WIRELESS IMAGE TRANSMISSION USING TURBO CODES AND OPTIMAL UNEQUAL ERROR PROTECTION

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ABSTRACT

A novel image transmission scheme is proposed for the communication of SPIHT image streams over wireless channels. The proposed scheme employs Turbo codes and erasure-correction codes in order to deal effectively with burst errors. An algorithm for the optimal unequal error protection of the compressed bitstream is also proposed. The resulting scheme is tested for the transmission of images over wireless channels. Experimental evaluation clearly demonstrates the superiority of the proposed scheme in comparison to well-known robust coding schemes.

1. INTRODUCTION

During the past few years mobile/wireless systems have become dominant means of communication. The advantages of mobile/wireless communications, however, come at the cost of significant additional complexity in the design of suitable coding and transmission systems. The specific application of image transmission over wireless channels poses a challenging research problem, requiring among others, appropriate selection of the set of channel codes for effective forward-error-correction (FEC).

A variety of error-resilient techniques [1, 2, 3] have been recently proposed in the literature. Most are based on Set Partitioning In Hierarchical Trees (SPIHT) [4] source coder which generates embedded bitstreams, *i.e.* streams in which lower rates are prefixes of higher rates.

In the present paper, a novel methodology for the transmission of images over wireless channels is proposed. The proposed scheme is based on the SPIHT source coder applied in conjunction with the application of Turbo codes [5] across rows of data in a product code consisting of Turbo codes and Reed-Solomon codes (RS). Due to the systematic form of Turbo codes, immediate extraction and decoding of source information from the channel-coded stream is possible whenever the stream is not corrupted.

The optimal allocation of Reed-Solomon symbols is also examined in the present paper and an algorithm for efficient Unequal Error Protection (UEP) is proposed. The UEP algorithm is based on the formulation of channel blocks of constant size, *i.e.* blocks of information in which the source bytes vary but the sum of source and channel bytes is fixed. This approach admits a fast dynamic programming solution. The resulting robust transmission system is evaluated and is shown to outperform the best-performing known schemes for the transmission of images over wireless channels.

The paper is arranged as follows. In Section 2, the Forward Error Correction methodology used with the present system is described. In Section 3, the proposed channel rate allocation technique is described. Experimental results are reported in Section 4. Finally, conclusions are drawn is Section 5.

2. FORWARD ERROR CORRECTION USING TURBO CODES

In this section we employ a product code, *i.e.* a code which generates parity bits for data arrays in both horizontal and vertical directions (across rows and columns of the array respectively). The row code consists of a Cyclic Redundancy Code (CRC) combined with a systematic Turbo code [5], while the column code is an erasure-correction shortened systematic Reed-Solomon code [6].

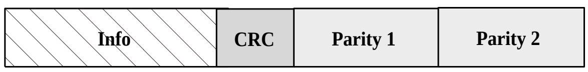

Fig. 1. Arrangement of data in a Turbo coded packet.

A different amount of protection, provided by RS codes, is first allocated to each portion of the stream. Some overhead information is added to the stream to indicate the Reed-Solomon protection level. All packets (containing information and RS symbols) are subsequently protected using concatenated Turbo/CRC codes of the same code rate. The CRC code is highly efficient for error detection during the decoding of a packet. Such errors occur quite often due to deep fades. Concatenated Turbo/CRC codes are preferable for transmission over slow fading channels compared to the usual RCPC/CRC combination because of the higher performance of Turbo codes when large source packets are used.

During the Turbo decoding of a transmitted packet, the CRC indicates if the packet is corrupted. In the event of a corrupted packet, the Turbo codes are used to recover the information. If, however, the packet is found not to contain errors, due to the systematic form of the Turbo codes, the source information can be directly extracted without the need for channel decoding. Specifically, the Turbo-coded information has the form shown in Fig. 1. As shown in [6] the CRC check can indicate the corruption of the information bits with high reliability (99.99%). Therefore, if, during decoding, the CRC indicates no corruption of the information bitstream, then the information bits can be directly decoded using the source decoder without the need to perform Turbo-decoding. In this respect, the use of Turbo codes in our system has a significant advantage over the RCPC/CRC coding approach followed in [1, 2], which requires decoding of convolutional codes even for uncorrupted streams. This feature of our system partially outbalances the additional decoding complexity that Turbo codes have in cases of corrupted streams. Therefore, the resulting scheme is of similar overall complexity while being significantly more efficient. In the ensuing Section, an algorithm for the optimal allocation of protection to the source stream is presented.

3. FAST CHANNEL RATE ALLOCATION

A UEP algorithm for channel rate allocation is presented in this section. The amount of protection allocated to data varies in the vertical direction (columns) of a data array which will be hereafter termed a “block”. The proposed algorithm takes into account the importance of each block and allocates more channel symbols (Reed-Solomon symbols) to blocks carrying important information and fewer to other blocks. In this way, blocks that achieve higher distortion improvement are better protected than the rest.

All channel blocks are assumed to be of constant size. The rate allocation algorithm, based on the importance of source information, determines the number of source symbols in each channel block so that the remaining positions are reserved for Reed-Solomon symbols. The problem formulated as above can be solved optimally under a specific target rate constraint using the Viterbi algorithm (VA) [6]. The optimization procedure is facilitated by the constant number of $source + channel$ bytes R_{s+c} [7] in each channel block.

As mentioned in the previous section, the decoding of the present scheme consists in row-wise decoding of Turbo-codes (in case the CRC check indicates a row is corrupted) and then column-wise decoding of RS codes. Therefore, in order to perform efficient allocation of RS symbols, the probability p of a row being entirely discarded due to corruption and Turbo decoding failure should be known in advance. We denote by $P(n)$ the probability that exactly n rows, out of the N rows in the array, are erased during transmission. Since RS codes are used, the probability that the k-th block is erased is equal to the probability that the number of erased rows is greater than the number of RS symbols in each column of the block:

$$P_L(k) = \sum_{i=Q(k)+1}^{N} P(i) \tag{1}$$

where $Q(k)$ denotes the number of RS symbols in the k-th block. We shall assume that the total rate budget is $R_B = M \cdot R_{s+c}$, where M denotes the total number of channel blocks to be transmitted. In this way, the computed allocation policy is optimal for the specific target rate.

In order to facilitate the allocation of protection to the source stream, we originally assume that whenever a block is plagued by uncorrectable errors, all subsequent blocks are rendered useless and do not further lower the resulting distortion. Suppose that n rows are lost. Then the expected distortion is trivially seen to equal

$$\begin{aligned}\overline{D} = D_0 \cdot P\left(n > Q\left(1\right)\right) + D_1 \cdot P\left(n > Q(2), n \le Q(1)\right) + \\ + \cdots + D_k \cdot \ P\left(n > Q(k+1), n \le Q(k)\right) + \cdots + \\ + D_M \cdot P\left(n \le Q\left(M\right)\right)\end{aligned} \tag{2}$$

where D_k is the resulting distortion after the successful transmission of the first k blocks. The last term in the sum expresses the distortion when all blocks are received intact. Due to the strictly descending Reed-Solomon protection across blocks the probability that all blocks are decodable is equal to the probability that the last block is correctly decoded. Note that

$$P\left(n > Q\left(k\right), n \le Q\left(k-1\right)\right) = P_L\left(k\right) - P_L\left(k-1\right) \tag{3}$$

We define P_d as

$$P_d\left(k\right) = \begin{cases} P_L\left(k\right) & , if\ k=1 \\ P_L\left(k\right) - P_L\left(k-1\right) & , otherwise \end{cases} \tag{4}$$

Thus, eq.(2) can be equivalently expressed as:

$$D = D_0 \cdot P_d\left(1\right) + \sum_{k=2}^{M} D_{k-1} \cdot P_d\left(k\right) + \left(1 - P_L\left(M\right)\right) \cdot D_M \tag{5}$$

The minimization of the above average distortion D can be achieved using the Viterbi algorithm [8]. Whenever two or more paths merge in one trellis node, *i.e.* they have the same cumulative total rate and the same channel rate, only the path having the minimum distortion is retained and the others are discarded.

In the above formulation, we disregard the fact that even in blocks containing uncorrectable errors, the first few rows before the occurrence of a corrupted row are useful since the information they contain is still decodable. This observation can be further exploited in practice by reordering information in consecutive blocks for which equal amounts of protection have been allocated. Such blocks attain the obvious

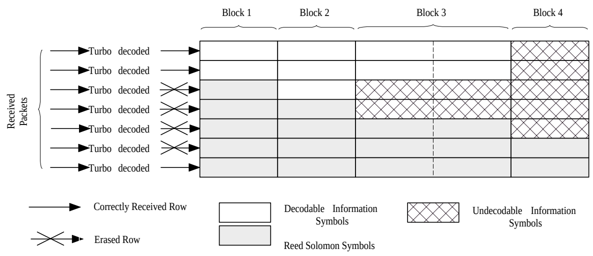

Fig. 2. Decodable bitstream when the number of errors in the stream exceeds the error correction capability of Reed-Solomon codes.

property that either they will all be transmitted successfully or will all fail. This is due to the fact that the number of erased rows that renders a block undecodable is the same for all such blocks since they are all protected equally. Rearranging the source bytes is advantageous over the initial information ordering in blocks and leads to lower distortion since more bytes are decodable in case of failure of the Reed-Solomon codes whereas there is no change in the distortion when the blocks are transmitted correctly. The reordering of information can be seen as merging of consecutive blocks. This is explained in Fig. 3.

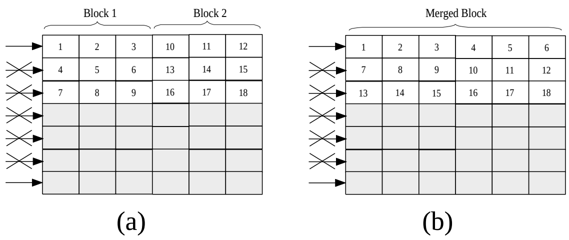

Fig. 3. The second row is unrecoverably corrupted, (a) Only source symbols 1-3 are decodable. (b) Symbols 1-6 are decodable.

The above observations dictate the use of an optimization policy which is different than that expressed using eq.(5).

The resulting modified problem of the channel rate allocation can be solved optimally using dynamic programming techniques. The two paths displayed in red color in Fig. 4(a) merged in node n_3. The upper path corresponds to the allocation of equal amounts of protection for blocks 2 and 3 whereas the lower path corresponds to different RS protection. If block merging is not permitted, the conventional tree growing shown in Fig. 4(a) must be followed. If however, block merging is assumed, the trellis diagram in Fig.4(a) must be modified. Fig. 4(b) shows the modifications occurring when two successive blocks are allocated the same protection. In this case, the node n_2 in the upper path is cancelled and the path linking n_1 and n_3 via n_2 is replaced by a new one connecting nodes n_1 and n_3 directly. This is due to the fact that blocks 2 and 3 share the same

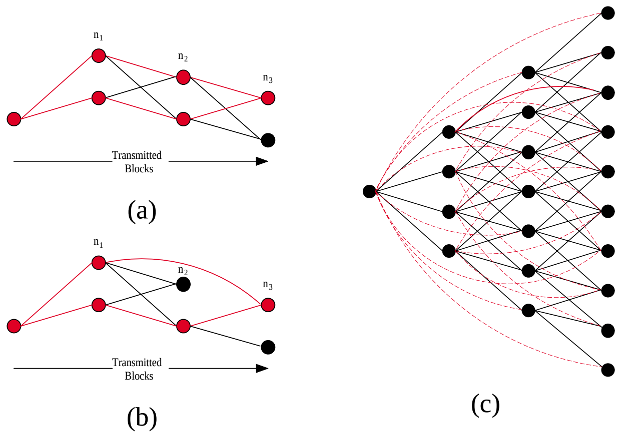

Fig. 4. (a) Conventional tree growing, (b) proposed tree growing and (c) Modified Trellis.

probability of failure. In a similar manner, whenever two or more consecutive blocks are allocated the same protection, the intermediate nodes are cancelled (only for these paths) and the initial and the final node are connected using a new branch.

The extension of the above methodology to the case of three or more merged blocks is straightforward. The resulting modified trellis in its entirety is presented in Fig. 4(c). Using the approach described above, the optimal path in the sense of minimum reconstruction error at the decoder can be found directly. In the ensuing section, experimental results demonstrating the efficiency of our method are presented.

4. EXPERIMENTAL RESULTS

The proposed scheme was experimentally evaluated for the transmission of the 512×512 test image "Lenna" over a flat-fading Rayleigh channel simulated using the Jakes model [9]. The channel model was selected so as to accurately simulate fading channels which are common in mobile and wireless communications.

The method proposed in this paper was compared to the methods in [1, 2]. For the results in this paper we assume a normalized Doppler spread 10^{-5} Hz/bps and an average SNR equal to 10 dB. The Peak-Signal-to-Noise-Ratio (PSNR) is used as a measure of the reconstruction quality[1].

Two protection strategies, termed Turbo-coded SPIHT (TSPIHT) were implemented and tested, one applying Equal Error Protection (EEP) and another applying Unequal Error Protection (UEP). In both cases $(31, 27)_8$ Turbo codes [5] were applied for the protection of symbols in the horizontal direction. For the case of equal error protection, (16,5) Reed-Solomon codes were applied to the entire image stream. For the determination of the channel code-rates,

[1]Following the approach adopted in [1, 2], the reported mean PSNR values are computed by averaging decoded MSE values and then converting the mean MSE to the corresponding PSNR value rather than averaging the PSNR values directly.

the algorithm of the previous section was used and the resulting code rates were applied to the SPIHT source stream.

Transmission scheme	*Code Rate*	*Mean PSNR*
Sherwood [1]	0.28	27.71
MDFEC [2]	0.37	28.38
TSPIHT-EEP	0.31	27.76
TSPIHT-UEP	0.33	28.54

Table 1. Performance comparison for the 512×512 "Lenna" image (0.25 bpp). PSNR results are reported in dB.

Both EEP and UEP schemes were evaluated for the transmission of images over wireless channels. Results are reported in Table 1. As seen, our UEP scheme generally outperforms its EEP variant. Our coders were also compared to the SPIHT-based coders in [1, 2]. In particular, our UEP scheme outperforms the system in [1] by 0.8 dB and the best scheme in [2] by approximately 0.15 dB. The superior performance of our scheme is due to the use of Turbo-codes, and the efficient channel-rate allocation.

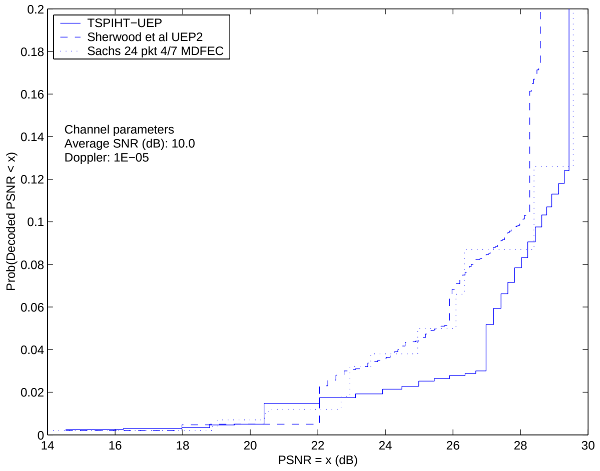

Fig. 5. Cumulative distribution of decoded PSNR for the 512×512 image "Lenna" transmitted at 0.25 bits/pixel.

The superiority of our method is seen even more clearly when comparisons are made in terms of cumulative quality distributions. Results in terms of the *cumulative quality distribution* are reported in Fig. 5. As seen, the proposed UEP-based scheme outperforms the methods presented in [1] and [2] since the decoding of low quality images is far more infrequent with our method. Moreover, due to the higher code rate used by our scheme, the gain over the method in [1] in terms of the maximum achievable PSNR is approximately 1.0 dB.

The proposed schemes were also evaluated for transmission in channel mismatch conditions, *i.e.* when the actual channel parameters do not match the parameters assumed during channel coding. As seen in Table. 2, the scheme

Encoding	10	9	8	7
Sherwood [1]	27.71	27.30	26.87	26.20
TSPIHT-UEP	28.54	28.01	27.36	26.68
TSPIHT-EEP	27.76	27.21	26.40	25.46

Table 2. Average MSE converted to PSNR of the proposed schemes in comparison to the method in [1] for channel mismatch. All schemes were optimized for $f_d = 10^{-5}$ and $\overline{SNR} = 10dB$.

based on the TSPIHT-UEP coder demonstrates significantly better performance in comparison to the scheme in [1].

5. CONCLUSIONS

A novel image transmission scheme was proposed for the communication of compressed SPIHT image streams over wireless channels. The proposed scheme employs product codes consisting of Turbo codes and erasure-correction codes in order to deal effectively with burst errors. A novel methodology for the optimal unequal error protection of compressed streams was also proposed. The resulting system and was shown to be superior in comparison to well-known schemes for the transmission of images over wireless channels.

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