A NEW FAMILY OF CHANNEL CODING SCHEMES FOR REAL-TIME VISUAL COMMUNICATIONS

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ABSTRACT

In this paper, we extend our work in [4] which employed Partial Reed-Solomon (PRS) Codes at coding rates near channel capacity on a Binary Erasure Channel (BEC). We demonstrated that an appropriately designed PRS code outperforms the classical Reed-Solomon (RS) code for a performance criterion tailored for realtime applications. This paper extends this analysis for a general BEC with varying channel conditions (under/above channel capacity). We illustrate that PRS codes exhibit a graceful degradation in erasure recovery performance and, hence, are suitable for multimedia communication. Our video simulation results outline that the enhanced erasure recovery yields a profound improvement in the perceived media quality. Finally we investigate the performance of the dividend rendered by PRS codes operating above channel capacity. In particular we define a paradigm for a unique "fixed rate" adaptive FEC scheme based on PRS codes.

1. INTRODUCTION

The unprecedented demand for data communications over unreliable systems, such as the Internet and wireless networks, has made the use of linear block codes (LBC) in Forward error correction (FEC) schemes increasingly popular. Modern Internet and wireless applications have employed LBC for unicast and multicast transmission of realtime multimedia and other non-realtime data types over erasure channels. Performance criteria for LBC codes, which are used for non-realtime data, are based on a hard requirement to *perfectly* recover all of the original message symbols. It is accepted that for a given block length of symbols the best-known codes for *perfect recovery* are Reed Solomon Codes.

For real-time multimedia applications, *perfect* recovery, and consequently perfect reconstruction, of the original message symbols is not a hard requirement, because a variety of practical application-layer error resilience and concealment methods can be used to compensate for lost data (e.g.,[1],[2]). Meanwhile, it is crucial to deliver the realtime application layer with the maximum number of the message symbols that are transmitted by the system. Therefore, the probability of a *message* symbol loss (*after* channel decoding) is a key performance parameter. We denote this probability by p_m. Hence, the parameter $\tau_m=(1-p_m)$, which represents the probability of receiving a message symbol by the realtime application (after channel decoding), is a measure of the end-to-end message symbol throughput. One of the key objectives of the family of PRS codes that were proposed in [4] was to maximize this throughput measure τ_m. (For the remainder of this paper, we will refer to τ_m as the *message throughput*.) It was shown in [4] that the optimal PRS codes can outperform RS codes when the criterion for performance evaluation is τ_m. These results have been replicated in Figure 1 to facilitate a more clear discussion.

Error Concealment techniques usually work well only when the number of losses is limited to a certain *loss threshold*. Therefore, codes that maintain very low end-to-end (effective) message losses are more desirable than codes that provide perfect recovery under good channel conditions (e.g., under very low loss probability) but provide low recovery under adverse channel conditions. This desirable feature highlights one of the key problems with current LBC codes that are used widely for real-time video. Consequently, it is very crucial for LBC codes to show a graceful degradation in their erasure recovery capability when the number of losses increases. In section 3 we show that unlike traditional RS codes, which exhibit a very sharp degradation in their ability to recover lost packets around the point ($L=N-K$) the proposed PRS codes provide a graceful transition in their lost-message-recovery.

The organization of the rest of the paper is as follows: In section 2 of this paper we give a brief introduction to the general structure of PRS codes. In section 4 we provide the results of actual video simulations and provide a subjective comparison of media quality supported by the two coding schemes. Finally in section 5 we make a case for designing adaptive FEC schemes based on PRS-1 codes for time-varying channels.

2. BACKGROUND (PRS)

Unlike non-realtime applications that may have the flexibility in selecting N and $R=K/N$, realtime applications, in general, have to employ (adhere to) a block code with a pair-constraint (N, K)[1]. For a given realtime-pair constraint (N, K), we denote a general PRS code of order s by $(N, K, \Lambda_s)_q$. Here q represents the underlying field[2]. The order of the field is constrained by the equation $q > N$, where N represents the total number of symbols in a single codeword and K represents the number of message symbols in a codeword. Λ_s represents a $2\times(s+1)$ matrix given by $\begin{bmatrix} N_1 \cdots N_{s+1} \\ K_1 \cdots K_{s+1} \end{bmatrix}$. The entries of matrix Λ_s are constrained by the following equations:

$$N_i > K_i \ \forall\, i \in [1,s],\ K_i > 0 \ \forall\, i \in [1,s],\ N_{s+1} = K_{s+1}$$
$$\text{and } N = \sum_i N_i,\ K = \sum_i K_i .$$

Thus Λ_s gives an s-partition on the set of parity symbols and a $(s+1)$-partition on the set of message symbols. The code is designed such that, $\forall\, i \in [1,s]$, the pair (N_i, K_i) forms an RS-subcode over $GF(q)$ and the K_{s+1} number of message symbols are transmitted without any protection. In general, a PRS code with $N_{s+1} = K_{s+1} = 0$ does not include any subset of message symbols that are not protected.

It was shown in [4] that for a BEC the optimal PRS code is given by an order 1 PRS code. As the design of a PRS code is completely determined by our choice of K_1, we use a shortened notation for order 1 PRS code. Thus a PRS code denoted by (N, K, K_1) is equivalent to a PRS code denoted by (N, K, Λ_1) where $\Lambda_1 = \begin{bmatrix} N-K+K_1 & K-K_1 \\ K_1 & K-K_1 \end{bmatrix}$. Thus the optimal PRS –1 code is obtained by choosing an optimal value of K_1, denoted by K^*. The probability of a *message* symbol loss (*after* channel decoding) for a (N, K, K_1) PRS-1 code over a BEC with probability of erasure p is given by

$$p_m = (1/K)\cdot\left((K-K_1)\cdot p + \left(\frac{K_1}{(N-K)+K_1}\right)\cdot \left(\sum_{i=(N-K)+1}^{N-K+K_1} i\cdot\binom{N-K+K_1}{i}\cdot p^i\cdot(1-p)^{(N-K)+K_1-i} \right) \right)$$

Equation 1

The optimal value of K_1 can be obtained by minimizing Equation-1. Since $\tau_m=(1-p_m)$, this is equivalent to maximizing the message throughput. Figures 1 compares the performance of RS and optimal PRS codes for rates near (but under) channel capacity. An interested reader is referred to [4] for a more detailed discussion.

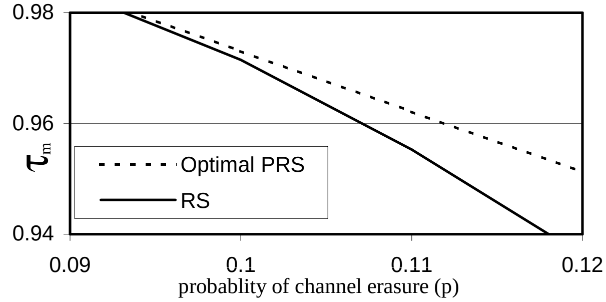

Figure 1 Performance Comparison of Optimal PRS –1 codes and RS codes for near capacity coding rates [4].

3. GRACEFUL DEGRADTION

Figure 2 shows the comparative performance of (100,88) codes of rate $R = 0.88$ as a function of number of packet losses (L). It should be noted that the avg. no. of packets dropped = $R \cdot L$. The performance of an RS code is compared with PRS – 1 codes optimized for various erasure probabilities. It can be observed that when a RS code block experiences a number of losses that is larger than the number of parity symbols, then the code is incapable of recovering any of the lost message data. Experiencing a number of losses that is larger than the number of parity symbols is quite feasible, even if, "on average", the message rate R is lower than the channel capacity. This is particularly true when the message rate R is close to (but may still be lower than) the channel capacity. On the contrary the performance of PRS – 1 code shows a graceful degradation in performance. Depending on the channel conditions, this property can be suitably exploited to provide better packet recovery than an RS based FEC scheme. The above phenomenon is responsible for PRS-1 codes showing better performance than RS codes in Figure 1. Video simulations provided in the next section shall further illustrate the significance of a graceful degradation in performance

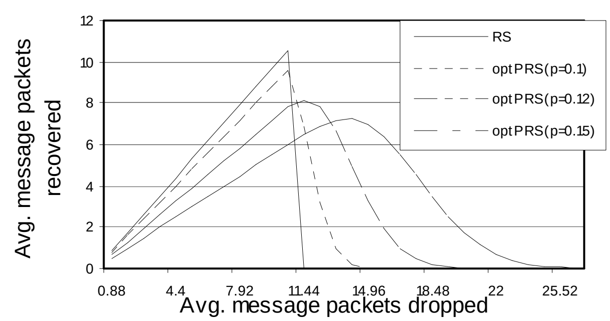

Figure 2 Comparison of recovery capability of codes optimized for different channel conditions.

[1] Each symbol in a codeword can be written to a distinct packet, thus an entire packet can be treated as a symbol.

[2] In all further discussion we shall drop q from the notation and assume that the order of the field has been pre-specified.

4. VIDEO SIMULATIONS

The overall performance due to the graceful degradation in performance of PRS codes, as the number of losses in a code block increase, is further improved when the performance is measured in terms of perceptual image quality instead of message throughput. This can be attributed to the limitations of error concealment algorithms, which are effective only when the numbers of losses (after channel decoding) are not substantial. We used the newly emerging JVT standard as an underlying video coding technique to compare the performance of RS and PRS channel coding schemes under identical channel conditions and identical loss patterns.

We use the standard test sequence *foreman* to present our results. The sequence was coded at 1MBps at 30 HZ. A GOP size of 15 with a frame sequence IPPP was used. A packet size of 512 bytes and slice size of 512 bytes were used for the purpose of our simulations. Figure 2 just shows instances in a particular ensemble of the simulations, but similar results were observed for numerous repetitions of the experiments. Figure 2 shows the results obtained by using (100,88) RS and (100,88,72) PRS-1 (optimized for p=0.11) codes. When the number of losses in a code block is less than N-K the performance of RS codes is better than that of the PRS code. The difference in performance between the two schemes is the maximum when L=N-K. As against this the performance of a PRS code is better than an RS code when the number of losses are greater than N-K. The improvement due to a PRS code is the least significant when the number of losses L = N-K+1.

In our simulations we forced the number of losses in each code block to be equal to L. Figures 3 and 4 shown below present the results for the cases when L = N-K and L =N-K+1. Moreover for L = N-K these figures show the comparison of the worst affected frames for a PRS coded sequence. Moreover, for L=N-K+1, comparison of frames when the improvement due to PRS codes is not exaggerated[3] has been presented. Thus figure 2 shows the performance comparison of a RS and PRS for a "worst case scenario" for PRS.

It can be clearly seen in the above mentioned figures that when L=12 the image quality for an RS coded sequence is better than that of a PRS coded sequence. Nevertheless the distortion in the PRS coded sequence is not very significant. On the contrary the performance of the RS coded sequence when L=13 is much worse than that of the PRS code. It can be seen that though the quality of the image for a PRS sequence also deteriorates, the increase in distortion is not significant. However the increase in distortion for an RS coded sequence is high enough to almost make the frame unintelligible. For such low quality images PSNR does not reflect the true quality of the image and hence only visual results have been presented.

[3] There were many instances when a particular frame in an RS coded sequence was significantly distorted but a PRS coded sequence had absolutely no artifacts, we avoid presenting such comparisons.

Figure 3 Clockwise an instance in the foreman Sequence for L= 12 RS code, L=12 PRS – 1 code optimized for p=0.11, L=13 PRS – 1 code optimized for p=0.11, L = 13 RS code.

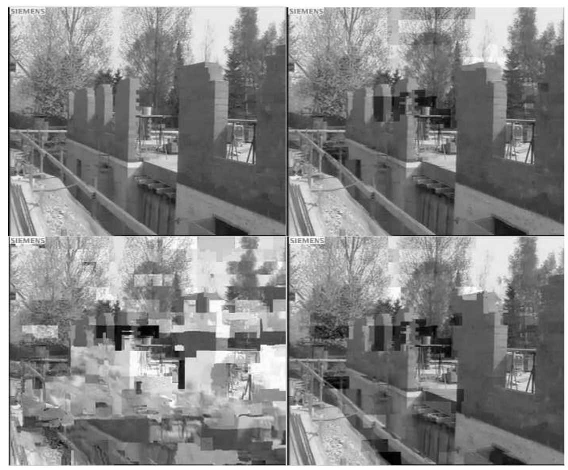

Figure 4 Clockwise an instance in the foreman Sequence for L= 12 RS code, L=12 PRS – 1 code optimized for p=0.11, L=13 PRS – 1 code optimized for p=0.11, L = 13 RS code.

In the above experiments no knowledge about the source model was used for allocation of parity symbols i.e. the symbols to be protected in a PRS code block were chosen without taking into consideration the importance of I frames or the temporal proximity of P frames to a particular I frame. Thus we are not attempting to provide a new unequal error protection scheme, however in this case the best PRS code for a BEC is an unequal distribution of parity. A more appropriate interpretation of such a code would be to recognize it as an irregular graph code. In addition the error robustness features in the standard were kept at a minimal. i.e. features such as forced intra coded blocks, data partitioning, use of B-frames etc. were turned off. Taking all the above features into consideration can significantly improve the performance of PRS codes, but even without these features and even for worst cases the performance improvement of PRS codes is significant.

5. PRS-1 BASED ADAPTIVE FEC SCHEMES

Over channels with time-varying characteristics multiple code blocks can experience a number of losses that are larger than the number of parity symbols. (e.g., the Internet [3], and wireless networks). Thus, though "on-average" coding rate is lesser than channel capacity, it is possible for the coding rate to be greater than the channel capacity for a period of time. If the change in channel conditions is slow enough and if a channel can provide some feedback information about the channel conditions, then the underlying error control code in an FEC scheme can be changed to adapt to the channel conditions. Most of the current FEC schemes adapt to the channel conditions by changing the coding rate R. If the loss probability increases the number of parity symbols are also increased (thus the rate is adapted to always transmit below channel capacity). For a real–time application this is equivalent to increasing the transmission bit-rate. Increasing the transmission bit-rate is not always feasible and thus changing the coding rate in an adaptive FEC scheme is not always suitable.

Using a PRS code based adaptive FEC scheme can mitigate the above problem. In such a scheme the coding rate is kept fixed, but the underlying PRS -1 code can be changed. The feedback information about the erasure probability from the channel can be used to optimise the design of the underlying PRS –1 code. It should be noted that the coding rate of the PRS code could be greater than channel capacity for a limited period of time. Thus a performance analysis of PRS codes with rates greater than channel capacity is required. Figure 5 shows such a analysis. It compares the performance of $(100,88)$ PRS – 1 codes optimised for different channel conditions, with the performance of $(100,88)$ RS code. It can be observed that the PRS – 1 codes perform significantly better than an RS code and can recover more than 85% of the lost message information even when the coding rate is well above channel capacity.

It should be realized though, that it is possible to design an RS based fixed transmission rate adaptive FEC scheme. This can be achieved by changing the rate of a code without changing the block-length and transmission rate. The two possible ways to achieve this are (a) transmitting only a subset of K^* message packets out of the K message packets and protecting these K^* message packets by $N-K^*$ parity packets instead of $N-K$. (b) transmitting only a subset $N\cdot(1-p)$ message packets out of the K message packets and protecting these $N\cdot(1-p)$ message packets by $N\cdot p$ parity packets instead of $N-K$. Figure 5 shows that performance of scheme (a) is much worse than optimal PRS –1 code. The performance of (b) is better than RS code but still inferior to that of an optimal PRS code. Never the less we believe that it is possible to get performance comparable to the optimal PRS –1 codes by optimally dropping packets before transmission and decreasing rate as described in (a) and (b). Even such a hypothetical scheme, on account of being an RS based scheme will not exhibit graceful degradation. As the feedback about channel conditions is an estimate over multiple code blocks, it is possible for an RS code to be ill designed for individual blocks. In such a event the performance of a PRS-1 code will not deteriorate as rapidly as an RS based code.

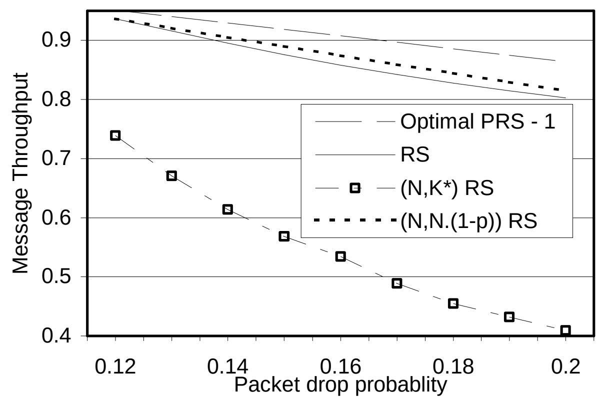

Figure 5 Comparison of (100,88) optimal PRS –1 with (100,88) RS, (100,K*) RS and $(100,100\cdot p)$ RS for coding rate greater than channel capacity.

6. CONCLUSIONS

In this paper it was observed that degradation in performance of PRS codes is more graceful than that of the RS codes. This feature can be suitably exploited to facilitate improved performance, for time varying channels and also satisfy the needs of modern robust multimedia communication schemes. JVT based video simulations were used to further illustrate the utility of the PRS scheme. The PRS codes are capable of recovering partial information even when the number of losses is higher than redundancy. Thus it was also shown that it is possible to design a "*fixed coding rate*" adaptive FEC scheme based on these PRS codes.

7. REFERENCES

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