OPTIMAL UNEQUAL ERROR PROTECTION WITH USER COOPERATION FOR TRANSMISSION OF EMBEDDED SOURCE-CODED IMAGES

Andres Kwasinski and K. J. Ray Liu
Department of Electrical and Computer Engineering, University of Maryland, USA.

ABSTRACT

This paper studies the transmission of images encoded using an embedded source encoder over a wireless network allowing user cooperation. A dynamic programming algorithm is applied to optimally allocate to each source coded packet error protection in the form of a choice of channel code and a decision on the use of cooperation. The results show that for degraded source-destination channels, the use of user cooperation on all source coded packets significantly improves the reconstructed quality. As the source-destination channel improves the optimal policy becomes a hybrid that uses user cooperation only for the most important source packets. When the source destination channel is sufficiently good, all source packets are sent without cooperation. Thus, a test is presented to estimate the channels states when cooperation is first used.

Index Terms— Image communication, cooperative systems, adaptive coding, channel coding, source coding

1. INTRODUCTION

User cooperation is new paradigm in wireless communications that takes advantage of the broadcast nature of the wireless channel and associate user to help each other in improving the communication quality by relaying information through several paths. Although several research works have been published since the idea of user cooperation was first introduced in [1], few of these works focus on the transmission of multimedia sources. Notably for the present paper, [2] presented a simulation-based study of transmission of a 2-layer encoded multimedia source with and without the use of cooperation for the base layer. In [3] we compared different source encoding schemes in terms of their performance when transmitted over user-cooperative networks. We concluded that layered coding presented the best performance.

Computational complexity limitations restricted the study in [2] to two layers and the one in [3] to three. Both works considered synthetic sources modeling the source samples with a standard Gaussian distribution. In this paper we consider the transmission of actual images encoded using an embedded (successively refinable) source encoder, i.e. the number of layers is very large. Due to the inherent hierarchical order of embedded bit streams, it is imperative to apply unequal error protection (UEP) schemes that protect each bits in accordance to its relative hierarchical importance. The design of optimal UEP for transmission of embedded coded images is a challenging problem that has been considered in [4] using a dynamic programming approach.

In this paper we study the transmission of embedded coded images over wireless networks that allow user cooperation. We are able to study what is the optimal policy in using user cooperation by applying a dynamic programming algorithm that for each successive source packet optimally decides on the use of user cooperation and allocates a channel code. From the presented results we show that the use of cooperation significantly improves the reconstructed image quality for degraded source-destination channels. When the source-destination channel is sufficiently good, the best policy is the use of weak error protection with no user cooperation. Over intermediate values of source-destination channel signal-to-noise ratio (SNR) the optimal policy is a hybrid solution where weak codes with user cooperation are used to protect the most important source packets and strong codes without user cooperation are used to protect the less important source packets. Because of this behavior we present a test to estimate the channels states when cooperation is first needed.

2. SYSTEM MODEL

Consider the transmission of an image over a wireless network subject to a transmitted bit budget and through a channel with fading that we assume remains constant for the duration of each transmission period. The image is first encoded using an embedded source encoder, i.e. the source coded bit stream has a hierarchy where each additional bit that is added to the ones already decoded improves the reconstructed quality. The input to the source encoder is a block of N_s pixels. We assume that the output is packetized into fixed-length *source packets* of k_s bits.

Before transmission, each source packet is fed into a variable-rate channel encoder. The particular channel coding rate (channel code) that is applied to each source packets depends on its hierarchy within the source coded bit stream. In this way, we address the particular challenge associated with transmission of embedded sources over channels with errors, where the presence of an error in the bit stream renders all subsequent bits unusable. In this paper we assume that the channel code is chosen from a family of rate-compatible, punctured convolutional (RCPC) codes [5]. In the sequel we will be interested in knowing the *source packet decoding failure*, i.e. the probability that there are errors in a source block after channel decoding errors. This probability can be approximated through a tight upper bound as, [6],

$$P_e \approx 1 - \left(1 - \sum_{d=d_f}^{\infty} a(d) P_e(d|\gamma)\right)^{k_s}, \qquad (1)$$

1-4244-0481-9/06/$20.00 ©2006 IEEE

where γ is the channel SNR, d_f is the free distance of the code and $a(d)$ is the number of errors events with Hamming weight d and probability of occurrence $P_e(d|\gamma)$. As noted previously, if the channel decoder is unable to completely correct all errors, a source packet decoding error is declared and the erred packet and all subsequent ones are discarded. The source is reconstructed only using those source packets received before the first packed with a source packet decoding error.

Communication may be carried on using or not user cooperation. In a cooperative scheme a third node, the *relay node*, is associated with the source node to achieve user-cooperation diversity. Communication in a cooperative setup takes place in two phases. In phase 1, a source node sends information to its destination node that is also overheard by the relay node (which is likely in a wireless network). In phase 2, the relay cooperates by forwarding to the destination the overheard information. At the receiver the signals received from the source and the relay are combined and the transmitted message is detected. We assume that a Maximum Ratio Combiner (MRC) is used to combine the symbols arriving through different paths. This operation improves the quality of the communication channel as compared to that of a peer-to-peer communication. The cost of this improvement is a reduction in bandwidth efficiency due to the transmission in two phases. User cooperation can be implemented using different techniques, depending on the particular signal processing at the relay node. In this paper we will consider *amplify-and-forward* (AF) cooperation. It will become clear that this choice will not affect the generality of our proposed design. For AF cooperation, it can be shown that the symbol SNR at the output of the MRC is [7]

$$\gamma_A = \gamma_{sd} + \frac{\gamma_{sr}\gamma_{rd}}{1 + \gamma_{sr} + \gamma_{rd}}. \tag{2}$$

where γ_{sd} is the source-destination channel SNR, γ_{sr} is the source-relay channel SNR and γ_{rd} is the relay-destination channel SNR.

3. PROBLEM FORMULATION

At transmission time, each source packet has associated a transmission policy. The transmission policy for each source packet is formed by a choice of a channel code and a decision on whether it has to be sent using user-cooperation or not. We will denote by π_i the policy assignment for source packet i and by π the complete set of policy assignments for all source packets. The policy assignment is performed subject to a constrain on the total number of transmitted bits. For convenience, we will measure this constrain in bits per source sample, and we will denote it by R. Let the family of available channel codes used in policy assignment be denoted by $\mathcal{C} = \{c_1, c_2, \ldots, c_M\}$. Let the channel codes rates be denoted by $r_c(c_i)$, $i = 1, \ldots, M$ and $r_s = k_s/N_s$ be the single source packet rate measured in bits per sample. Then, the total number of channel bits necessary to transmit a source packet with index i that is transmitted with channel code c_i, is given by

$$R_{T_i} = \frac{r_s}{\phi_i r_c(c_i)}, \tag{3}$$

where the function ϕ_i takes into consideration the effects of using cooperation on bandwidth efficiency. The introduction of this function is key in integrating the use of user cooperation into the design as an instance of forward error control, which will allow us to find an optimal solution. Let

$$\phi = \begin{cases} 1, & \text{when no cooperation is used.} \\ 1/2, & \text{when cooperation is used.} \end{cases} \tag{4}$$

We note that the total number of transmitted source packet is also a design variable because of the presence of a transmit bit budget and the variable number of bits used to transmit each source packet. Thus, we denote with $N(\pi)$ the total number of transmitted source packet.

The design goal is to find the transmission policy for each source packet and the number of transmitted source packets that maximizes the average quality subject to a constrained on the total transmitted channel bits. Introducing peak signal-to-noise ratio (PSNR) as our quality measure and defining $R_T^\pi(k) = \sum_{i=k}^{N(\pi)} R_{T_i}$, the design problem can be stated as

$$\max_{\pi} \bar{Q}, \quad \text{subject to } R_T^\pi(1) \leq R \tag{5}$$

where $\bar{Q}$ is the mean PSNR.

4. OPTIMAL POLICY ASSIGNMENT

Note that the use of cooperation provides another instance of error correcting code over a better channel but at a cost of twice the total numbers of bits (i.e. those send during phase 1 and resend during phase 2) of that when no cooperation is used. Because of this, we are able to draw our solution for optimal unequal error protection and cooperation decision from [4], where the optimal design of a joint source-channel coder for transmission of embedded sources was considered. We summarize next the policy assignment algorithm.

The algorithm is a dynamic programming algorithm based on the computation of the incremental reward, denoted by δ_i, when a new source packet i can be used at the source decoder to improve the reconstructed quality. We define $\delta_i = Q(r_s i) - Q(r_s(i-1))$, where $Q(x)$ is the reconstructed quality associated with a source coding rate equal to x bits per source sample. Next, for allocation policy $\pi = \{c_1^\pi, \phi_1^\pi, c_2^\pi, \phi_2^\pi, \ldots, c_N(\pi)^\pi, \phi_N(\pi)^\pi\}$, and $k = 1, \ldots, N(\pi)$, define

$$\Delta(k, \pi) = \sum_{i=k}^{N(\pi)} \Big(\sum_{j=k}^{i} \delta_j \Big) P_{i|k-1}(\pi), \tag{6}$$

where $P_{i|k-1}(\pi)$ is the conditional probability that exactly the first i source packets are decoded correctly given that the first $k-1$ packets are decoded correctly, when using policy π. Let $P_e(c, \phi)$ be the source packet decoding failure associated with code c and user-cooperation decision ϕ, it can be shown [4] that for $k = 1, \ldots, N(\pi)$, and $i = k, k+1, \ldots, N(\pi)$ the following recursions hold

$$R_T^\pi(k) \quad = \quad R_{T_k}^\pi + R_T^\pi(k+1) \tag{7}$$

$$\Delta(k, \pi) \quad = \quad \begin{cases} \big(1 - P_e(c_{N(\pi)}^\pi, \phi_{N(\pi)}^\pi)\big)\delta_{N(\pi)}, \\ \qquad \text{for } k = N(\pi) \\ \big(1 - P_e(c_k^\pi, \phi_k^\pi)\big)(\delta_k + \Delta(k+1, \pi)), \\ \qquad \text{for } k = 1, 2, \ldots, N(\pi) - 1. \end{cases} \tag{8}$$

Also, it can be show [4] that $\Delta(1,\pi) = \bar{Q} - Q(0)$. Then, problem (5) can be stated as $\max_\pi \Delta(1,\pi)$, subject to $R_T^\pi(1) \leq R$. Using recursions (7)-(8) the optimal policy that solves this problem by allocating channel codes and deciding on the use of cooperation for each source packet can be found through the following dynamic programming algorithm:

1. Compute the state trellis with states
$$(\text{source packet index}, R_T^\pi(k)).$$
2. Compute for each trellis state the optimal value of the objective function $\Delta(k, R_T^\pi(k))$,
$$\Delta^*(k, R_T^\pi(k)) = \begin{cases} 0, \quad \text{if } R_T^\pi(k) < r_{min} \\ \max\limits_{c\in\mathcal{C},\phi_k} \big(1 - P_e(c_k^\pi, \phi_k^\pi)\big)\big(\delta_k + \\ \qquad + \Delta^*(k+1, R_T^\pi(k+1))\big), \ \text{otherwise.} \end{cases}$$
3. The total number of source packet sent is found by
$$N^*(k,R) = \begin{cases} N^*(k+1, R_T^\pi(k) - R_{T_k}^\pi), \\ \quad \text{if } \Delta^*(k+1, R_T^\pi(k) - R_{T_k}^\pi) > 0 \\ k, \ \text{otherwise.} \end{cases}$$
4. The optimal policy π is the set of solutions to step 2 that finishes at state $\Delta^*(1, R)$.

As we will see in the next section, the subset of source packets that are transmitted using cooperation changes depending on the channels states. Then, from a network design and control perspective it is important to identify when it is better to use some level of user cooperation. We will next use properties of the design problem and its solution to estimate the channel conditions corresponding to the transition from no use of cooperation to use of cooperation. Firstly, we remark that the use of user cooperation improves the error performance of any channel code due to the better communication channel but at a cost of doubling the number of transmitted bits. Secondly, earlier packets need to be assigned a higher level of error protection because if received with errors all successive packets are rendered useless. The combined effect of these observations is that the policy allocation algorithm tends to use up the code assignments without user cooperation up to the point when the cost associated with the assignment of a high rate code with user cooperation becomes competitive. Also, policies with user cooperation will be assigned first to the first transmitted packets.

Therefore, we approximate the policy assignment for the worst channel conditions that do not make use of user cooperation as that assigning the same channel code, c_{nc} to all packets, i.e. π_{nc} is $c_i^\pi = c_{nc}$ and $\phi_i = 0$, for all $i = 1, 2, \ldots, N(\pi_{nc})$. If c_1 is the code with largest rate, c_{nc} is chosen so that $r_s/r_c(c_{nc}) \approx 2r_s/r_c(c_1)$. The rationale for this choice is that the algorithm will try to first exhaust the use of lower cost codes that do not use cooperation and the fact that small differences in allocation for the least important packets have small effect on the overall performance. Next, we approximate the first policy that uses cooperation, π_c as $c_1^\pi = c_c = c_1$, $\phi_1 = 1$, and $c_i^\pi = c_{nc}$ and $\phi_i = 0$, for all $i = 2, \ldots, N(\pi_c)$, where $N(\pi_c) = N(\pi_{nc}) - 1$. The transition to the use of cooperation will occur whenever the channels state are such that the sign of $\Delta^*(1,\pi_c) - \Delta^*(1,\pi_{nc})$ changes from negative to positive, using (8) we compute

$$\begin{aligned} \Delta^*(1,\pi_c) &= \big(1 - P_e(c_c, \phi = 1)\big)(\delta_1 + \Delta(2,\pi_c)) \\ \Delta^*(1,\pi_{nc}) &= \big(1 - P_e(c_{nc}, \phi = 0)\big)(\delta_1 + \Delta(2,\pi_c) + K), \end{aligned}$$

where $K = \big(Q(N(\pi_{nc})r_s) - Q((N(\pi_{nc})-1)r_s)\big)\big(1 - P_e(c_{nc}, \phi = 0)\big)^{N(\pi_{nc})-1}$. It may be the case that the sign of $\Delta^*(1,\pi_c) - \Delta^*(1,\pi_{nc})$ never changes because $c_c = c_1$ is too weak to outperform c_{nc}, in such case the evaluation needs to be repeated successively changing $c_c = c_2, c_3, \ldots$ until a solution is found. When c_c is such that $r_s/r_c(c_{nc}) \leq 2r_s/r_c(c_c)$ always, the search needs to be done with $r_c = c_M, c_{M-1}, \ldots$, where c_M is the strongest channel code.

5. SIMULATION RESULTS

We used the algorithm shown in the previous section to evaluate the difference between networks that allow user cooperation and networks that do not. We also studied how cooperation is allocated among the different source packets, considering channel states and the embedded source hierarchy.

We considered two different images: "Lena" and "Barbara". Both images were 256×256 pixels in size. For embedded image source codec we used our implementation of the SPIHT codec [8] using 9/7 wavelets and 6 level of analysis. For channel coding we choose a memory 8, mother code rate 1/4, RCPC code family from [9], with possible channel codes 4/5, 2/3, 1/2, 4/9, 4/10, 4/11, 1/3, 2/7 and 1/4.

Figures 1 and 2 show the results for the case of $\gamma_{sr} = \gamma_{rd} = 2$ dB. We choose these values because we found the corresponding results to be representative of our complete set of results. Figure 1 shows the average reconstructed quality (measured as PSNR in dBs) as a function of the source-destination channel SNR. The results are consistent with those from [3] in that for sufficiently good source-destination channel the optimal solution do not use user-cooperation. This is because the error correcting code performance outweighs the cost in bandwidth efficiency associated with user cooperation. The results also show that as the source-destination channel degrades the use of cooperation provides a significant improvement in performance.

Figure 2 shows on top the incremental rewards associated with each source packet and at the bottom the policy assignment for different system setups. Due to the particular choice of results we are presenting, the policy assignment can be represented through the overall (including cooperation) channel coding rate. In this way, any policy with an associated rate less than 1/4 corresponds to the use of cooperation and the assignment of channel code with rate twice the one shown. As it is natural for embedded bit streams, the results show that larger error protection is assigned to earlier source packets. The results also show that as the source-destination channel degrades the optimal policies gradually shift from no use of cooperation to complete use of cooperation. Between the two extremes of no cooperation/cooperation there are policy assignments that are hybrid where cooperation is used to transmit those source packets that are more important in the hierarchical order. This shows that the use of cooperation can provide a level of error protection that outweighs the sacrifice in bandwidth efficiency. It is also interesting to note that the presence of hybrid policies contradicts our results in [3]. The difference is because, due to computational complexity limitations, in [3] we considered a reduced subset of channel codes and no more than 3 source packets (while in the present case we are transmitting 14 or more). Finally, we performed the test to evaluate the value of γ_{sd} for which cooperation is first used. We obtained $\gamma_{sd} = 2.02$ dB, which is just 0.35 dB above the true value (obtained through exhaustive search).

6. CONCLUSIONS

In this paper we have presented a scheme to transmit images encoded with the use of an embedded source codec over a wireless network. The presented scheme applies, subject to a budget on transmitted bits, unequal error protection to the source coded bit stream not only by choosing a channel code from a family of variable rate code, but also by deciding in an optimal fashion whether to send each source packet using user-cooperation or not. Also, we presented a test to estimate the channels states when cooperation is first used.

In the presented scheme, the use of cooperation extends the range of possible choices for error protection. The use of user cooperation presents an improved communication channel but comes at the cost of reducing the bandwidth efficiency. Our results show that the use of cooperation significantly improves the reconstructed image quality when the channel between source and destination is degraded. When the source-destination channel is sufficiently good, there is no need to resort to user-cooperation. In intermediate source-destination channels the optimal unequal error protection policy is a hybrid where the most important source packets are sent using user cooperation.

7. REFERENCES

[1] A. Sendonaris, E. Erkip, and B. Aazhang, “User Cooperation Diversity Part I and Part II”, *IEEE Trans. on Comm.*, Vol.51 No.11, 2003, pp. 1927-1948.

[2] X. Xu, Y. Wang, and E. Erkip, “Layered Cooperation for Wireless Multimedia Communications”, *Proc. 2004 Picture Coding Symposium.*

[3] A. Kwasinski, Z. Han, and K. J. R. Liu, “Cooperative Multimedia Communications: Joint Source Coding and Collaboration”, *Proc. Global Telecommunications Conf., GLOBECOM*, 2005.

[4] V. Chande and N. Farvardin, “Progressive Image Transmission over Memoryless Noisy Channels”, *IEEE J. of Sel. Areas in Comm.*, Vol.18 No.6, 2000, pp. 850-860.

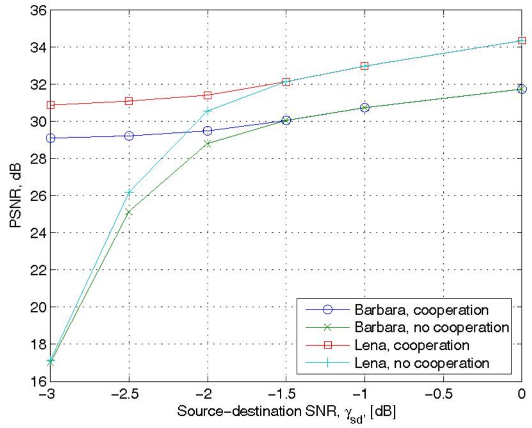

Fig. 1. Comparison of quality (PSNR) between networks with and without user cooperation.

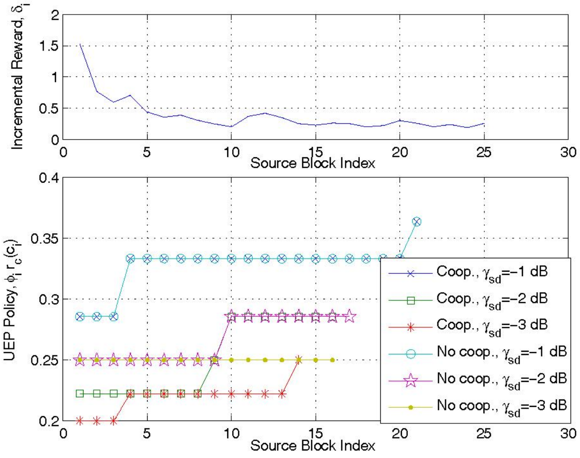

Fig. 2. Incremental rewards (top) and policy assignment (bottom) for each source packet.

[5] J. Hagenauer, “Rate Compatible Punctured Convolutional (RCPC) Codes and their Applications”, *IEEE Trans. on Comm.*, Vol.36 No.4, 1988, pp. 389-399.

[6] E. Malkamaki and H. Leib, “Evaluating the Performance of Convolutional Codes Over Block Fading Channels”, *IEEE Trans. on Inf. Theory*, Vol. 45, No.5, 1999, pp. 1643-1646.

[7] J.N. Laneman, D.N.C. Tse and G.W. Wornell, “Cooperative Diversity in Wireless Networks: Efficient Protocols and Outage Behavior”, *IEEE Trans. Inf. Theory*, Vol. 50, No. 12, 2004, pp. 30623080.

[8] A. Said and W. A. Pearlman, “A New, Fast and Efficient Image Codec Based on Set Partitioning in Hierarchical Trees”, *IEEE Trans. on Circuits and Systems for Video Tech.*, Vol.6 No.3, 1996, pp. 243-250.

[9] P. Frenger, P. Orten, T. Ottosson, A. B. Svensson, “Rate-Compatible Convolutional Codes for Multirate DS-CDMA Systems”, *IEEE Trans. on Comm.*, Vol.47 No.6, 1999, pp. 828-836.