Video Communications with Optimal Intra/Inter-Mode Switching over Wireless Internet

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***Abstract*—A robust scheme is presented for the efficient transmission of packet video over a heterogeneous channel. The channel consists of a wireless link with bit errors and a wired (e.g., Internet) channel with packet erasures. The scheme uses a source encoder that switches optimally between intra-coding and inter-coding with fixed-length packets. Different re-synchronization schemes are considered and compared. A cyclic redundancy check (CRC) outer coder concatenated with an inner rate-compatible punctured convolutional (RCPC) coder are used as Forward Error Correction (FEC). The scheme is evaluated over the simulated wireless Internet channel, and is shown to have promising performance.**

I. System Overview

Packet video is becoming more common, but network congestion and wireless channel errors can degrade video quality. The transmitted bitstream should be organized to minimize the possible corruption and error propagation. We assume the wireless channel will introduce random bit errors with probability P_b, and congestion will erase packets with probability p. We assume P_b and p are both constant and known at the transmitter in advance. The major resource shared between the source and channel encoder here is the given target transmission rate. If the channel condition is poor, more bits are needed for channel error detection and correction, thus fewer bits are used for source encoding.

In this paper, we propose a robust scheme for the efficient transmission of packet video. The basic system diagram is shown in Fig. 1. The source encoder uses a rate-distortion optimized mode-switching algorithm, designed to switch between intra/inter modes optimally for fixed-length packets, with a certain re-synchronization method. The channel encoder uses an adaptive coding algorithm, with a rate-compatible punctured convolutional (RCPC) inner coder for error correction and a cyclic redundancy check (CRC) outer coder for error detection. We will explain the source encoding and channel encoding strategies in detail in Sections II and III, respectively. Experimental results and conclusions are reported in Section IV.

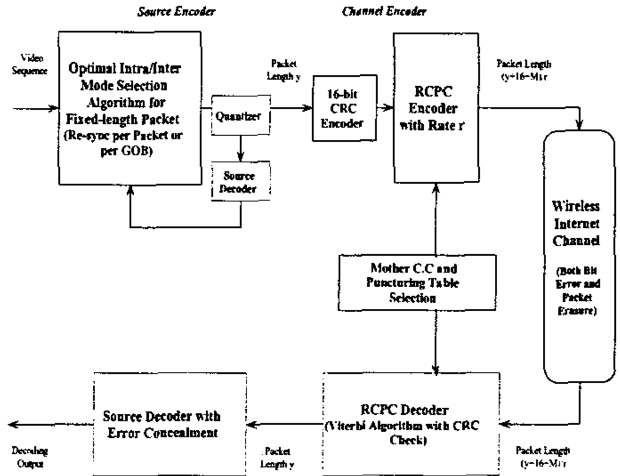

Fig. 1. System Overview

II. The Source Encoder with Optimal Mode Selection

Inter-coding is an efficient approach for video coding, but may suffer from potentially severe error propagation when channel conditions are bad, because a single error in a previous frame may corrupt all subsequent frames if inter-coding is used repeatedly. Intra-coding, by encoding the current macroblock (MB) by itself, can stop the error propagation successfully, but is costly in bits. It is desirable to switch between intra and inter coding intelligently according to the channel condition. We wish to use optimal distortion estimation and mode switching in the style of ROPE [1], but for different channels.

ROPE is designed for a packet erasure channel without bit errors. Each Group of Blocks (GOB, a horizontal slice of MBs) is carried in a separate variable-length packet; one packet loss entails loss of the whole GOB, but will not affect decoding of other packets (GOBs), thus the probability of pixel loss equals the probability of packet erasure.

To integrate the source encoder with the Forward Error Correction (FEC), we must modify ROPE to produce fixed-length packets, in which case there is no one-to-one correspondence between a GOB and a packet. As packet boundaries usually are not MB boundaries, one packet loss may cause loss of synchronization. We examine two re-synchronization methods: the first inserts re-sync bits at the beginning of each GOB (i.e., re-sync once per GOB), and the second inserts re-sync bits at the beginning of the first MB in each packet (i.e., re-sync once per packet).

For re-sync per GOB, a MB will not be reconstructed at the decoder, if either the packet including this MB, or any former MBs in the same GOB are lost, as the decoder will lose synchronization until the next re-sync bits are recognized. Thus, we count the packet number from the first packet of each GOB. Assume the current MB extends to packet m of this GOB. The probability that this MB can be reconstructed at the decoder is the probability that all these m packets of this GOB are received by the decoder. This equals $(1-p)^m$, where p is the packet erasure rate. If $P_{\bar{R}}$ denotes the probability that a MB cannot be reconstructed at the decoder, we have $P_{\bar{R}} = P_{\bar{R}}(m) = 1-(1-p)^m$.

Another determinant of the distortion at the decoder is the concealment method. We make use of a temporal concealment method that uses the motion vectors (MVs) of the three nearest MBs (denoted A, B, C from left to right) above the lost MB to define the substitute motion vector (SMV). The SMV indicates which MB in the previous frame will be used for concealment. We assume, if any of A, B, and C were intra-coded, that its own MV is equal to $(0,0)$. We define:

$$P_{\bar{A}} = P(A\ lost);\quad P_A = P(A\ received) = 1 - P_{\bar{A}};$$

$$P_{\bar{B}|A} = P(B\ lost \mid A\ received);$$

$$P_{\bar{C}|AB} = P(C\ lost \mid A\ received\ and\ B\ received);$$

$$P_{A\bar{B}} = P(A\ received\ and\ B\ lost) = P_A P_{\bar{B}|A};$$

$$P_{AB\bar{C}} = P(A\ and\ B\ received\ and\ C\ lost)$$

$$P_{ABC} = P(A,\ B\ and\ C\ are\ all\ received)$$

where "lost" means not reconstructable at the decoder and "received" means reconstructable. We see that:

$$P_{\bar{A}} = 1-(1-p)^{m_A} \tag{1}$$

$$P_{\bar{B}|A} = 1-(1-p)^{l_B} \tag{2}$$

$$P_{\bar{C}|AB} = P_{\bar{C}|B} = 1-(1-p)^{l_C} \tag{3}$$

$$P_{AB\bar{C}} = P_A(1-P_{\bar{B}|A})P_{\bar{C}|AB} \tag{4}$$

$$P_{ABC} = P_A(1-P_{\bar{B}|A})(1-P_{\bar{C}|AB}) \tag{5}$$

where m_A is the number of packets that A extends from the beginning of its GOB, l_B is the number of packets that B spans beyond the end of the packet with A, and l_C is the number of packets that C spans beyond the end of the packet with B. Note that these probabilities are computed and stored at the time the MVs are encoded.

Let MV_A, MV_B, and MV_C denote the MV's of A, B, and C, respectively, and let MV_{med} denote their median. Let $k1$, $k2$, $k3$ and $k4$ correspond to the pixels in the previous frame that are used to conceal pixel i, using MV_A, MV_B MV_C and MV_{med}, respectively. Our concealment for the current lost pixel is as follows: If A is lost (with probability $P_{\bar{A}}$), so are B and C, so we set SMV= 0. Given A is received (with probability $1-P_{\bar{A}}$), if B is lost and so is C, we set SMV=MV_A; if B is received but C is lost, we set SMV=MV_B; lastly, if both B and C are received, we set SMV=MV_{med}.

Now we are ready to derive the expected decoder distortion per pixel. Denote by f_n^i the original value of pixel i in frame n, which is compressed and reconstructed at the encoder as $\hat{f}_n^i$ (only quantization error is included). The decoded (and possibly error-concealed) reconstruction at the receiver is denoted by $\tilde{f}_n^i$, which must be treated as a random variable for the encoder. Then the expected distortion for pixel i is:

$$d_n^i = E\{(f_n^i - \tilde{f}_n^i)^2\} = (f_n^i)^2 - 2f_n^i E\{\tilde{f}_n^i\} + E\{(\tilde{f}_n^i)^2\} \tag{6}$$

Calculation of d_n^i requires the first and second moments of the random variable $\tilde{f}_n^i$, which can be computed recursively. For re-sync per GOB, these two moments for a pixel in an intra-coded MB are given by:

$$E\{\tilde{f}_n^i\} = (1-P_{\bar{R}})\hat{f}_n^i + P_{\bar{R}}\ [P_{\bar{A}}E\{\tilde{f}_{n-1}^i\} + P_{A\bar{B}} E\{\tilde{f}_{n-1}^{k1}\} + P_{AB\bar{C}}E\{\tilde{f}_{n-1}^{k2}\} + P_{ABC}E\{\tilde{f}_{n-1}^{k4}\}] \tag{7}$$

$$E\{(\tilde{f}_n^i)^2\} = (1-P_{\bar{R}})(\hat{f}_n^i)^2 + P_{\bar{R}}[P_{\bar{A}}E\{(\tilde{f}_{n-1}^i)^2\} + P_{A\bar{B}} E\{(\tilde{f}_{n-1}^{k1})^2\} + P_{AB\bar{C}}E\{(\tilde{f}_{n-1}^{k2})^2\} + P_{ABC}E\{(\tilde{f}_{n-1}^{k4})^2\}\ ] \tag{8}$$

For an inter-coded MB, assume the current pixel i is predicted from pixel j in the previous frame. The prediction error, e_n^i, is compressed and the quantized residue is $\hat{e}_n^i$. Then the first and second moments of $\tilde{f}_n^i$ for a pixel in an inter-coded MB are given by:

$$E\{\tilde{f}_n^i\} = (1-P_{\bar{R}})[\hat{e}_n^i + E\{\tilde{f}_{n-1}^j\}] + P_{\bar{R}}[P_{\bar{A}}E\{\tilde{f}_{n-1}^i\} + P_{A\bar{B}}E\{\tilde{f}_{n-1}^{k1}\} + P_{AB\bar{C}}E\{\tilde{f}_{n-1}^{k2}\} + P_{ABC}E\{\tilde{f}_{n-1}^{k4}\}] \tag{9}$$

$$E\{(\tilde{f}_n^i)^2\} = (1-P_{\bar{R}})\ [\ (\hat{e}_n^i)^2 + 2\hat{e}_n^i E\{\tilde{f}_{n-1}^j\} + E\{(\tilde{f}_{n-1}^j)^2\}\ ] + P_{\bar{R}}[P_{\bar{A}}E\{(\tilde{f}_{n-1}^i)^2\} + P_{A\bar{B}}E\{(\tilde{f}_{n-1}^{k1})^2\} + P_{AB\bar{C}}E\{(\tilde{f}_{n-1}^{k2})^2\} + P_{ABC}E\{(\tilde{f}_{n-1}^{k4})^2\}\ ] \tag{10}$$

A similar analysis is done for encoding with re-sync per packet. In this case, a MB can be reconstructed at the decoder if and only if all the packets that contain this current MB are received. So we count the number m of packets that include this MB. Again we use $P_{\bar{R}}$ to denote the probability that a MB cannot be reconstructed at the decoder, and $P_{\bar{R}} = P_{\bar{R}}(m) = 1-(1-p)^m$. Because usually the compressed bit stream corresponding to one MB is much smaller than the fixed packet length, m is equal to 1 or 2 most of time.

Concealment also needs to be modified. Using the same notation, this time, loss of A does not necessarily mean loss of B or C. It is also possible that A and C are received but B is lost, although this is very unlikely because it means B occupies more than one packet. For this situation, we let the SMV equal to the MV of A or C if only one of them is inter-coded. If both A and C are inter-coded, we use the MV with smaller value. Let $k5$ denote the pixel used for concealment under this situation. We summarize all the situations, the pixels used to conceal, and the corresponding probabilities, in Table I. For example, the first line means A, B and C are all lost, we use pixel i in the previous frame for the concealment (i.e., SMV=0), and the probability corresponding to this situation is $P_{\bar{A}\bar{B}\bar{C}}$.

TABLE I
THE CONCEALMENT METHOD FOR DIFFERENT SITUATIONS

Situation	Pixel	Corresponding Probability
$\bar{A}\bar{B}\bar{C}$	i	$P_{\bar{A}\bar{B}\bar{C}} = P_{\bar{A}}P_{\bar{B}\mid\bar{A}}P_{\bar{C}\mid\bar{A}\bar{B}}$
$\bar{A}\bar{B}C$	$k3$	$P_{\bar{A}\bar{B}C} = P_{\bar{A}}P_{\bar{B}\mid\bar{A}}(1-P_{\bar{C}\mid\bar{A}\bar{B}})$
$\bar{A}BC or \bar{A}B\bar{C}$	$k2$	$P_{\bar{A}B} = P_{\bar{A}}(1-P_{\bar{B}\mid\bar{A}})$
$AB\bar{C}$	$k2$	$P_{AB\bar{C}} = (1-P_{\bar{A}})(1-P_{\bar{B}\mid A})P_{\bar{C}\mid AB}$
ABC	$k4$	$P_{ABC} = (1-P_{\bar{A}})(1-P_{\bar{B}\mid A})(1-P_{\bar{C}\mid AB})$
$A\bar{B}\bar{C}$	$k1$	$P_{A\bar{B}\bar{C}} = (1-P_{\bar{A}})P_{\bar{B}\mid A}P_{\bar{C}\mid A\bar{B}}$
$A\bar{B}C$	$k5$	$P_{A\bar{B}C} = (1-P_{\bar{A}})P_{\bar{B}\mid A}(1-P_{\bar{C}\mid A\bar{B}})$

Then, for an intra-coded MB, the two moments of $\tilde{f}_n^i$ are:

$$E\{\tilde{f}_n^i\} = (1-P_{\bar{R}})\hat{f}_n^i + P_{\bar{R}}\,[P_{\bar{A}\bar{B}\bar{C}}E\{\tilde{f}_{n-1}^i\} + P_{\bar{A}\bar{B}C} E\{\tilde{f}_{n-1}^{k3}\} + (P_{\bar{A}B} + P_{AB\bar{C}})E\{\tilde{f}_{n-1}^{k2}\} + P_{ABC} E\{\tilde{f}_{n-1}^{k4}\} + P_{A\bar{B}\bar{C}}E\{\tilde{f}_{n-1}^{k1}\} + P_{A\bar{B}C}E\{\tilde{f}_{n-1}^{k5}\}] \quad (11)$$

$$E\{(\tilde{f}_n^i)^2\} = (1-P_{\bar{R}})(\hat{f}_n^i)^2 + P_{\bar{R}}\,[P_{\bar{A}\bar{B}\bar{C}}E\{(\tilde{f}_{n-1}^i)^2\} + P_{\bar{A}\bar{B}C}E\{(\tilde{f}_{n-1}^{k3})^2\} + (P_{\bar{A}B} + P_{AB\bar{C}})E\{(\tilde{f}_{n-1}^{k2})^2\} + P_{ABC}E\{(\tilde{f}_{n-1}^{k4})^2\} + P_{A\bar{B}\bar{C}}E\{(\tilde{f}_{n-1}^{k1}\})^2 + P_{A\bar{B}C}E\{(\tilde{f}_{n-1}^{k5}\})^2] \quad (12)$$

And for an inter-coded MB, the two moments are:

$$E\{\tilde{f}_n^i\} = (1-P_{\bar{R}})\;[\hat{e}_n^i + E\{\tilde{f}_{n-1}^j\}] + P_{\bar{R}}\,[\,P_{\bar{A}\bar{B}\bar{C}} E\{\tilde{f}_{n-1}^i\} + P_{\bar{A}\bar{B}C}E\{\tilde{f}_{n-1}^{k3}\} + (P_{\bar{A}B} + P_{AB\bar{C}})E\{\tilde{f}_{n-1}^{k2}\} + P_{ABC}E\{\tilde{f}_{n-1}^{k4}\} + P_{A\bar{B}\bar{C}}E\{\tilde{f}_{n-1}^{k1}\} + P_{A\bar{B}C}E\{\tilde{f}_{n-1}^{k5}\}] \quad (13)$$

$$E\{(\tilde{f}_n^i)^2\} = (1-P_{\bar{R}})\,[\,(\hat{e}_n^i)^2 + 2\hat{e}_n^i\,E\{\tilde{f}_{n-1}^j\} + E\{(\tilde{f}_{n-1}^j)^2\}\,] + P_{\bar{R}}\,[\,P_{\bar{A}\bar{B}\bar{C}}E\{(\tilde{f}_{n-1}^i)^2\} + P_{\bar{A}\bar{B}C} E\{(\tilde{f}_{n-1}^{k3})^2\} + (P_{\bar{A}B} + P_{AB\bar{C}})\,E\{(\tilde{f}_{n-1}^{k2})^2\} + P_{ABC} E\{(\tilde{f}_{n-1}^{k4})^2\} + P_{A\bar{B}\bar{C}}E\{(\tilde{f}_{n-1}^{k1}\})^2 + P_{A\bar{B}C}E\{(\tilde{f}_{n-1}^{k5}\})^2] \quad (14)$$

We compute the overall expected distortion per pixel recursively, and incorporate this distortion computation within the rate-distortion framework at the encoder to optimally switch between intra- and inter-coding. The goal is to minimize the total estimated distortion of the current MB subject to a bit rate constraint. Both the coding mode and the quantization parameter (QP) are chosen to minimize the Lagrangian cost:

$$\min_{(mode,QP)} J_{MB} = \min_{(mode,QP)} (D_{MB} + \lambda R_{MB})$$

This optimal mode selection algorithm is designed for packet erasure channels. Wireless bit errors may increase the packet loss rate if the corrupted packet cannot be corrected. As we describe in Section III, we choose the channel code rate r according to the bit error rate P_b of the wireless channel, such that the probability of dropping a packet due to uncorrectable bit errors is about 1% or lower. After determining r, the source encoder determines the source code rate. The packet erasure rate due to congestion is p, the packet drop probability due to uncorrectable bit errors is roughly 1% , thus the total packet loss rate ($\hat{p}$) encountered at the source decoder is approximately: $\hat{p} = p + 0.01 - p \times 0.01 = 0.99p + 0.01$. Having the target source code rate and the total packet loss rate $\hat{p}$, we can use our modified (packetized) optimal algorithm for intra/inter mode selection directly.

III. THE CHANNEL ENCODER

We use a concatenated code consisting of a CRC outer coder followed by an inner RCPC coder. Each packet, containing a fixed number y of source information bits, is appended with a 16-bit CRC and M zero ending bits to flush the memory and terminate the trellis decoding in the zero state. Then the block is convolutionally encoded using a rate r RCPC coder. The CRC is used for error detection with extremely low computational complexity and great flexibility in selecting the block length. We used the optimal 16-bit CRCs proposed in [2], [5] in our system.

RCPC codes are an extension of punctured convolutional codes, by puncturing a low rate mother code periodically. For a family of RCPC codes, fewer bits punctured entails lower coding rate, and more powerful error correction. The RCPC codes we used are from [3], [4]. The rate is chosen to make the probability of a dropped packet due to uncorrectable bit error roughly 1%, under the given channel bit error rate P_b for most of the transmission rates of interest. We used rate 2/7, 2/3, and 8/9 RCPC codes for $0.15 \geq P_b > 0.05$, $0.05 \geq P_b > 0.005$, and $0.005 \geq P_b > 10^{-5}$, respectively. No channel coder is used if $P_b \leq 10^{-5}$. All the RCPC codes have memory $M = 6$ and puncturing period length 8, and the details of their construction are given in Table II.

For the efficient detection of uncorrected errors, the serial list-Viterbi algorithm at the channel decoder was used [4], [6], [7]. That is, the optimal path in the Viterbi decoding is chosen among those paths that satisfy the CRC checksum equations. If at a given depth of trellis decoding, none of them satisfied the checksum equations, then an uncorrected error is declared and the packet is discarded.

The simulation result shows that it is quite reasonable to choose the packet drop rate due to uncorrectable bit error

TABLE II

RCPC CODES

RCPC Code Rate	Mother Convolutional Code			Puncturing Table
	Rate	Memory	Generation Matrix	
8/9	1/3	6	1011011 1111001 1100101	11110111 10001000 00000000
2/3	1/3	6	1011011 1111001 1100101	11111111 10101010 00000000
2/7	1/4	6	1101101 1010011 1011111 1100111	11111111 11111111 11111111 10101010

to be roughly 1%. For example, Fig. 2 shows the PSNR loss over different target packet drop rates, where PSNR loss (shown on the y-axis) refers to the gap between the PSNR with zero packet drop rate and the PSNR under the given drop rate. When the drop rate is high, the loss is large, but when the drop rate goes down to roughly 1%, the PSNR gap is very small. There are diminishing returns when the drop rate due to uncorrectable bit errors is pushed below 1%.

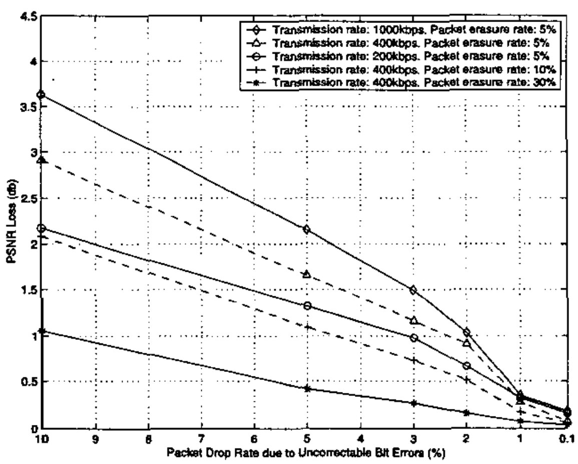

Fig. 2. PSNR loss over different target packet drop rates. "Carphone" QCIF sequence at 10fps and fixed-packet length 400.

IV. RESULTS AND CONCLUSIONS

In our experiments, the system was evaluated by modifying an H.263+ codec with standard QCIF (176 × 144) video sequences "Carphone", "Container" and "Salesman" at frame rates of 10, 15 or 30 frames per second (fps). The effect of various target transmission bit rates ranging from 100kbps to 500kbps was tested. The packet erasure rates were $p = 5\%$ and $p = 10\%$, and bit error probabilities ranged from $P_b = 0$ to $P_b = 0.15$.

Fig. 3 shows PSNR performance versus bit error rate for "Carphone" at 400kbps and 30fps with $p = 10\%$. Re-sync per packet yields much better performance than re-sync per GOB. Note that the gap between them decreases as the bit error goes up.

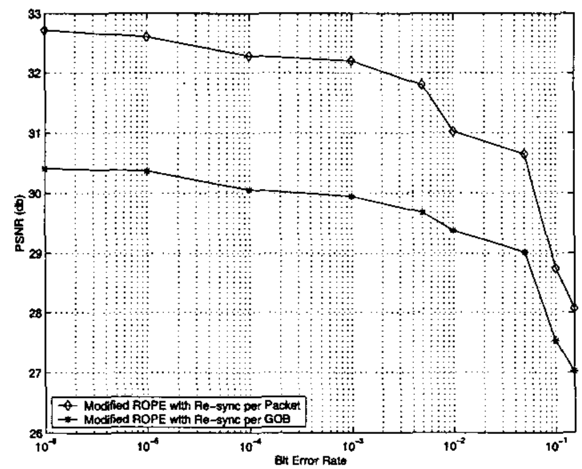

Fig. 3. PSNR performance versus bit error rate. "Carphone" QCIF sequence at 30fps and 400kps, packet erasure rate p=10% and fixed-packet length 400.

Table IV shows some parameters corresponding to Fig. 3. The source encoding bit rate decreases as the bit error rate increases, and thus a more powerful RCPC code is applied. The total packet loss rate used at the source encoder is roughly the same as that found at the decoder, which means the RCPC codes successfully controlled the packet loss due to uncorrectable bit errors to around 1% as intended.

TABLE III

SOME SIMULATION PARAMETERS FOR RE-SYNC PER PACKET OF FIG. 3

Carphone QCIF Re-synchronization per Packet target transmission rate 400 kbps, packet erasure rate 10%, frame rate 30 fps, and fixed packet length 400 bits									
bit error rate	10^{-6}	10^{-5}	10^{-4}	10^{-3}	0.005	0.01	0.05	0.10	0.15
actual source bit rate	390kbps	390kbps	328kbps	328kbps	328kbps	246kbps	246kbps	106kbps	106kbps
total packet loss rate used at source encoder	10% + 1% -(10%)(1%) = 10.9%								
actual total packet loss rate found at decoder	10.04%	10.35%	10.06%	10.58%	12.86%	10.89%	12.80%	11.52%	13.21%
PSNR (dB)	32.7251	32.6114	32.2844	32.2020	31.8047	31.0277	30.6449	28.7502	28.0722

Fig. 4 is for "Container" at 150kbps and 15fps with $p = 5\%$. Similar trends are again seen. Table IV gives the corresponding parameters.

Fig. 5 shows PSNR versus target transmission rate. "Salesman" is encoded at 10fps with packet length 800 bits, $p = 10\%$ and $P_b = 0.01$. Again re-sync per packet outperforms re-sync per GOB, and the gap between them increases with target bit rate. In Fig. 6, PSNR versus time (frame number) is shown for "Salesman" at 300kbps, 10fps with 800-bit packets, $p = 10\%$ and $P_b = 0.01$.

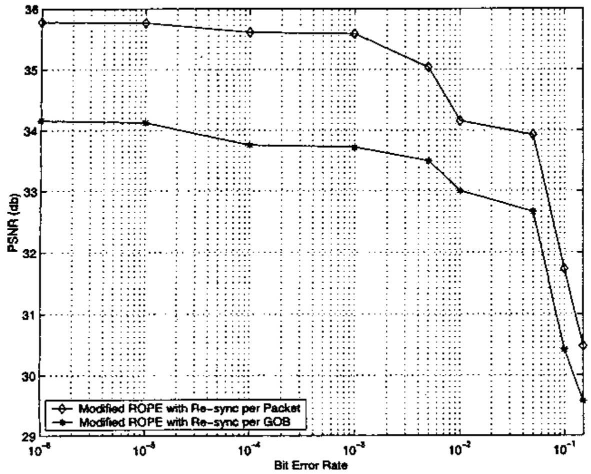

Fig. 4. PSNR performance versus bit error rate. "Container" QCIF sequence at 15fps and 150kps, packet erasure rate p=5% and fixed-packet length 400.

TABLE IV

SOME SIMULATION PARAMETERS FOR RE-SYNC PER PACKET OF FIG. 4

Container QCIF Re-synchronization per Packet Level target transmission rate 150 kbps, packet erasure rate 5%, frame rate 15 fps, and fixed packet length 400 bits									
bit error rate	10^{-6}	10^{-5}	10^{-4}	10^{-3}	0.005	0.01	0.05	0.10	0.15
actual source bit rate	132kbps	132kbps	117kbps	117kbps	117kbps	88kbps	88kbps	39kbps	39kbps
total packet loss rate used at source encoder	5% + 1% - (5%)(1%) = 5.95%								
actual total packet loss rate found at decoder	5.04%	5.38%	5.06%	5.61%	8.04%	5.93%	7.91%	6.61%	8.32%
PSNR (dB)	35.7693	35.7558	35.5960	35.5699	35.0404	34.1482	33.9280	32.7215	30.4662

In conclusion, we proposed a robust scheme for the transmission of packet video over a hybrid wireless/Internet channel, with optimal intra/inter mode switching and an efficient channel adaptive FEC. The novelty of the system is in its ability to cope with both bit errors and packet erasures, while performing optimal video mode switching that accounts for distortion from all loss mechanisms. Simulation results were performed to evaluate the performance, and showed good robustness to random bit error and packet erasure.

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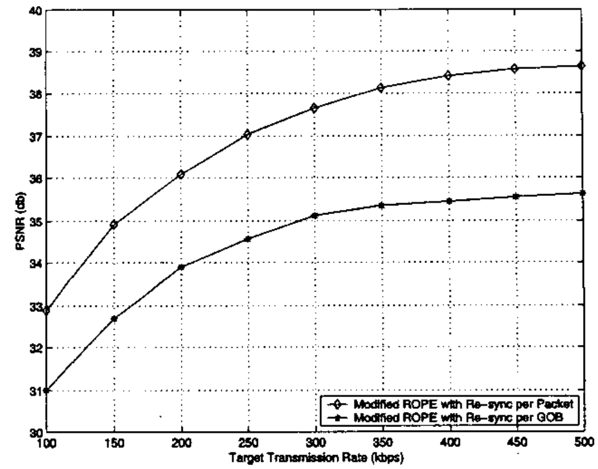

Fig. 5. PSNR performance versus transmission rate. "Salesman" QCIF sequence at 10fps, packet erasure rate p=5%, bit error rate Pb=0.01, and fixed-packet length 800.

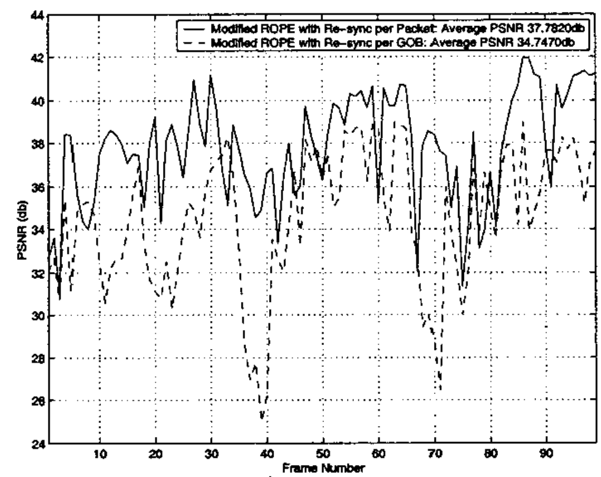

Fig. 6. PSNR performance versus frame number. "Salesman" QCIF sequence at 300kbps and 10fps, packet erasure rate p=5%, bit error rate Pb=0.01, and fixed-packet length 800.

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