rate-distortion function (ORDF).

One way to proceed is to experimentally obtain the expected distortion for all possible combinations of source and channel coding rates and all possible channel conditions. However, this may become prohibitively complex for even a small set of admissible source and channel rates and channel conditions. Thus, we choose to solve this in a two step process as described below.

1. Given a set of parameters for the channel SNRs and channel coding, the probability of bit error, P_b, is calculated for the set of channel rates of interest. It establishes a reference as to the performance of the channel coding over the particular channel with the given parameters. Furthermore, this channel performance analysis needs to be done only once.
2. Towards calculating the impact of the errors due to both source coding and channel transmission on a set of data, it is realized that the total distortion D_{s+c}, given a particular set of source coding rates for all the layers, is a function of bit-error rate, P_b (obtained as above for a particular channel condition and a channel coding rate) and size of the layer. Thus, D_{s+c} is obtained experimentally by corrupting each layer with independent errors with the probability given as

$$LP_{l,f} = 1 - (1 - P_b)^{N_{l,f}}, \tag{10}$$

where $LP_{l,f}$ is the probability of losing (dropping) layer l of frame f and $N_{l,f}$ is the size (bits) of layer l of frame f. The bitstream is then decoded and the mean squared error (MSE) is computed. The experiment is repeated many times (in our case, 20 times).

4.2. Scheme 2: FEC Using Product Code RS+RCPC/CRC

4.2.1. Setup

As compared to the scheme proposed in the previous section, this scheme differs only in the channel coding structure. This method employs a product code structure which can be described as a two-dimensional code constructed by encoding a rectangular array of data with one code along rows and with another code along columns. In the product code used here, the row code consists of CRC and RCPC code while the column code is an erasure correction systematic RS code. The structure of the product code is depicted in Fig. 2. Here the product code is applied on a frame-by-frame basis. Each layer (of the corresponding frame) is first divided into packets of equal size and is encoded using RS codes. All packets are subsequently protected using RCPC/CRC code giving unequal protection among all the layers. In this work, we have used a fixed as well as variable RS rates for all layers.

As in the previous section, a layered video is produced which is protected using the product code RS+RCPC/CRC. At the receiver, row-wise Viterbi decoding for RCPC codes is done and erroneous packets after CRC detection are marked as "erased". After receiving all the packets (for a layer of the corresponding frame), the column-wise RS decoding is performed. As we know, block of data encoded using (n, k) RS code can correct up to $2t = n - k$ erasures, hence if the number of "erased" packets in a layer are more than $2t$, the layer is dropped. The decoded bitstream is then source decoded to get the reconstructed video sequence.

4.2.2. Optimal Bit Allocation

Again, the objective here remains the same, i.e., to optimally allocate the resources and to minimize the average distortion (MSE) under a transmission rate constraint and given channel conditions, as given in (2) and (8).

To obtain the expected distortion for the given set of source and channel rates and channel conditions, we use the same two step process of first getting the bit error probability P_b and then obtaining the total distortion D_{s+c} experimentally using simulations as described in the previous section. However, to calculate D_{s+c}, first the packet loss probability is calculated as given below.

$$PLP_{l,f} = 1 - (1 - P_b)^{(N_{l,f}/k)} \tag{11}$$

where $PLP_{l,f}$ is the probability of a packet of layer l of frame f being erroneous (and hence being marked as "erased") after Viterbi and CRC decoding. Also, as all the packets of the corresponding layer and frame are

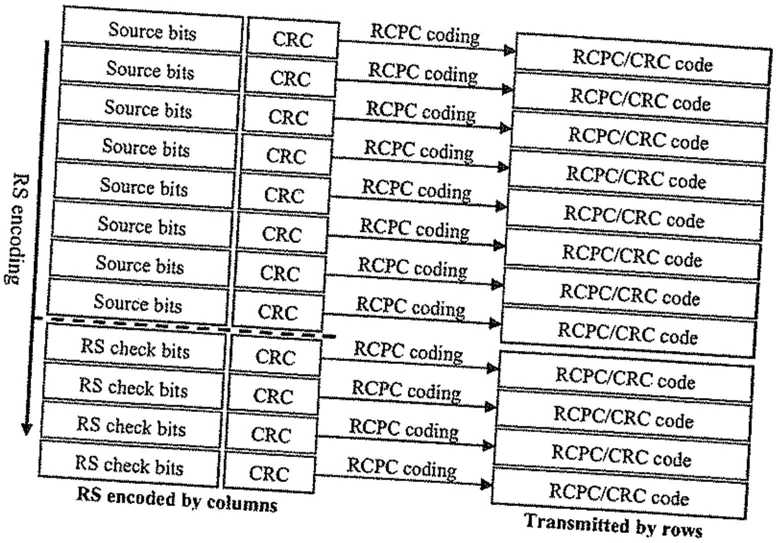

Figure 2. Structure of RS and RCPC/CRC product code

protected equally, this probability is same for all of them. $N_{l,f}$ is the size (bits) of layer l of frame f and k is the number of packets that a layer is divided into.

Further the bitstream is corrupted with independent errors with the probability now given as

$$LP_{l,f} = \sum_{i=k+1}^{n} \binom{n}{i} (PLP_{l,f})^{i}(1 - PLP_{l,f})^{(n-i)} \tag{12}$$

where $LP_{l,f}$ is the probability of losing (dropping) layer l of frame f and $i = k+1, \ldots, n$ is the number of packets out of n RS packets detected as "erased". The bitstream is then decoded and the MSE is computed. The experiment is repeated many times (in our case, 20 times).

5. EXPERIMENTAL RESULTS

In this section we present experimental results using the "Foreman" and "Akiyo" color sequences (QCIF format). The performance of HSMDC is compared with SC, i.e., optimal single-pass SNR scalable codec as proposed in Ref. 5. Both the source codecs are used to encode the video sequences into three layers, a base layer and two enhancement layers. It is also important to mention that both the source codecs produce the identical base layer and hence, for comparison purposes the base layer is always assumed to be transmitted error-free. For HSMDC, three different values of α={1, 1.2, 1.4} (for different amount of redundancy) are used. Experiments are performed for a wide range of channel conditions, $SNR = \{10, 12, 14, 16, 18\}\ dB$.

Various sets of source coding rates are used which are hereafter mentioned in the following manner,

$$SR = \{R_{base}, (R_{l1}, R_{l2})_1, ..., (R_{l1}, R_{l2})_Z\},$$

where R_{base} is the source rate (kbps) for the base layer, R_{l1} and R_{l1} are the source rates (kbps) for the two enhancement layers and Z is the total number of enhancement layers source rates considered here. To encode the video sequence using HSMDC, two sets of admissible source coding rates used are

$$SR_{H1} = \{32, (16, 16)_1, (24, 24)_2, (32, 32)_3, (48, 48)_4, (64, 64)_5\}.$$
$$SR_{H2} = \{60. (15, 15)_1, (25, 25)_2, (30, 30)_3, (34, 34)_4, (44, 44)_5, (60, 60)_6\},$$

Similarly, using optimal SC, the admissible sets of source rates used are

$$SR_{S1} = \{32, (16, 16)_1, (24, 24)_2, (32, 32)_3, (48. 48)_4, (64, 64)_5\},$$
$$SR_{S2} = \{60, (25. 20)_1, (30, 24)_2, (41, 16)_3, (41, 40)_4, (60, 48)_5, (60, 60)_6\},$$

For the first channel coding scheme (RCPC/CRC), the admissible channel coding rates used for the two enhancement layers are $\{\frac{1}{2}, \frac{2}{3}, \frac{4}{5}, \frac{8}{9}\}$. These rates are also used for the product code (RS+RCPC/CRC) scheme along with a fixed RS rate $\{\frac{8}{12}\}$ or variable RS rates $\{\frac{8}{10}, \frac{8}{12}, \frac{8}{14}\}$.

In Figs. 3, 4, 5 and 6, a comparison of optimal rate-distortion (R-D) functions is shown for the "Foreman" sequence using the RCPC/CRC channel coding scheme and different sets of source rates. It is shown that HSMDC with $\alpha = 1$ and $\alpha = 1.2$ outperforms the scalable codec for all the transmission rates and channel SNR values under consideration. However, HSMDC with $\alpha = 1.4$ shows quite similar rate-distortion performance as compared to the scalable codec. Similar observations can be made from Figs. 7 and 8 where the "Akiyo" sequence is used for comparison.

Using product code (RS+RCPC/CRC) scheme with fixed RS rate=$\frac{8}{12}$, Figs. 9, 10 and 11, show the R-I performance similar to RCPC/CRC scheme, i.e., HSMDC with $\alpha = 1$ and $\alpha = 1.2$ still outperforms the scalabl codec for all the given transmission parameters. Figs. 12, 13, 14, 15 and 16 present the optimal R-D curves usin product code with variable RS rates, i.e., both RCPC and RS are used for UEP. It is shown that HSMDC fo all α values (including $\alpha = 1.4$) under consideration outperform scalable codec. Also, for SNR={10,12} dB, th product code scheme proves to give a better R-D performance as compared to RCPC/CRC scheme. The reaso for this is the erasure correction capability of the RS codes. However for SNR={16,18} dB, higher PSNR valu (after decoding) can be obtained for the same given rate using RCPC/CRC as compared to the product co scheme. Thus, we can say that using product code is more beneficial when transmitting video over low SN channels. This can be observed clearly in Figs. 17 and 18.

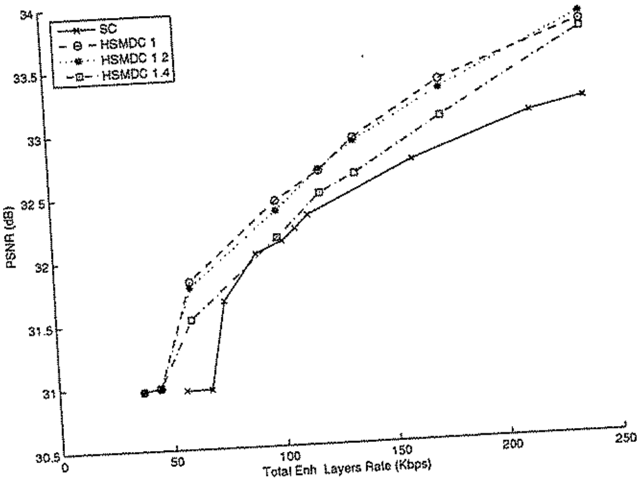

Figure 3. Comparison using "Foreman" sequence with RCPC/CRC scheme for $\{SR_{H2}, SR_{S2}\}$ and SNR=12 dB.

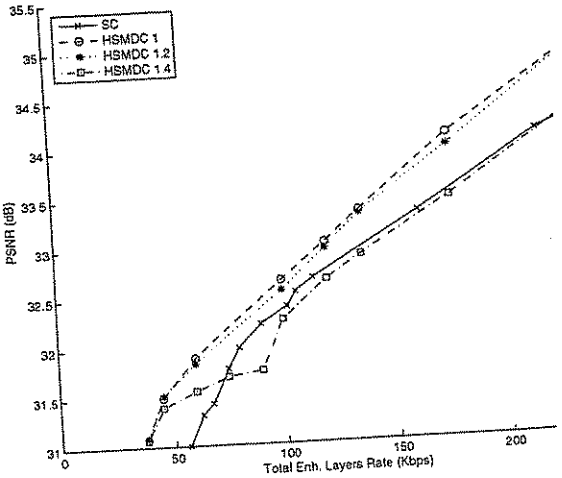

Figure 4. Comparison using "Foreman" sequence RCPC/CRC scheme for $\{SR_{H2}, SR_{S2}\}$ and SNF dB.

6. CONCLUSIONS

In this work, we have proposed error-resilient techniques and optimal bit allocation for the transmissi HSMDC coded video over wireless channels. We have shown that using the functionality of having mu description enhancement layers from HSMDC improves the performance (in the R-D sense) of a wireless transmission system as compared to scalable coding (SC). The experimental results clearly demonstrat effectiveness of the proposed system for different channel coding schemes and channel conditions. We developed an optimal strategy for selecting the source and channel coding rates over a given number of given the characteristics of the source and channel. Given a target overall bitrate, the channel, and the s codec, this algorithm provides appropriate breakdown of the rate into the subrates such that the overall e end distortion is minimized.

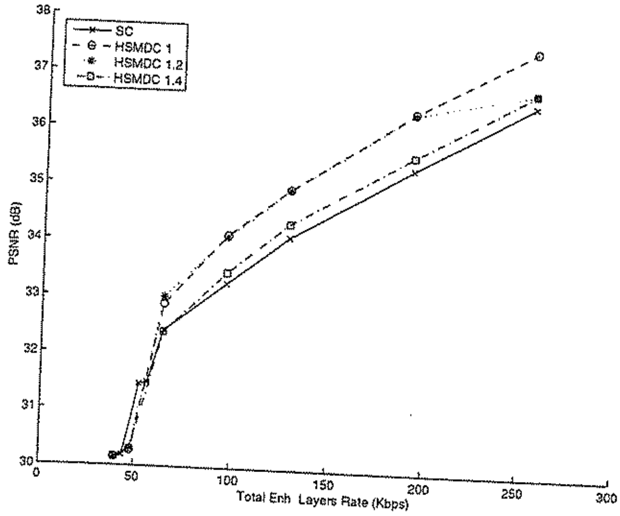

Figure 5. Comparison using "Foreman" sequence with RCPC/CRC scheme for $\{SR_{H1}, SR_{S1}\}$ and SNR=14 dB.

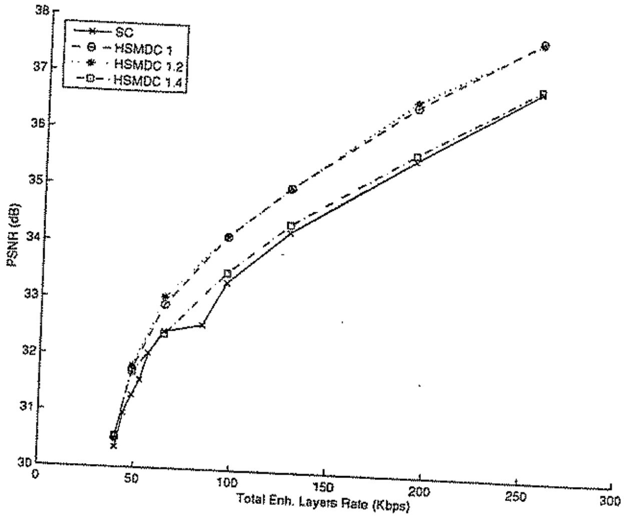

Figure 6. Comparison using "Foreman" sequence with RCPC/CRC scheme for $\{SR_{H1}, SR_{S1}\}$ and SNR=18 dB.

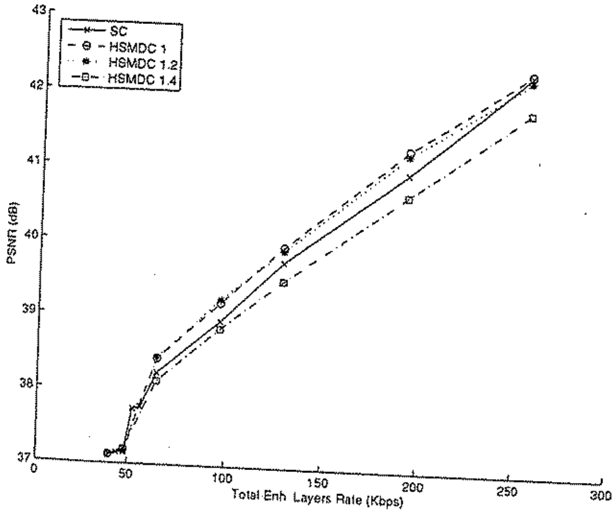

Figure 7. Comparison using "Akiyo" sequence with RCPC/CRC scheme for $\{SR_{H1}, SR_{S1}\}$ and SNR=14 dB.

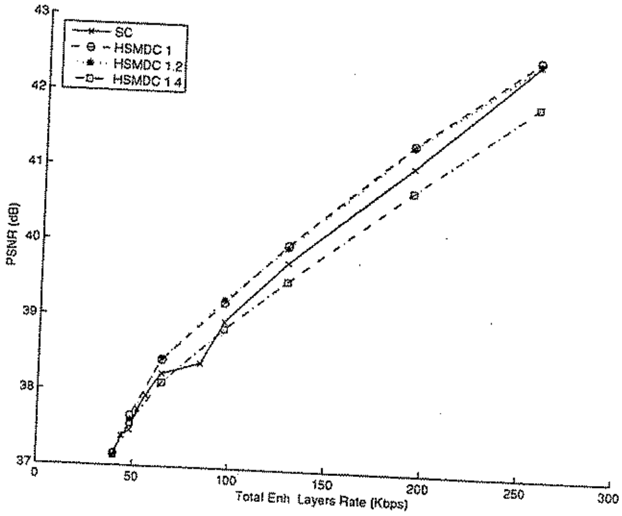

Figure 8. Comparison using "Akiyo" sequence with RCPC/CRC scheme for $\{SR_{H1}, SR_{S1}\}$ and SNR=16 dB.

REFERENCES

1. International Telecommunication Union Recommendation H.263, *Video coding for low bitrate communications*, January 1998.
2. R. Koenen, "MPEG-4: multimedia for our time," *IEEE Spectrum* **36**, pp. 26–33, Febuary 1999.
3. Y. Andreopoulos, A. Munteanu, G. V. der Auwera, P. Schelkens, and J. Cornelis, "Wavelet-based fully-scalable video coding with in-band prediction," in *Proceedings of the Benelux Signal Processing Symposium*, (Leuven, Belgium), 2002.
4. K. Rose and S. L. Regunathan, "Toward optimality in scalable predictive coding," *IEEE Transactions on Image Processing* **10**, pp. 965–976, July 2001.
5. L. P. Kondi and A. K. Katsaggelos, "An operational rate-distortion optimal single-pass SNR scalable video coder," *IEEE Transactions on Image Processing* **10**, pp. 1613–1620, November 2001.

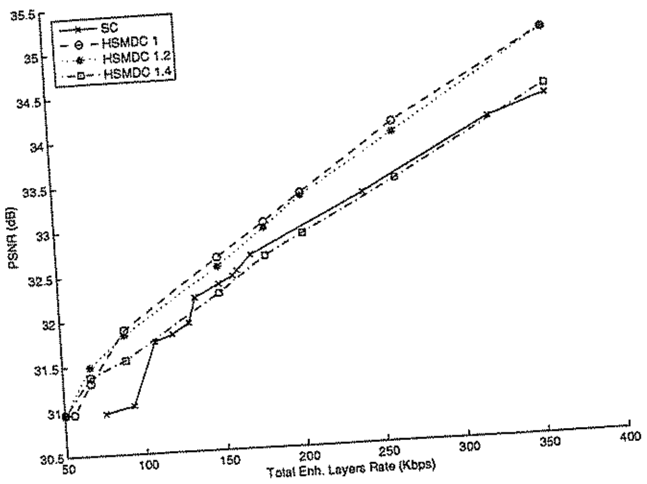

Figure 9. Comparison using "Foreman" sequence with RS+RCPC/CRC scheme for RS = $\frac{8}{12}$, $\{SR_{H2}, SR_{S2}\}$ and SNR=12 dB.

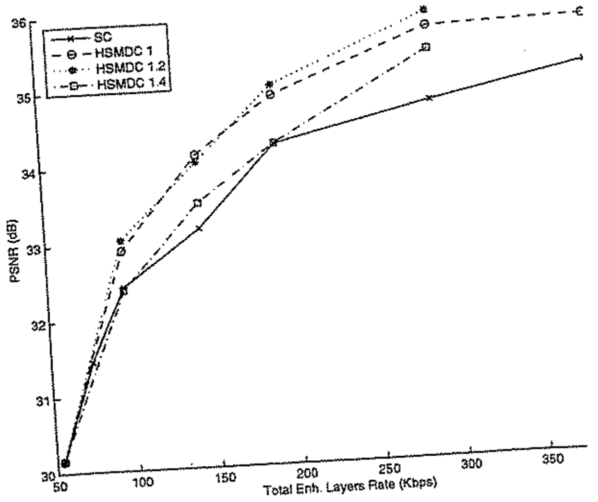

Figure 10. Comparison using "Foreman" s quence with RS+RCPC/CRC scheme for RS = $\{SR_{H1}, SR_{S1}\}$ and SNR=10 dB.

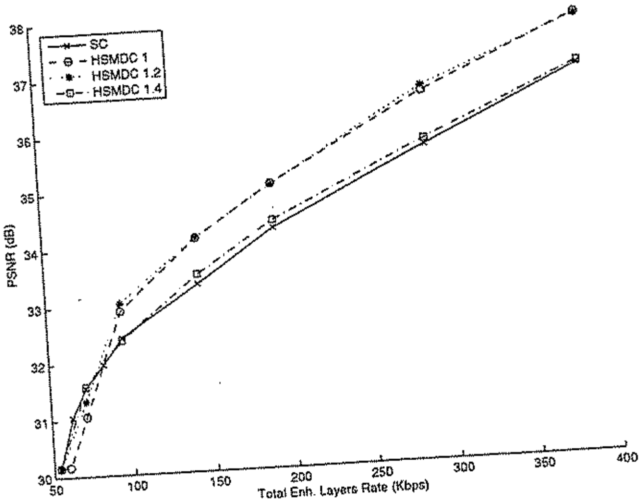

Figure 11. Comparison using "Foreman" sequence with RS+RCPC/CRC scheme for RS = $\frac{8}{12}$, $\{SR_{H1}, SR_{S1}\}$ and SNR=14 dB.

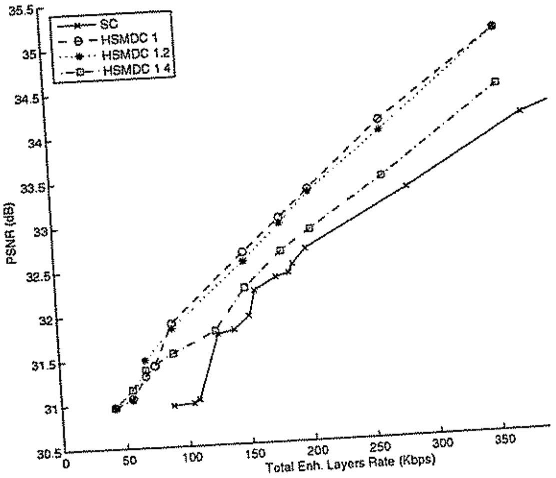

Figure 12. Comparison using "Foreman" seq with RS+RCPC/CRC scheme for $\{SR_{H2}, SR_{S2}$ SNR=12 dB.

6. M. A. Robers, L. P. Kondi, and A. K. Katsaggelos, "SNR scalable video coder using progressive transm of DCT coefficients," in *SPIE*, pp. 201–212, 1998.
7. L. P. Kondi, F. Ishtiaq, and A. K. Katsaggelos, "On video SNR scalability," in *International Confere Image Processing*, pp. 934–938, (Chicago, IL), 1998.
8. V. K. Goyal, "Multiple description coding: Compression meets the network," *IEEE Signal Processing azine* **18**, pp. 74–93, September 2001.
9. A. R. Reibman, H. Jafarkhani, Y. Wang, and M. Orchard, "Multiple description video using rate-dist splitting," in *International Conference on Image Processing*, (Thessaloniki, Greece), October 2001.
10. J. K. Wolf, A. Wyner, and J. Ziv, "Source coding for multiple descriptions," *Bell System Techinca nal* **59**, pp. 1417–1426, October 1980.
11. H. Wang and A. Ortega, "Robust video communication by combining scalability and multiple desc

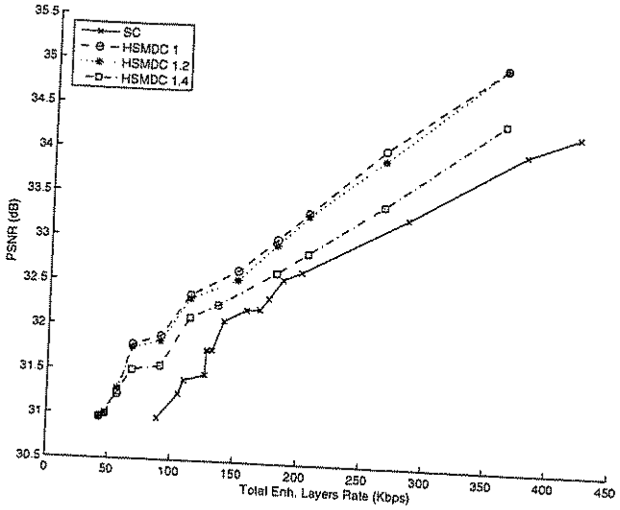

Figure 13. Comparison using "Foreman" sequence with RS+RCPC/CRC scheme for $\{SR_{H2}, SR_{S2}\}$ and SNR=14 dB.

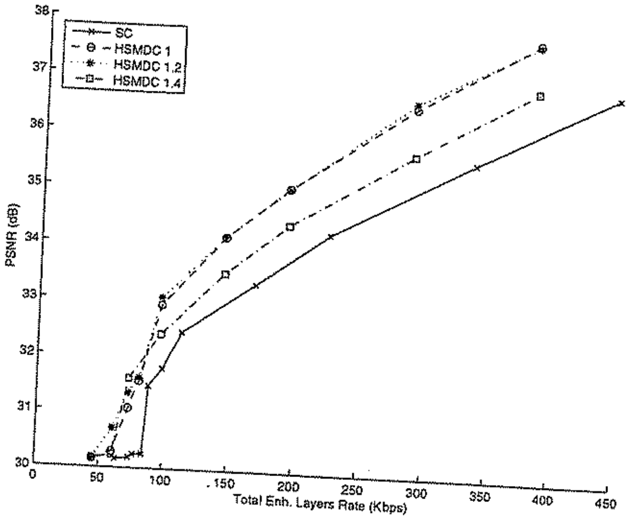

Figure 14. Comparison using "Foreman" sequence with RS+RCPC/CRC scheme for $\{SR_{H1}, SR_{S1}\}$ and SNR=14 dB.

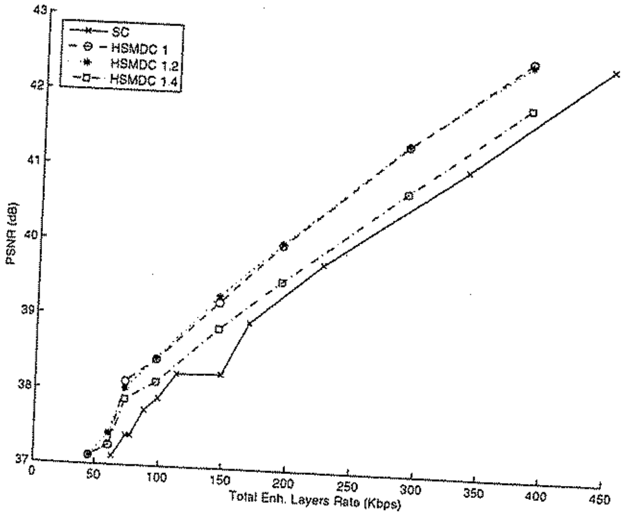

Figure 15. Comparison using "Akiyo" sequence with RS+RCPC/CRC scheme for $\{SR_{H1}, SR_{S1}\}$ and SNR=14 dB.

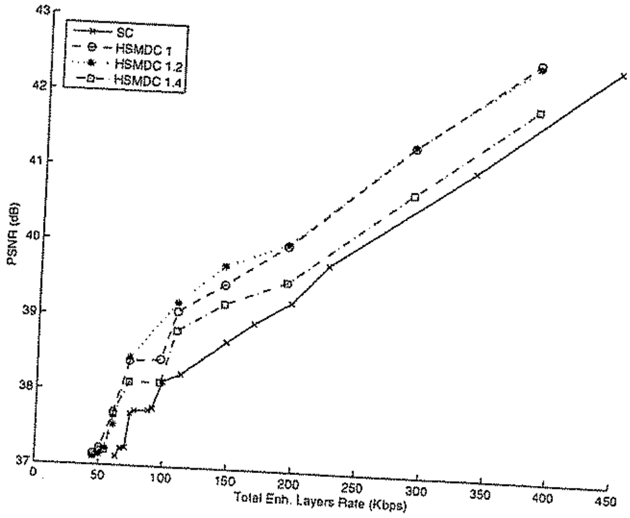

Figure 16. Comparison using "Akiyo" sequence with RS+RCPC/CRC scheme for $\{SR_{H1}, SR_{S1}\}$ and SNR=16 dB.

coding techniques," in *Conference on Image and Video Communications and Processing*, pp. 111–124, (Santa Clara, California), January 2003.

12. P. A. Chou, H. J. Wang, and V. N. Padmanabhan, "Layered multiple description coding," in *Packet Video Workshop*, (Nantes, France), April 2003.
13. L. P. Kondi, "A rate-distortion optimal hybrid scalable/multiple-description video codec," *IEEE Transactions on Circuits and Systems for Video Technology* **15**, pp. 921 – 927, July 2005.
14. L. P. Kondi, "A rate-distortion optimal hybrid scalable/multiple-description video codec," in *International Conference on Acoustics, Speech and Signal Processing*, **3**, pp. 269–272, (Montreal, Canada), May 2004.
15. J. Hagenauer, "Rate-compatible punctured convolutional codes (RCPC codes) and their applications," *IEEE Transactions on Communications* **36**, pp. 389–400, April 1988.
16. W. H. Press, B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling, *Cyclic redundancy and other checksums*, Cambridge University Press, 1992.

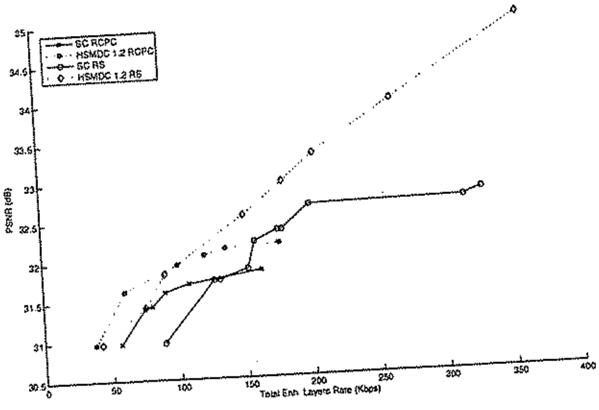

Figure 17. Comparison between RCPC/CRC and RS+RCPC/CRC schemes using "Foreman" sequence for $\{SR_{H2}, SR_{S2}\}$ and SNR=10 dB.

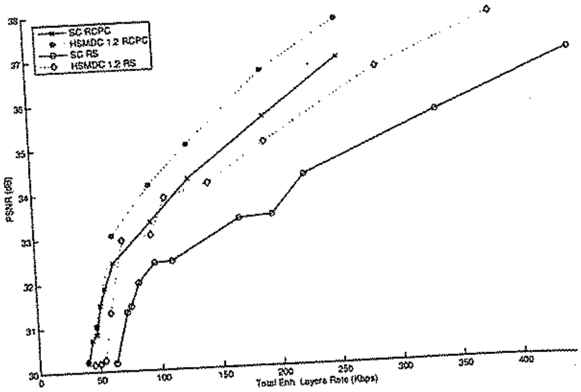

Figure 18. Comparison between RCPC/CRC and RS+RCPC/CRC schemes using "Foreman" sequence for $\{SR_{H1}, SR_{S1}\}$ and SNR=16 dB.

17. I. S. Reed and G. Solomon, "Polynomial codes over certain certain finite fields," *Journal of the Society for Industrial and Applied Mathematics* , 1960.
18. L. P. Kondi, F. Ishtiaq, and A. K. Katsaggelos, "Joint source-channel coding for motion-compensated DCT-based SNR scalable video," *IEEE Transactions on Image Processing* **11**, pp. 1043–1054, September 2002.
19. L. P. Kondi, F. Ishtiaq, and A. K. Katsaggelos, "Joint source-channel coding for SNR scalable video," *Image and Video Communications and Processing 2000* **3974**, pp. 324–335, April 2000.
20. G. Cheung and A. Zakhor, "Joint source/channel coding of scalable video over noisy channels," in *IEEE International Conference on Image Processing*, pp. 767 – 770, (Lausanne, Switzerland), September 1996.
21. M. Bystrom and J. W. Modestino, "Combined source-channel coding for transmission of video over an additive white Gaussian noise channel," *IEEE Journal on Selected Areas in Communications* **18**, pp. 880 – 890, June 2000.
22. G. Cheung and A. Zakhor, "Bit allocation for joint source/channel coding of scalable video," *IEEE Transactions on Image Processing* **9**, March 2000.
23. Q. Chen and K. P. Subbalakshmi, "Joint source-channel decoding for MPEG-4 video transmission over wireless channels," *IEEE Journal Selected Areas in Communications* , 2003.