Progressive Image Transmission with RCPT Protection

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In this paper, a joint source-channel coding scheme is proposed for progressive image transmission over channels with both random bit errors and packet loss by using rate-compatible punctured Turbo codes (RCPT) protection only. Two technical components which are different from existing methods are presented. First, a data frame is divided into multiple CRC blocks before being coded by a turbo code. This is to secure a high turbo coding gain which is proportional to the data frame size. In the mean time, the beginning blocks in a frame may still be usable although the decoding of the entire frame fails. Second, instead of employing product codes, we only use RCPT, along with an interleaver, to protect images over channels with combined distortion including random errors and packet loss. With this setting, the effect of packet loss is equivalent to randomly puncturing turbo codes. As a result, the optimal allocation of channel code rates is required for the random errors only, which largely reduces the complexity of the optimization process. The effectiveness of the proposed schemes is demonstrated with extensive simulation results.

Keywords: Progressive image transmission, source-channel coding, multiple CRC, RCPT, interleaving

1. INTRODUCTION

Many joint source and channel coding systems for image transmission over noisy channels have been proposed in recent years. The state-of-the-art image coders such as SPIHT[1] and JPEG 2000[2] provide a progressive mode of transmission. That is, the image can be reconstructed with any given number of consecutively received bits. The decoding of later transmitted data depends on the decoding of previously received data and refines the image quality incrementally. However, these coders are very sensitive to channel noise because one bit error or packet loss may cause the loss of synchronization between the encoder and the decoder. As a result, received data after the first bit error may be useless and are discarded completely.

Sherwood[3] first described a successful packet-based forward error correction (FEC) technique for image transmission over BSCs, where a fixed channel code rate is given to the entire bitstream. Rate-compatible punctured convolutional (RCPC) codes were used as the inner code to protect SPIHT coded source bits from channel errors and CRC codes were adopted as the outer coder for error detection. Whenever an error is detected by CRC, the whole packet and all following packets will be discarded to avoid error propagation. RCPT with high coding gain was also considered recently[4] to achieve stronger error protection.

Rate allocation for unequal error protection was also extensively discussed[5–12, 16] which has shown better performance than equal error protection (EEP) methods.[3] These methods were discussed for one type of channel noisy only. When both random errors and packet loss co-exist, product channel codes have been exploited.[13–15] In general, RCPC/CRC (or RCPT/CRC) codes are used in one direction to correct random errors and Reed-Solomon (RS) codes are used in the other direction to combat packet loss. For a given product coding system, optimal allocation of channel rates for UEP has been studied in a few ways. First, RS code rate is fixed while the rate of RCPC is changed for UEP.[13] Then, RCPT rate is fixed and RS code rate varies.[15] Finally, rates in both direction can be iteratively optimized for UEP,[14] but with very high optimization complexity.

In this research, we study the UEP for channels with both random errors and packet loss by using RCPT/CRC only. Since the coding gain of turbo codes improves as the interleaver size (i.e., the frame length) increases, the

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frame size is in general large in practice to secure a high channel decoding performance. For instance, coded frame length of 4136 bits was used.[4] In such case, if we only use one CRC code for the entire frame, even a single bit error can result in the failure of CRC detection and hence the discarding of the entire frame. Consequently, the correctly decoded bits before the first bit error in the same frame, which could be used in source decoding, are also discarded. In this research, we propose to use multiple CRC, i.e., partitioning one information frame into several blocks and each block being followed by a CRC code. Therefore, if an error is detected, we do not need to discard the correct blocks before this error. As a result, with slightly added redundancy of multiple CRC parity bits, more blocks of data could be used to improve the source decoding. Another novel technical component of this paper is that we propose to use RCPT/CRC codes only for the image transmission with both random errors and packet loss. We apply an interleaver to each coded packet before the data are transmitted. Therefore, the packet loss will be equivalent to random bit erasures throughout the frame. The effect can be further regarded as randomly puncturing a turbo code with reduced data rate. The punctured positions can be exactly determined by the interleaver and the positions of the lost packets. As a result, when both packet loss and random errors occur, the channel coding design can be considered as the design of optimal punctured turbo code rates for packets, given a specific random bit error rate (BER).

The rest of paper is organized as follows. In section 2, we present the interleaved RCPT/CRC protection technique used in this research and formulate the optimization problem. In section 3, we describes the multiple CRC technique in details. Simulation results are then presented in section 4. Finally, conclusion is drawn in section 5.

2. RCPT/CRC PROTECTION FOR BOTH TYPES OF DISTORTIONS

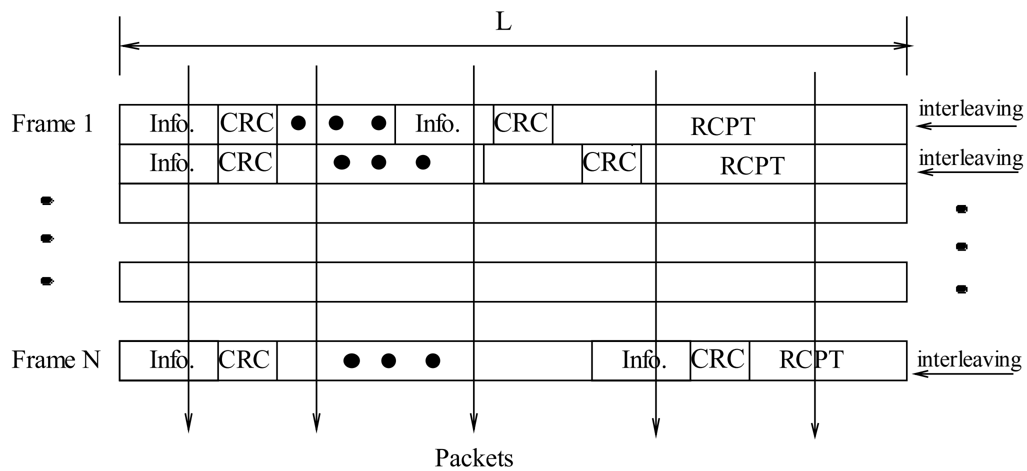

Figure 1. Proposed coding structure

Fig. 1 shows our proposed protection structure, where fixed channel codeword length is used. We consider a source-channel coding scheme that consists of the SPIHT coder as source encoder and RCPT/CRC as channel encoder. The embedded source bit stream is partitioned into frames with different frame lengths based on the channel code rates determined in the optimization process. CRC parity bits are then added for error detection after the turbo decoding. These data are then protected by the systematic Turbo codes. Whenever a bit error is detected, we discard this frame as well as the following frames. The received image is reconstructed based on the correctly decoded source bits. Suppose the overall transmission rate is given as R and there are N coded frames each of which has length L. Then $R = NL/n^2$ for an image with $n \times n$ pixels. Let $\mathbf{R} = \{r_1, r_2, \cdots, r_M\}$ be the set of possible RCPT channel code rates where $r_1 < r_2 < \cdots < r_M$. Our objective is to find a channel code rate allocation $\{r_{k_1}, r_{k_2}, \ldots, r_{k_N}\}$, where $r_{k_i} \in \mathbf{R}$, $1 \leq k_i \leq M$ and $1 \leq i \leq N$, corresponding to the N packets that maximizes the expected quality of the received image (i.e., minimizes the expected distortion $\bar{D}$ of the image), subject to the given total transmission rate.

In this research, we interleave each RCPT/CRC coded data frame randomly along the row direction. The same L-size interleaver can be used for all frames repeatedly. Then, image packets are organized in the column direction (across frames) for transmission. When one packet loss occurs in transmission, it is equivalent to having a few random bit erasures in each frame for turbo decoding. With more blocks being lost, the turbo decoding in the row direction behaves close to the decoding of a randomly punctured turbo code. As a result, the optimization of rate allocation along two directions can be converted into the optimization in only one direction, i.e., design of the appropriate RCPT rates along for the row direction only, with the consideration of puncturing rate in the column direction. For noisy channels with both packet loss and random bit errors, we can first optimize the RCPT to handle the random bit errors and get a rate allocation $\{r_{k_1}, r_{k_2}, \cdots, r_{k_N}\}$ to protect packets $\{1, 2, \cdots, N\}$ with information length $\{s_1, s_2, \cdots, s_N\}$. Then, we reduce these code rates to handle the additional bit erasures converted from the packet loss. For packet loss rate (PLR) P_l, we have

$$\lfloor (1-P_l)/r^*_{k_i} \rfloor = 1/r_{k_i} \quad 1 \le k_i \le M \tag{1}$$

where $r^*_{k_i}$ is the new RCPT code rate. Since packet loss is random, punctured positions caused by packet loss are random as well. The performance of random puncturing is inferior to the conventionally regular puncturing. Therefore, we add additional protection by increasing denominator value of $r^*_{k_i}$ by 1. Simulation results show that this scheme gives more performance improvement.

This method provides a few benefits evidently. First, the optimization complexity could be significant reduced compared with the method where optimization is iteratively designed for both direction. In addition, a drawback in the scheme[14] is that any residual bit error after the turbo decoding in the row direction will cause a symbol error in the column direction so that an increased BER due to channel variation could largely impair the RS decoding performance. This is the reason that turbo code rate[14] is in general very low to ensure the complete recovery of random errors. However, in our method, block loss and random errors are considered under one RCPT code scheme so that the effects of the variation of block loss rate and random errors could be treated simultaneously. For example, for the case of increased BER and reduced packet loss simultaneously due to the channel variation, it may result in an optimal rate allocation similar to the one obtained before the channel is changed.

Our objective is to find a channel code rate allocation $\{r_{k_1}, r_{k_2}, \cdots, r_{k_N}\}$, $r_{k_i} \in \mathbf{R}$, corresponding to the N frames that maximizes the expected quality of the received image, i.e., minimizes the expected distortion $\bar{D}$ of the image, and is subject to the given transmission rate. Let $p(i)$ be the probability of decoding error in the i^{th} frame protected by channel code rate r_{k_i}. The probability of no decoding error in all decoded N frames is $P_N = \prod_{j=1}^{N}(1-p(j))$. When the first i frames are turbo decoded without errors but the $(i+1)^{th}$ frame has errors, we denote the corresponding probability and distortion as P_i and D_i. Then, we have

$$P_i = p(i+1)\prod_{j=1}^{i}(1-p(j)) \qquad 0 < i < N, \tag{2}$$

$$\overline{D} = \sum_{i=0}^{N} P_i D_i \tag{3}$$

D_0 denotes the distortion when no correct frame is received. The probability of a decoding error in the first frame is $P_0 = p(1)$.

The candidate solutions of the brute force search is M^N. Since the most important source bits are placed in the beginning frames and the source rate-distortion function is convex, the Turbo code rate can be assumed nondecreasing with n, $1 < n \le N$ and the number of candidate allocations is reduced from M^N to $\binom{N+M-1}{M-1}$.[12] The value is still very large for big M and N values. For example, it is 1.4714×10^{10} for $M = 10$ and $N = 32$. We proposed a GA based optimization algorithm[17] which can get almost the same result with brute force search with very low complexity. In this paper, this GA-based optimization algorithm is used to allocate the channel code rates.

3. MULTIPLE CRC STRUCTURE BASED PROTECTION

Denote $\mathbf{S} = \{s_1, s_2, \cdots, s_N\}$ as the number of source bits in N frames. In our scheme, we propose to partition s_i source bits of the i^{th} frame into K blocks. Consequently, each block has $L_B = s_i/K$ bits, and totally there are $N \times K$ blocks. At the end of each block, CRC parity bits are added for error detection. As a result, with slightly added redundancy of multiple CRC parity bits, more blocks of data could be used to improve the source decoding.

Let $p_B(i)$ be the probability of decoding error for blocks in the i^{th} frame protected by channel code rate r_i. This value is directly connected with the frame error rate p_i by equation $p_i = 1 - (1 - p_B(i))^K$. The probability of no decoding error in all decoded $N \times K$ blocks is $P_{N\times K} = \prod_{j=1}^{N}(1 - p_B(j))^K$. When the first i blocks after turbo decoding have no errors but the $i + 1^{th}$ block has errors, we denote the corresponding probability and distortion as $P_{B,i}$ and $D_{B,i}$. Then, we have

$$P_{B,i} = \begin{cases} p_B(\lfloor i/K \rfloor + 1)(1 - p_B(\lfloor i/K \rfloor + 1))^{i - \lfloor i/K \rfloor K}, & 0 \le i < K, \\ p_B(\lfloor i/K \rfloor + 1)(1 - p_B(\lfloor i/K \rfloor + 1))^{i - \lfloor i/K \rfloor K} \prod_{j=1}^{\lfloor i/K \rfloor}(1 - p_B(j))^K, & i \ge K \end{cases} \tag{4}$$

$$\overline{D} = \sum_{i=0}^{N\times K} P_i D_{B,i} \tag{5}$$

Here, $D_{B,0} = D_0$ is the distortion of the case that no correct block is received. The probability of a decoding error in the first block is $P_{B,0} = p_B(1)$.

We know that Turbo codes with very low code rate may correct almost all errors in a large range of channel error rates. In addition, Turbo codes with high code rates may result in high number of residual errors in a decoded frame. In these two cases, there is no need to use multiple CRC in a packet. Simulation results show that when the frame error rate of a channel code rate is within (0.01, 0.8), multiple CRC improves the decoding performance. As a result, in this research, multiple CRC is only applied for certain frames whose channel code rates give the residual frame error rate to be in the range of (0.01, 0.8), whereas other frames without errors or with too many errors still have one CRC parity for the entire frame.

4. EXPERIMENTAL RESULTS

In this paper, we propose and test the following two algorithms based on previous discussion for image transmission over channels with both packet loss and random errors.

Algorithm 1:

1. Use GA-based optimization with original channel BER to minimize equation (3).
2. Based on equation (1), reduce the obtained RCPT code rate for each frame to take into account of PLR.
3. Add additional protection by increasing 1 for the denominator of each code rate.

Algorithm 2:

1. Use algorithm 1 to design the RCPT code rates for all frames.
2. Check code rates and channel conditions, based on the analysis of the section 3, choose some frames for the use of use multiple CRC.
3. Partition those frames into three blocks and add CRC to every block.

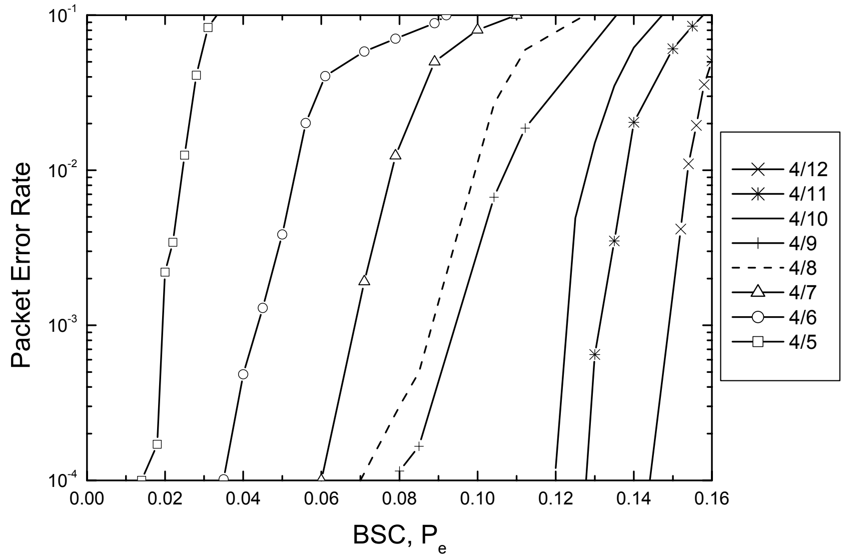

Figure 2. Probability of frame error after decoding. BSC, coded frame length = 4096 bits, 20 iterations of log-MAP decoding.

The test image is 512 × 512 8 bpp Lena image which is first coded by the SPIHT algorithm[1] and then protected by RCPT/CRC. The coded frame length is set as 4096 bits for all cases. A 16-bit CRC with generator polynomial 0x8005 is used. The turbo code is $(21, 37)_{octal}$ and the set of RCPT code rates is (4/12, 4/11, 4/10, 4/9, 4/8, 4/7, 4/6, 4/5).[18] Log-MAP decoding is adopted and the decoding ends after 20 iterations. All experiment results were obtained with 5000 independent simulations.

Fig. 2 shows the residual frame error rate after turbo decoding with 20 iterations. These error probabilities are further used to calculate the expected PSNR (or distortion) in the optimization process. It needs to note that for different frame size the result shown in Fig.2 is different. In general, for a given code rate, the larger frame size, the better decoding performance.

Fig.3 gives the PSNR comparison of GA based UEP and EEP protection for BSC cases. Evidently, an appropriate channel EEP in low BER case causes much performance degradation in high BER cases, and a high protection in a high noise case causes much redundancy in the low noise cases and reduces the source decoding performance. The UEP shows consistent performance improvement over EEP throughout the BER range. Fig.4 presents the decoding performance of three algorithms in BSC: equal error protection (EEP) with one CRC per packet, brute force UEP search with one CRC per packet and the GA-based UEP with three CRCs for some packets. Simulations were executed for the overall transmission rates of 0.25 bpp and 0.5 bpp. The optimal rate allocations were designed for different P_e from 0.01 to 0.1. It clearly shows that the Brute Force UEP with one CRC outperforms the EEP algorithm. the GA-based optimization with multiple CRC provides even better results than those of the brute force search with one CRC. This result shows that by carefully using multiple CRC structure, slightly added redundancy due to the CRC parity bits can result in more useful information bits and hence the better quality of the reconstructed image.

Then, we consider channels with both random bit errors and packet loss. We compare our results with those based on the structure of Sherwood[13] but with RCPT/CRC and RS codes. Sherwood[13] gave the structure of the product code to handle the channels have both random bit errors and packet loss. RCPC/CRC (RCPT/CRC) was used to correct random bit error and RS code was used to handle packet loss. In algorithm 1, packet loss is converted into the bit erasures in every row by interleaving. This effect can be further regarded as randomly puncturing a turbo code with reduced data rate. Algorithm 2 incorporates with multiple CRC technique based on

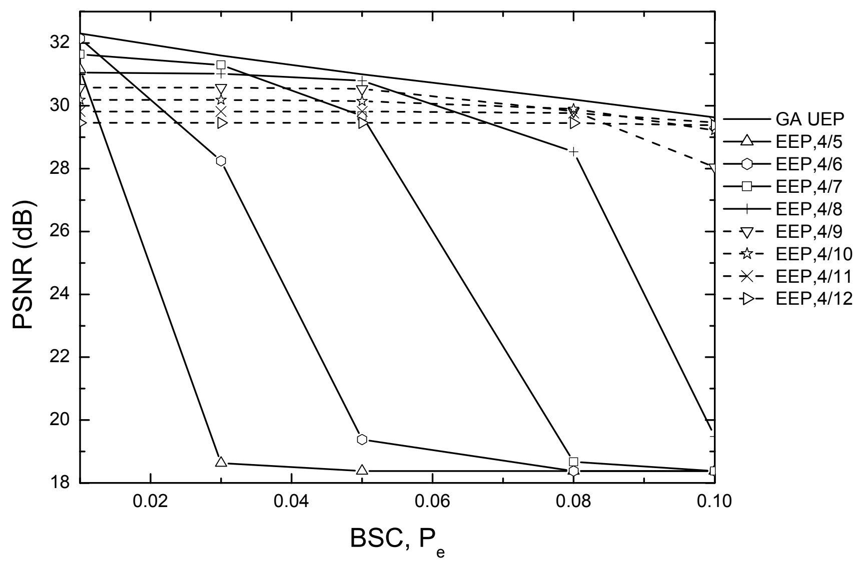

Figure 3. Expected PSNR performance of EEP and UEP for the Lena image over BSCs.

algorithm 1. Fig. 5 gives the performance of the Sherwood[13] algorithm and our two algorithms. Simulations were executed for the overall transmission rate of 0.25 bpp and 0.5 bpp, respectively. The optimal rate allocations were designed for different P_e from 0.01 to 0.1. It shows that our two algorithms outperform the algorithm of Sherwood consistently. This is due to the use of the interleaving in each data frame before the transmission which converts the packet loss into random bit error and produces a more efficient source-channel rate allocation. Algorithm 2 improves the performance even more by using multiple CRC. It needs to notice that we assigned three CRC codes in one frame based on the simulation results. Different number of CRC codes may be used dynamically for different frames to achieve even better result. However, this may cause additional side information in transmission.

5. CONCLUSION

This paper presents a new joint source-channel coding scheme for the transmission of progressive images over noisy channel. First, before each packet is transmitted over noisy channels, an interleaver is applied to convert the packet loss into random bit erasures in terms of the punctured turbo codes. Therefore, a noisy channel with both packet loss and random bit errors is equivalent to a channel with only random bit errors so that a single RCPT/CRC code can be designed for channel protection. Then we propose to use multiple CRC structure for source information frames whose PER falls into a specific range. Experiment results have demonstrated promising performance of the proposed scheme.

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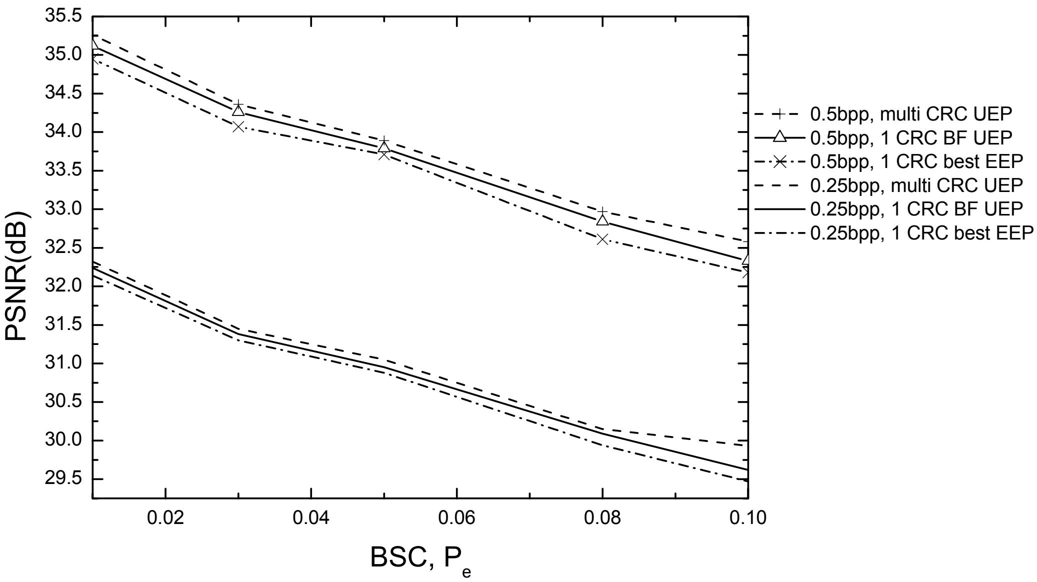

Figure 4. Expected PSNR (dB) performance of the best EEP/one CRC, brute force UEP/one CRC and UEP/multiple CRC for the Lena image over BSCs. Total transmission rate is 0.25 bpp and 0.5 bpp, respectively.

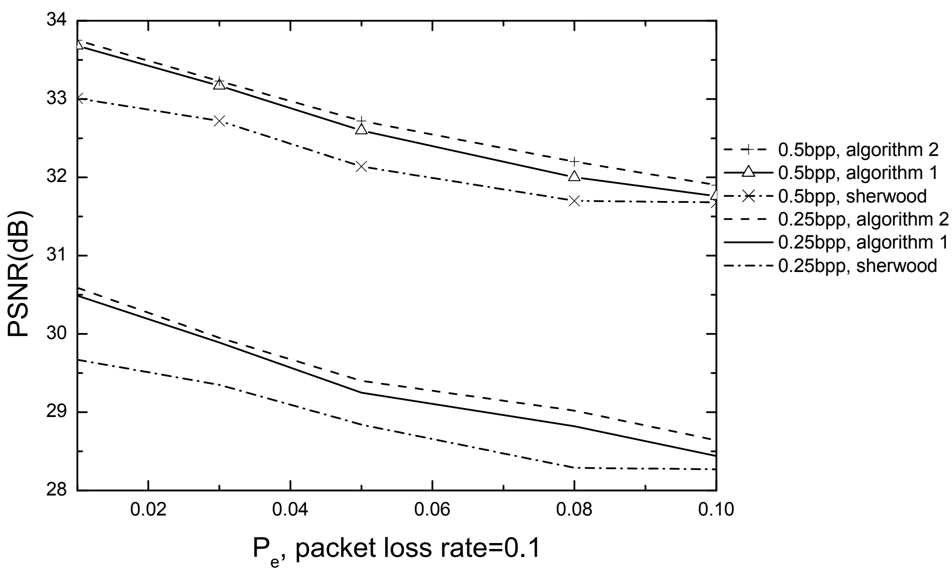

Figure 5. Expected PSNR (dB) for LENA image at transmission rate 0.25 *bpp* and 0.5 *bpp*. The optimization was done for channels with 0.1 packet loss rate and different BERs for Sherwood algorithm, our proposed algorithm 1 and algorithm 2.

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