JOINT SOURCE CODING DIVERSITY AND COOPERATIVE DIVERSITY FOR MULTIMEDIA COMMUNICATIONS

Andres Kwasinski, Zhu Han, and K.J. Ray Liu
Department of Electrical and Computer Engineering, University of Maryland, College Park.

ABSTRACT

Source coding diversity produces multiple independent source descriptions so as to improve the received quality. Cooperative diversity exploits the broadcast nature of wireless networks by allowing multiple users to relay information for each other, so as to create multiple signal paths. This paper studies what is the best strategy in combining these two types of diversity for real-time multimedia communications by comparing the distortion-rate performance of different joint diversity schemes. Results show that exploring both types of diversity improves the system performance most, but in most of cases, only one type of diversity can achieve most of the diversity gain. The best performance is obtained when the mobile can switch between cooperative and non-cooperative operation depending on the channel conditions. Thus, we remark that it is important to design efficient protocols that manage this switch and provides motivation for all users to cooperate.

1. INTRODUCTION

Future wireless communications systems will support real-time multimedia (voice, video, audio, etc.) traffic with good quality of service, while transmitting at reduced power levels in environments impaired by signal fading. One very effective way in overcoming these challenges is the use of diversity techniques, which combine at the receiver ideally independent fading copies of the transmitted signal.

One diversity technique is spatial diversity, which transmits copies of the signal through different paths by using multiple physically-separated antennas at the transmitter, the receiver or both. Although spatial diversity provides useful performance gains, its practical implementation is limited by the size of mobile terminals. Nevertheless, due to its broadcast nature, in most multiple-user radio networks there are few constraints to user overhearing each other transmitted signals. This allows for the implementation of cooperation diversity, where multiple users collaborate by creating multiple signal paths to relay information for each other. These multiple signals are combined at a destination node so as to create spatial diversity. Cooperation diversity builds upon early studies on the relay channel [1]. More recently, the idea of achieving spatial diversity through user cooperation was presented in [2]. While [2] introduced the idea of cooperation through "decode and forward", in [3] the authors introduced the idea of implementing cooperation through "amplify and forward" and further studied the achievable capacity of user-cooperation schemes.

This work is partially supported by MURI AFOSR F496200210217.

Also, when the physical layer presents to upper layers multiple communications paths, diversity can be exploited at the source codec. *Multiple Description Coding* is a form of this source coding diversity ([4]) that had been studied for error resilient source coding applications [5], especially in communications over parallel channels [4]. Here, different coded descriptions are sent through each path. At the receiver, each description can be decoded independently or, if possible, combined together to obtain the reconstructed source with a lower distortion[6].

Diversity techniques can be combined together to further improve performance. Our goal in this paper is to study what is the best strategy in combining source coding and cooperation diversity for multimedia communications. The solution to this problem and its dependence on network conditions does not appear readily due to the unique challenges involved in real-time multimedia communications. Refinable single description coding combined with amplify-and-forward and coded cooperation was considered in [7] and [8], respectively. Here, we will consider four cooperative diversity techniques: amplify and forward, adaptive decode and forward, non-adaptive decode and forward, and no cooperation, and two types of source coding diversity techniques: multiple description source coding and single description coding (no diversity). Our results show that multiple description always performs better than single description source coding. However, in most cases, the performance gain is significant mainly in a system with no cooperation. The best overall performance is obtained when the mobile can switch between cooperative and non-cooperative operation depending on the channel conditions. We also remark that an adaptive decode-and-forward cooperative technique shields the best performance in most of the cases. So it is important to design efficient protocols to manage the switch between operation with and without cooperation.

2. SYSTEM DESCRIPTION

We consider a wireless network that is shared between users by allocating to each call an orthogonal channel with fixed communication capacity F (measured in channel code symbols per transmission period). We focus on a source node transmitting real-time multimedia traffic to a destination node. Transmission is over a channel with fading that remains constant within the duration of each transmission period. During each sample period, a block of N input signal samples are presented to the source encoder for compression.

The source codec for schemes that operate without source coding diversity will be a *Single Description* (SD) source codec. This codec generates only one coded representation of the source using R_S bits per source sample. The performance of a source codec can be measured through its achievable distortion rate (D-R) function, which, for the SD source codec, is frequently of the form $D_S(R_S) = c_1 2^{-c_2 R_S}$. This form of D-R function can approximate or bound a wide range of practical systems such as video coding with an MPEG codec [9], speech using a CELP-type codec [10], or when the high rate approximation holds. Assuming that each of the input signal samples are memoryless, following a zero-mean, unit-variance Gaussian distribution and if long block source codes are used, we have $c_1 = c_2 = 1$ ([11]). Thus, without loss of generality, we assume,

$$D_S(R_S) = 2^{-2R_S}. \tag{1}$$

The source codec for schemes that operate with source coding diversity will be a *Multiple Description* (MD) source codec. This codec encodes the source into multiple (two in this paper) separate bit streams (or descriptions) at a combined rate of R_M bits per source sample. In each bit stream, the source is encoded at a rate $R_{D1} = \alpha R_M$ and $R_{D2} = \beta R_M$ bits per source sample. Here α and $\beta = 1 - \alpha$, are codec parameters that take values between 0 and 1 and that control the proportion of total coding rate allocated to each stream. If any of the two descriptions is decoded independently of the other, the achievable D-R function follows the same performance as for SD coding, i.e.

$$D_{D1}(R_{D1}) = 2^{-2R_{D1}}, \quad D_{D2}(R_{D2}) = 2^{-2R_{D2}}. \tag{2}$$

When the two descriptions are combined and decoded together, the achievable D-R function becomes [6]

$$D_M(R_{D1}, R_{D2}) = \frac{2^{-2(R_{D1}+R_{D2})}}{1 - \sqrt{\left(1 - 2^{-2R_{D1}}\right)\left(1 - 2^{-2R_{D2}}\right)}}. \tag{3}$$

After source encoding, the source-encoded bits are grouped into b-bits symbols and protected for transmission with a channel code. We assume that delay constraints exclude the use of capacity-achieving codes or ARQ techniques. Thus, we consider block codes in the form of Reed-Solomon (RS) codes with parameters (n, k), i.e. the encoder operates at a rate $r = k/n$, encoding k b-bits symbols into an n-symbols codeword. We assumed that the different RS codes are generated by puncturing and adding / subtracting parity symbols as needed. Note that all these codes will maintain the maximum distance separable property [12]. Also, we assume that the receiver discards channel-decoded frames containing codewords with errors. This is common practice in conversational communications due to the strict delay constraints. In a communication setup with no user-cooperation, if the frame contains L codewords, the probability that the frame will have errors after channel decoding is $\widetilde{P}(\gamma, L) = 1 - \left(1 - q(\gamma)\right)^L$, where γ is the channel signal to noise ratio (SNR) during the transmission period and $q(\gamma)$ is the probability of channel decoder failure when using a bounded distance decoder [12]. For the case of RS codes this probability is approximated as

$$\begin{aligned} q(\gamma) &= P\left[\text{erred symbols in codeword} > \lfloor \frac{n-k}{2} \rfloor\right] \\ &= \sum_{j=\lfloor \frac{n-k}{2} \rfloor + 1}^{n} \binom{n}{j} P_s^j (1 - P_s)^{n-j}, \end{aligned} \tag{4}$$

where P_s is the probability of a symbol error. For b-bits symbols we have $P_s(\gamma) = 1 - \left(1 - P_b(\gamma)\right)^b$, where P_b is the bit error probability, which depends on the modulation scheme and the channel conditions. In this work we will assume BPSK modulation with coherence detection and maximum likelihood decoding.

The communication process may be carried on with or without using a user-cooperation setup. 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. During phase 2, assuming that the relay nodes can overhear this information, each relay node cooperates by forwarding to the destination the overheard information. Being fixed, the communication capacity for each call, F, need to be split between the two phases.

We will consider three schemes that implement cooperation. In *decode-and-forward*, the relay decodes the signal from the source and sends a re-encoded copy if decoding was successful. At the receiver we assume that a Maximum Ratio Combiner (MRC) is used to combine and detect each transmitted symbol arriving through different paths. The relay will idle during phase 2 if it fails to decode the source signal. It can be shown, [13] that in this case the received SNR at the output of the MRC for a transmitted frame, γ_D, is

$$\gamma_D = \begin{cases} \gamma_{sd} + \gamma_{rd}, & \text{if correct decoding at relay;} \\ \gamma_{sd}, & \text{if incorrect decoding at relay,} \end{cases} \tag{5}$$

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. If we denote by $\mathcal{S}$ the event "correct decoding at relay" and by $\bar{\mathcal{S}}$ the event "incorrect decoding at relay", the probability of having a frame with errors is

$$\begin{aligned} \widetilde{P_D}(\gamma_D, L) &= \widetilde{P}(\gamma_D, L|\mathcal{S})P(\mathcal{S}) + \widetilde{P}(\gamma_D, L|\bar{\mathcal{S}})P(\bar{\mathcal{S}}) \\ &= \widetilde{P}(\gamma_{sd}+\gamma_{rd}, L)\left(1 - \widetilde{P}(\gamma_{sr}, L)\right) + \widetilde{P}(\gamma_{sd}, L)\widetilde{P}(\gamma_{sr}, L). \end{aligned} \tag{6}$$

Note that the relay idling during phase 2 if it fails to decode the source message introduces inefficiency. To improve efficiency, we consider a symmetric operation between the source and the relay, i.e. both nodes send their own data during phase 1 and cooperate with each other during phase 2. *Adaptive* decode-and-forward is a variation of the decode-and-forward scheme that deals with this issue by making the source or the relay switch during phase 2 to a non-cooperative mode (sending a copy of its own signal) when there is a failure in decoding the partners signal. Thus, the sources frame received SNR at the output of the MRC is

$$\gamma_{AD} = \begin{cases} 2\gamma_{sd}, & \text{if source and relay fail decoding,} \\ \gamma_{sd} + \gamma_{rd}, & \text{if source and relay succeed,} \\ \gamma_{sd}, & \text{if source succeeds and relay fails,} \\ 2\gamma_{sd} + \gamma_{rd}, & \text{if source fails and relay succeeds,} \end{cases}$$

and the probability of having a frame with errors is

$$\begin{aligned} \widetilde{P_{AD}}(\gamma_{AD}, L) &= \widetilde{P}(2\gamma_{sd}, L)\widetilde{P}(\gamma_{sr}, L)^2 \\ &+ \widetilde{P}(\gamma_{sd} + \gamma_{rd}, L)\left(1 - \widetilde{P}(\gamma_{sr}, L)\right)^2 + \\ &+ \left[P(\gamma_{sd}, L) + P(2\gamma_{sd} + \gamma_{rd}, L)\right]\widetilde{P}(\gamma_{sr}, L)\left(1 - \widetilde{P}(\gamma_{sr}, L)\right), \end{aligned} \quad (7)$$

where we have assumed inter-node channels to be reciprocal, i.e., $\gamma_{sr} = \gamma_{rs}$.

The third cooperative scheme is *amplify-and-forward*. In this scheme the relay retransmits the source's signal without further processing. It can be shown, [13], that the SNR at the receiver after the MRC is

$$\gamma_A = \gamma_{sd} + \frac{\gamma_{sr}\gamma_{rd}}{1 + \gamma_{sr} + \gamma_{rd}}, \quad (8)$$

and the probability of having a frame with errors is simply $\widetilde{P_A}(\gamma_A, L) = \widetilde{P}(\gamma_A, L) = 1 - \left(1 - q(\gamma_A)\right)^L$.

3. OPTIMIZATION OF DIVERSITY

In this section we study how to combine the techniques for source coding and cooperation diversity. We also analyze their performances by studying the D-R performances.

3.1. Schemes with No Cooperation

These schemes correspond to a direct communication between source and destination through a channel with SNR γ_{sd} with no exploitation of cooperative diversity.

3.1.1. Single Description Source Coding:

If each of the N source samples are source encoded using R_{SN} bits and error protected with a (n, k) code there would be $L = NR_{SN}/(bk)$ codewords per frame. With $F = Ln$ channel code symbols per frame we have $R_{SN} = \frac{bkF}{nN}$ and

$$D_{SN} = \min_{n,k}\left\{D_F\widetilde{P}(\gamma_{sd}, L) + D_S(R_{SN})\left(1 - \widetilde{P}(\gamma_{sd}, L)\right)\right\} \quad (9)$$

where D_F is the distortion when the frame is received with errors ($D_F = 1$ for our source model and distortion measure setup).

3.1.2. Multiple Description Source Coding:

In this case both descriptions are transmitted over the same channel, one after the other in the same frame, with the aggregate communication capacity used being at most F. We assume that the first and second descriptions are source encoded into $R_{D1} = \alpha R_{MN}$ and $R_{D2} = \beta R_{MN}$ bits per sample, respectively, and protected with a (n_1, k_1) code and a (n_2, k_2) code, respectively. Therefore, each frame contains $L_1 = N\alpha R_{MN}/(bk_1)$ codewords from the first description and $L_2 = N\beta R_{MN}/(bk_2)$ from the second. Then, $F = L_1 n_1 + L_2 n_2$ and

$$R_{MN} = \frac{bF}{N}\left(\frac{\alpha n_1}{k_1} + \frac{\beta n_2}{k_2}\right)^{-1}. \quad (10)$$

For this setup the D-R performance becomes

$$\begin{aligned} D_{MN} = \min_{n_1,k_1,n_2,k_2,\alpha} \Big\{ & D_F\widetilde{P}(\gamma_{sd}, L_1)\widetilde{P}(\gamma_{sd}, L_2) \\ & + D_{D1}(R_{D1})\widetilde{P}(\gamma_{sd}, L_2)\left(1 - \widetilde{P}(\gamma_{sd}, L_1)\right) \\ & + D_{D2}(R_{D2})\widetilde{P}(\gamma_{sd}, L_1)\left(1 - \widetilde{P}(\gamma_{sd}, L_2)\right) \\ & + D_M(R_{D1}, R_{D2})\left(1 - \widetilde{P}(\gamma_{sd}, L_1)\right) \\ & \left(1 - \widetilde{P}(\gamma_{sd}, L_2)\right)\Big\}, \end{aligned} \quad (11)$$

where D_{D1}, D_{D2}, and D_M are as in (2) and (3). In (11), the first term accounts for the case when no description is successfully received, the second and third term consider the cases when only one of the descriptions is successfully received, and the last term account for the case when both descriptions are successfully received.

3.2. Schemes with Cooperation Diversity

3.2.1. Single Description Source Coding:

This is a case where only cooperative diversity is used. Because of our requirements for modulation scheme and orthogonal channels with fixed communication capacity, F needs to be split between each phase. More specifically, $F/2$ channel code symbols are used for communication during phase 1 and $F/2$ for communication during phase 2. Therefore, if the N source samples are source encoded at a rate R_{SC} and error protected with a (n, k) code we have in one frame $L_{SC} = NR_{SC}/(bk)$ codewords mapped into $F/2 = nL_{SC}$ channel code symbols. It follows that $R_{SC} = bkF/(2nN)$. For each of the three user-cooperation schemes considered in Section 2, the D-R performance functions have the same forms as in (9) with $\widetilde{P}(\gamma_{sd}, L) = \widetilde{P_D}(\gamma_D, L_{SC})$, from (6), when using decode-and-forward, $\widetilde{P}(\gamma_{sd}, L) = \widetilde{P_{AD}}(\gamma_{AD}, L_{SC})$, from (7), when using adaptive decode-and-forward, and $\widetilde{P}(\gamma_{sd}, L) = \widetilde{P_A}(\gamma_A, L_{SC})$ when using amplify-and-forward.

3.2.2. Multiple Description Source Coding:

In our setup for multiple description coding combined with cooperative diversity, description 1 is sent through a non-cooperative scheme and description 2 is sent using a cooperative scheme as was just discussed for a single description codec. In this way, we meet the need to send each description through a different channel. More importantly, by adapting α and β (in essence each description source coding rate) we are able to control the proportion of resources used for cooperation. This is important because, as should be clear from our analysis of the single description system with user cooperation, well-designed cooperative systems need to find a balance between the reduction in communication capacity to allow transmission during cooperative phase 2 and performance gains obtained by exploiting user-cooperation diversity.

We assume that the first and second descriptions are source coded at rate $R_{C1} = \alpha R_{MC}$ and $R_{C2} = \beta R_{MC}$, respectively, and protected with a (n_1, k_1) code and a (n_2, k_2) code, respectively. Therefore, a frame will contain $L_{C1} = N\alpha R_{MC}/(bk_1)$ codewords from the first description and $L_{C2} = N\beta R_{MC}/(bk_2)$ from the second. In this case we have $F = L_{C1}n_1 + 2L_{C2}n_2$ (where the factor 2 in the second term considers the two cooperative phases). Also,

$$R_{MC} = \frac{bF}{N}\Big(\frac{\alpha n_1}{k_1} + \frac{2\beta n_2}{k_2}\Big)^{-1}. \qquad (12)$$

Following the fact that description 1 is transmitted using a non-cooperative channel and that description 2 is sent through a cooperative channel, the D-R performance follows the same expression as Equation (11) with $R_{C1} = R_{D1}$, $R_{C2} = R_{D2}$, $R_{MN} = R_{MC}$ and with $\widetilde{P}(\gamma_{sd}, L_2)$ replaced by $\widetilde{P_D}(\gamma_D, L_{C2})$, $\widetilde{P_{AD}}(\gamma_{AD}, L_{C2})$ or $\widetilde{P_A}(\gamma_A, L_{C2})$, to consider decode and forward, adaptive decode and forward or amplify and forward, respectively.

4. NUMERICAL RESULTS

To evaluate the performance of each scheme studied in Section 3, we looked at each D-R performance for different source-destination channel SNRs. Figures 1 and 2 show these results. By changing the SNRs of the source-relay and relay-destination channels we considered two scenarios: the relay is close to the source and far from the destination (Figure 1) and the relay is far from the source and close to the destination (Figure 2). Other setups were also studied with results that can be inferred from the ones presented here. In all cases we set $b = 5$ bits, $N = 150$ samples and $F = 190$ channel code symbols per transmission period and call. Also, we studied in Figure 3 the value of β, the proportion of total source coding rate allocated to description 2 when using multiple description coding. When considering cooperative schemes, this magnitude provides a relative measure of the use of cooperation.

Our first observation from the results is that multiple description coding provides a performance improvement that

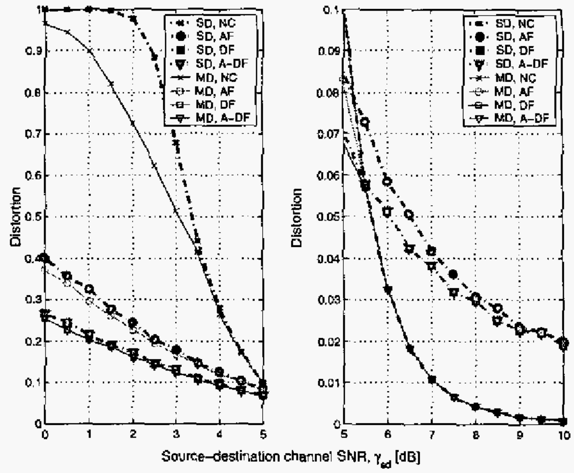

Fig. 1. Distortion for $\gamma_{sr} = 10$ and $\gamma_{rd} = 3$.

increases as the SNR in the source-destination channel decreases. Nevertheless, this improvement is significant mainly when used without cooperation. This shows that the reduction in communication capacity to allow for 2-phase cooperative schemes cannot be compensated by the gains that could be obtained by using multiple description source coding. The results also show that non-cooperative schemes provide the best performance when the source-destination channel has relatively high SNR and cooperative schemes yields significant performance improvement when the SNR between source and destination is small. More importantly, it is clear from the study of the value β that, approximately, the system tends to switch between the two extremes of no cooperation and full use of cooperation, following the guidelines already noted. Therefore, design of protocols that allow switching operation between cooperation and no cooperation is critical to obtain the best performance. The design challenge here is for the protocol to decide on the switching points (depending on all channels SNRs) shown in Figure 3. Also, a consequence of these results is that users enjoying good channels have no incentive to cooperate; this imposes a challenging issue into the protocol design.

Furthermore, we note that these results suggest the need for a source coding technique that provides both adaptability in the cooperation proportion and diversity gain when combined with cooperative techniques. This is a matter of current research to be presented in a future paper. Also, the results show that the choice for the cooperative technique that shields best performance depends on the specific combination of all involved channel SNRs. In general we can say that adaptive decode-and-forward shield better performance in most of the cases, except when the source-destination and the source-relay channels have very low SNR. We finally note that we expect these qualitative conclusions to hold even when using other channel coding and modulation techniques because they follow mostly from

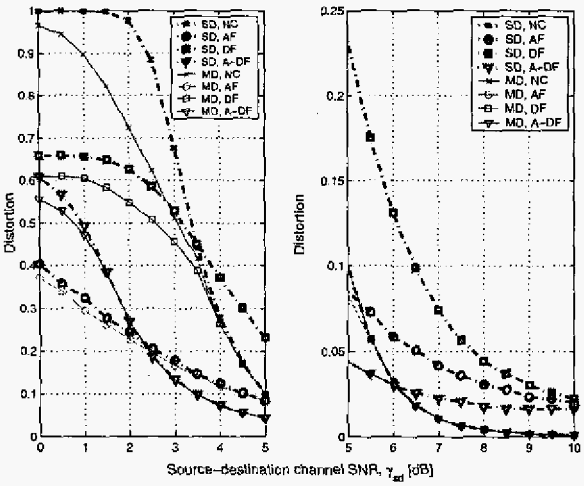

Fig. 2. Distortion for $\gamma_{sr} = 3$ and $\gamma_{rd} = 10$.

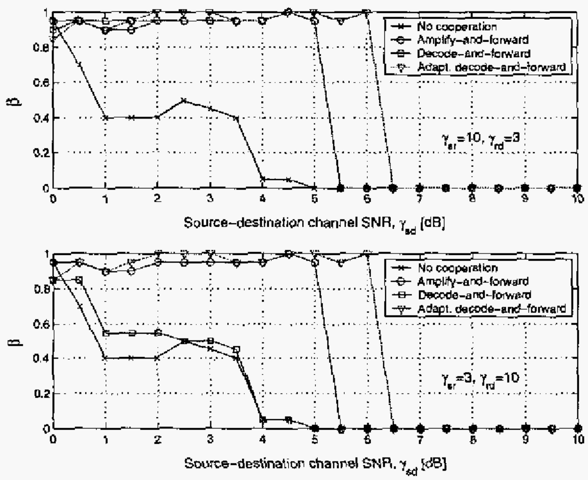

Fig. 3. $\beta = 1 - \alpha$, fraction of total source encoding rate allocated to description 2 in multiple description coding.

the functional behavior of each system component and not from their specific performance qualities.

5. CONCLUSIONS

We studied what is the best strategy in combining source coding and cooperative diversity for multimedia communications. We focused on three techniques that exploit cooperative diversity: amplify-and-forward, decode-and-forward, and adaptive decode-and-forward, and one technique that exploits source coding diversity: multiple description source coding. Also, we considered the cases when either of the two diversity techniques is not used. We concluded that multiple description coding always provides better performance than single description coding, but in most cases, only one type of diversity can achieve most of the diversity gain. Overall, the best performance is obtained when the mobile can switch between operation with and without cooperation depending on the channel conditions. This highlights the need for efficient protocols to manage this switch.

In this area we justified the design challenge of motivating collaboration to users in good channels conditions. We also note that an adaptive decode-and-forward cooperative technique shields the best performance in most of the cases and we conclude that further research, currently underway, is needed to study and develop more efficient combinations of source coding and user-cooperation diversity.

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