Source Transmission over Relay Channel with Correlated Relay Side Information

Deniz Gündüz*, Chris T. K. Ng†, Elza Erkip* and Andrea J. Goldsmith†

*Dept. of Electrical and Computer Engineering, Polytechnic University, Brooklyn, NY 11201 US
†Dept. of Electrical Engineering, Stanford University, Stanford, CA 94305 US
Email: *dgundu01@utopia.poly.edu, elza@poly.edu †{ngctk,andrea}@wsl.stanford.edu,

***Abstract*— We consider transmission of a Gaussian source over a Gaussian relay channel, where the relay terminal has access to correlated side information. We propose several cooperative joint source-channel coding strategies that utilize both the broadcast nature of the wireless transmission and/or the availability of the correlated side information at the relay, and compare these to distortion lower bounds obtained by the cut-set arguments. In general, the best performing scheme depends on the correlation among the source and the relay signals, and the average link qualities. We illustrate that the strategies introduced in this paper perform very close to the lower bound in most cases.**

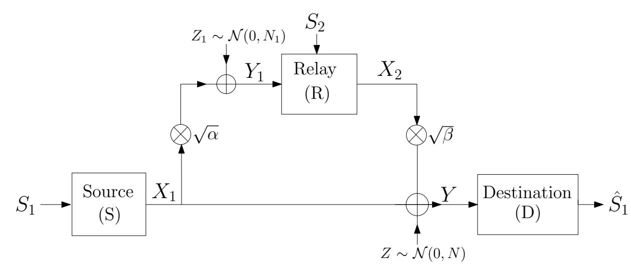

Fig. 1. Gaussian relay channel with correlated sources (S_1, S_2) at the source (S) and the relay (R) terminals.

I. Introduction

The relay channel [1], one of the basic components of a wireless network, has been analyzed extensively in terms of achievable rates [2]-[4]. However, the capacity of the relay channel in the most general setting is still open despite these ongoing efforts. In this work, we consider a Gaussian relay channel where the source terminal (S) has access to a memoryless Gaussian source signal S_1 that is to be transmitted to the destination terminal (D) subject to an average squared-error distortion, as illustrated in Fig. 1. We assume the existence of a relay terminal (R) which can assist the transmission from the source to the destination. We assume that the relay has access to correlated side information S_2. This system may model a sensor network in which nearby sensors in the environment have access to correlated observations and can help the main sensor transmit its observation with the highest fidelity.

When the relay side information S_2 is independent of S_1, it is possible to prove a source-channel separation theorem, even though the capacity of the relay channel is not known in the most general setting. However, for the scenario considered in this paper, it is not clear whether separation applies.

We propose source and channel coding techniques for the scenario in Fig. 1 and obtain their achievable average distortion values. Our schemes include various relaying methods coupled with source coding techniques to incorporate correlated relay information effectively. We also find a distortion lower bound using the cut-set arguments. In order to study fundamental gains and limitations, we investigate the performance of a full-duplex relay system, where the relay can receive and transmit simultaneously. We illustrate that the achievable performance is close to the distortion lower bound in most cases, while the best scheme depends on the correlation among the source and the relay signals, and the link qualities.

Source and channel coding for multi-user systems dates back to [5] which considers transmission of correlated sources over a multiple-access channel (MAC), where the destination is interested in reconstructing both sources. In [6], [7], we consider source transmission over fading relay channels focusing on the high SNR regime, and discuss joint source-channel codes that are optimal in terms of distortion exponent. The achievable strategies studied in this paper make use of the one-helper problem [8], which, unlike our scenario, assumes that both the main encoder and the helper have non-interfering links with certain preassigned capacities (bit pipes) to the destination.

The paper is organized as follows. We introduce the model and the problem in Section II, propose various achievable schemes in Section III and find their corresponding average distortion expressions. In Section IV, we find a lower bound to the achievable end-to-end distortion. Then we analyze both lower and upper bounds in Section V based on various channel and correlation models. Section VI concludes the paper.

II. System Model

Two zero-mean jointly Gaussian sources S_1 and S_2 generate the i.i.d. sequence $\{S_{1,k}, S_{2,k}\}_{k=1}^{\infty}$. The sequences $S_{1,k}$ and $S_{2,k}$ are available at the source and relay encoders, respectively. Let the covariance matrix of the sources be given by

$$C_{S_1 S_2} = \begin{bmatrix} \sigma_1^2 & \rho\sigma_1\sigma_2 \\ \rho\sigma_1\sigma_2 & \sigma_2^2 \end{bmatrix}, \qquad (1)$$

This work is supported by NSF grant No. 0430885, by the MURI award W911NF-05-1-0246, the ONR award N00014-05-1-0168, DARPA under grant 1105741-1-TFIND and by Intel.

where $\rho \in [-1,1]$ is the correlation coefficient.

The source encoder observes $S_1^n = (S_{1,1}, \ldots, S_{1,n})$ and maps it to the codeword $X_1^n = (X_{1,1}, \ldots, X_{1,n})$ with the encoding function f_1. Note that we assume equal source and channel bandwidths, i.e., one channel use per source sample; however extension of the proposed schemes in this paper to different bandwidth ratios is straightforward. At time instant k, the received signal at the relay is given by

$$Y_{1,k} = \sqrt{\alpha} X_{1,k} + Z_{1,k}, \tag{2}$$

where $Z_1^n = (Z_{1,1}, \ldots, Z_{1,n})$ is the i.i.d. zero-mean Gaussian noise vector with variance N_1 which is independent of X_1^n. The relay encoder is $f_2 = (f_{2,1}, \ldots, f_{2,n})$ where we have $X_{2,k} = f_{2,k}(Y_{1,1}, \ldots, Y_{1,k-1}, S_2^n)$, for $1 \le k \le n$.

The received signal at time k at the destination terminal is

$$Y_k = X_{1,k} + \sqrt{\beta} X_{2,k} + Z_k, \tag{3}$$

where $Z^n = (Z_1, \ldots, Z_n)$ is the i.i.d. zero-mean Gaussian noise with variance N, independent of X_1^n, X_2^n and Z_1^n. We assume separate average power constraints of P_1 and P_2 at the source and the relay terminals, respectively. The destination decoder g observes the received vector $Y^n = (Y_1, \ldots, Y_n)$ and outputs its estimate of the source $\hat{S}_1^n = (\hat{S}_1, \ldots, \hat{S}_n) = g(Y^n)$.

Definition 2.1: For the system described above, distortion D is achievable if, for any $\epsilon > 0$, there exist encoding and decoding functions (f_1, f_2, g) satisfying the power constraints $E\left[\|X_i^n\|^2\right] \le nP_i$, for $i = 1, 2$, that result in

$$\frac{1}{n} E\left[\sum_{i=1}^{n} \|S_{1,i} - \hat{S}_i\|^2\right] \le D + \epsilon. \tag{4}$$

The minimum achievable distortion D_{min} for given $P_1, P_2, N_1, N, \sigma_1^2, \rho$ is defined as $D_{min} \triangleq \inf\{D : D \text{ is achievable}\}$. Our goal in this paper is to find upper and lower bounds to D_{min} in terms of the known system parameters $P_1, P_2, \sigma_1^2, \rho$ and N_1, N. For ease of exposure, we assume $N = N_1 = 1$.

III. Average Distortion Upper Bounds

In this section, we propose various strategies and find the corresponding achievable distortion values. Our strategies can be categorized into three types: i) channel cooperation, where relay is used only for channel coding (Section III-A), ii) source cooperation, where relay is used only for transmitting its side information (Section III-B,III-C), and iii) hybrid schemes (Section III-D,III-E).

A. Channel cooperation: Separate source-channel coding ignoring the side information

We can simply ignore the side information at the relay and apply source-channel separation, where the source terminal first compresses S_1 and then transmits the compressed bits over the channel using either direct transmission or one of the relay channel coding techniques. Since the capacity of the relay channel is not known, we apply some of the achievable coding techniques given in the literature [2].

We consider direct transmission (DT) as a benchmark where we do not utilize the relay to help for either channel or source coding. The achievable distortion for DT can be simply found as $D^{DT} = \sigma_1^2(1+P_1)^{-1}$, using the distortion-rate function of a Gaussian source, $D(R) = \sigma_1^2 2^{-2R}$ and Gaussian channel capacity [11].

If we assume decode-and-forward relaying in the full-duplex case, where the relay decodes the source signal fully, then the achievable rate is found by [2]

$$R^{DF} = \max_{0 \le \xi \le 1} \min \left\{ \frac{1}{2}\log(1 + (1-\xi^2)\alpha P_1), \right. \\ \left. \frac{1}{2}\log(1 + P_1 + \beta P_2 + 2\xi\sqrt{\beta P_1 P_2}) \right\}, \tag{5}$$

which leads to an achievable distortion of

$$D^{DF} = \sigma_1^2 \min_{0 \le \xi \le 1} \left(1 + \min\left\{(1-\xi^2)\alpha P_1, \right.\right. \\ \left.\left. P_1 + \beta P_2 + 2\xi\sqrt{\beta P_1 P_2}\right\}\right)^{-1}. \tag{6}$$

In the compress-and-forward (CF) (also known as estimate-and-forward) scheme [2], the relay transmits a compressed version of its received signal and the achievable rate is [3]

$$R^{CF} = \frac{1}{2}\log\left(1 + P_1 + \frac{\alpha P_1 \beta P_2}{1 + (1+\alpha)P_1 + \beta P_2}\right), \tag{7}$$

leading to an achievable distortion of

$$D^{CF} = \sigma_1^2\left(1 + P_1 + \frac{\alpha P_1 \beta P_2}{1 + (\alpha+1)P_1 + \beta P_2}\right)^{-1}. \tag{8}$$

B. Uncoded transmission

In a point-to-point Gaussian channel, uncoded transmission is known to result in optimal average distortion for a Gaussian source. Even though the optimality of uncoded transmission may not hold in the most general multi-user setting, there are instances for which it still gives the best performance, such as in [10], where uncoded transmission over a MAC is optimal up to an SNR threshold, and in [9], where uncoded transmission is shown to be order optimal in a relay network with large number of relays.

We have $X_{1,k} = \sqrt{\frac{P_1}{\sigma_1^2}} S_{1,k}$ and $X_{2,k} = \sqrt{\frac{P_2'}{\sigma_2^2}} S_{2,k}$ for $k = 1, \ldots, n$ where P_2', $0 \le P_2' \le P_2$, is the part of the relay power used for uncoded transmission of its side information S_2. The relay does not make use of the signal received from the source. The destination simply outputs the MMSE estimate of S_1^m based on Y^n. The minimum distortion that can be achieved by uncoded transmission is

$$D^{UT} = \min_{0 < P_2' \le P_2} \sigma_1^2 \frac{(1-\rho^2)\beta P_2' + 1}{1 + P_1 + \beta P_2' + 2\rho\sqrt{\beta P_1 P_2'}}. \tag{9}$$

We optimize over P_2' since D^{UT} may not be decreasing with the relay power.

C. One-helper source coding with MAC channel coding

In this strategy, similar to uncoded transmission, the relay terminal only transmits its side-information ignoring its received signal from the source terminal. We call this strategy helper-MAC (hMAC). We consider separate source and channel coding, where the source coding part corresponds to the one-helper problem, whose distortion-rate function, $D_h(R_1, R_2)$ is given as [8]

$$D_h(R_1, R_2) = \sigma_1^2 2^{-2R_1}(1 - \rho^2 + \rho^2 2^{-2R_2}). \qquad (10)$$

Here R_1 is the rate from the main source coder and R_2 is the rate of the helper. Since the source and relay have a MAC towards the destination, R_1 and R_2 should lie on the boundary of the capacity region of the MAC. Obviously, it is preferable to operate on the segment of the boundary that is dominated by the sum rate constraint, that is, $R_t \triangleq R_1 + R_2 = 1/2 \log(1 + P_1 + \beta P_2)$. We can write (10) in terms of R_t as

$$D_h(R_1, R_2) = \sigma_1^2[(1 - \rho^2)2^{-2R_1} + \rho^2 2^{-2R_t})], \qquad (11)$$

which decreases with R_1. The best operating point is the corner of the boundary of the capacity region that maximizes R_1, corresponding to $R_1 = 1/2 \log(1 + P_1/N)$. This is consistent with the intuition that we need to maximize the rate of transmission from the original source, and then use the remaining rate for the helper's transmission. The minimum achievable distortion for this strategy is found as

$$D^{hMAC} = \sigma_1^2 \left[(1 - \rho^2)(1 + P_1)^{-1} + \rho^2(1 + P_1 + \beta P_2)^{-1}\right].$$

Note that in both uncoded and hMAC strategies, the relay ignores its received signal and acts only as a helper by transmitting its side information. Hence, we refer to these strategies as 'source cooperation'.

D. Hybrid source-channel cooperation

We observe from the previous strategy that one desires to transmit at the highest possible rate from the source to the destination and use the remaining resources for source cooperation. This motivates us to combine one-helper source coding with CF or DF relaying, that is, the relay is used for both source and channel cooperation. We analyze hybrid-CF (hCF) here, while hybrid-DF (hDF) follows similarly. In the hCF scheme, the relay divides its power among the two tasks and transmits a superposition of the two codewords corresponding to source cooperation and channel cooperation. Suppose the relay reserves γP_2 $(0 \le \gamma \le 1)$ for CF relaying and $(1 - \gamma)P_2$ for transmission of S_2 to the destination. The CF achievable rate becomes

$$R^{CF}(\gamma) = \frac{1}{2} \log \left(1 + P_1 + \frac{\alpha P_1 \beta \gamma P_2}{1 + (1 + \alpha)P_1 + \beta \gamma P_2}\right). \quad (12)$$

The rate at which the relay can send S_2 becomes

$$R_h(\gamma) = \frac{1}{2} \log \left(1 + \frac{\beta(1 - \gamma)P_2}{1 + P_1 + \beta \gamma P_2}\right), \qquad (13)$$

where we consider the transmissions from the source and the relay for CF as noise. Using (10), the achievable distortion D^{hCF} for helper-CF can be obtained as

$$D^{hCF} = \min_{0 \le \gamma \le 1} \sigma_1^2 \left(1 + P_1 + \frac{\alpha P_1 \beta \gamma P_2}{1 + (1 + \alpha)P_1 \beta \gamma P_2}\right)^{-1} \cdot \left[1 - \rho^2 + \rho^2 \left(1 + \frac{\beta(1 - \gamma)P_2}{1 + P_1 + \beta \gamma P_2}\right)^{-1}\right] \qquad (14)$$

Note that D^{CF} and D^{hMAC} are special cases of D^{hCF} for $\gamma = 1$ and $\gamma = 0$, respectively. For hDF, we only need to replace the rate in (12) with $R^{DF}(\gamma)$, the DF achievable rate.

E. Advanced hybrid source-channel cooperation

In order to improve the hybrid compress-and-forward (hCF) scheme of Section III-D we allow the source to transmit a private information to the relay that increases the relay's participation as helper. This is achieved by the source transmitting additional information, which will be decoded only at the relay using its side information.

Now, assume that the source allocates $(1 - \delta)P_1$ $(0 \le \delta \le 1)$ of its power for sending the private information, and reserves the rest for transmitting S_1 to the destination through channel cooperation. Also, as in Section III-D, assume that the relay allocates γP_2 $(0 \le \gamma \le 1)$ of its power for channel cooperation, and reserves the rest for source cooperation. The rate of private information is

$$R_p = \frac{1}{2} \log \left(1 + \frac{\alpha(1 - \delta)P_1}{(1 + \alpha \delta P_1)}\right),$$

where the relay considers the signal from the source for channel cooperation as noise. Let $I(S_1; S_1 + W_2 | S_2) = R_p$ for some $W_2 \sim N(0, \sigma_{W2}^2)$ independent of S_1. This guarantees the relay to receive the noisy version $S_1 + W_2$ of the source.

The relay uses $(1 - \gamma)P_2$ of its power to transmit at rate $R_h(\gamma)$ as in (13) providing helper information. But note that since the relay obtained $S_1 + W_2$ through the private communication with the source, it can send a better description of the source than before. We choose

$$I(S_1 + W_2, S_2; S_1 + W_2 + Z_2, S_2 + Z_1) = R_h(\gamma), \qquad (15)$$

where $Z_1 \sim N(0, \sigma_{Z1}^2)$ and $Z_2 \sim N(0, \sigma_{Z2}^2)$ are Gaussian and independent of each other and S_1, S_2. We will optimize the achievable average distortion over σ_{Z1}^2 and σ_{Z2}^2 which satisfy (15). This condition guarantees that both $S_1 + W_2 + Z_2$ and $S_2 + Z_1$ can be decoded at the destination.

Let $R^{CF}(\gamma, \delta)$ be the CF rate. Part of the source power allocated for private information transmission, which will not be decoded at the destination, acts as noise at the destination. We have

$$R^{CF}(\gamma, \delta) = \frac{1}{2} \log \left(1 + \frac{\delta P_1}{N_o} + \frac{\alpha \delta P_1 \beta \gamma P_2}{N_o + \alpha \delta P_1 N_o + \delta P_1 + \beta \gamma P_2}\right), \quad (16)$$

where $N_o = 1 + (1 - \delta)P_1$.

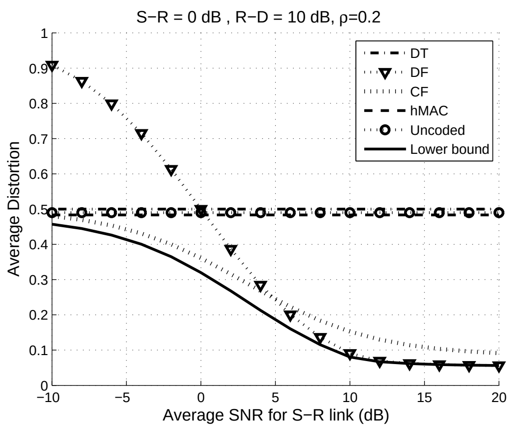

Fig. 2. Average distortion vs. S-R link quality.

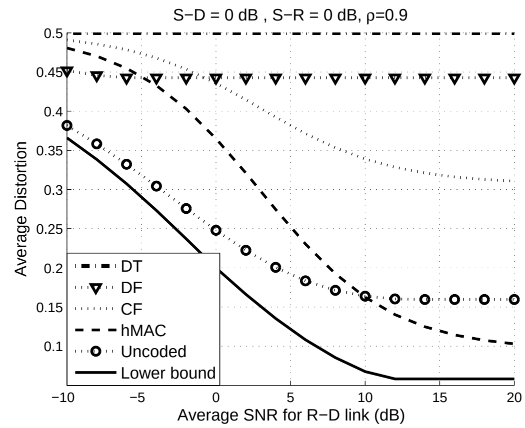

Fig. 3. Average distortion vs. R-D link quality.

The source will use $R^{CF}(\gamma,\delta)$ to send a compressed version of S_1. The compression of S_1 is done using Wyner-Ziv source coding with respect to the side information $S_1+W_2+Z_2$ and S_2+Z_1 at the destination. We need

$$I(S_1;S_1+W_1|S_1+W_2+Z_2,S_2+Z_1)=R^{CF}(\gamma,\delta), \quad (17)$$

so that S_1+W_1 can be decoded at the destination, for some $W_1\sim N(0,\sigma^2_{W1})$ independent of S_1. The destination, having access to three different noisy observations of the source, namely S_1+W_1, $S_1+W_2+Z_2$ and S_2+Z_1, uses MMSE estimation for reconstructing the original signal. Then we obtain the distortion for aCF scheme, D^{aCF} as

$$\begin{aligned} D^{aCF} &= \inf_{\gamma,\delta,\sigma^2_{Z1},\sigma^2_{Z2}} \left(\frac{1}{\sigma_1^2}+\frac{1}{\sigma^2_{W1}}+\frac{1}{\sigma_1^2(\sigma^2_{W2}+\sigma^2_{Z2})}\right. \\ &\quad \left. +\frac{\rho^2\sigma_2^2}{(1-\rho^2)\sigma_1^2\sigma_2^2+\sigma^2_{Z1}}\right)^{-1}, \quad (18)\end{aligned}$$

where the infimum is over $\gamma,\delta,\sigma^2_{Z1},\sigma^2_{Z2}$ that satisfy (15) and (17). Note that the choice of these parameters uniquely determines σ^2_{W1} and σ^2_{W2}.

We note that if, no private information is sent to the relay, that is, if $\delta=1$, we have $R_p=0$, $\sigma^2_{W2}=\infty$, and the aCF scheme boils down to the hCF scheme. Thus we have $D^{aCF}\le D^{hCF}$.

IV. Average Distortion Lower Bound

In order to find lower bounds, we use the usual cut-set arguments for source-channel networks [12]. First, consider the cut around the source, where S_1 and S_2 are on different sides of the cut. The maximum rate that can be transmitted across this cut is $C_1=I(X_1;Y,Y_1|X_2)$. Considering S_2 is also available at the receiver side of the cut, the achievable distortion can be lower bounded by the Wyner-Ziv distortion-rate function, $D^{WZ}_{S_1|S_2}(C_1)=(1-\rho^2)\sigma_1^2 2^{-2C_1}$. Similarly, for the cut around the destination, the rate can be upper bounded by $C_2=I(X_1,X_2;Y)$. Since S_2 is on the same side of the cut with S_1, it can be ignored, and we can lower bound the achievable distortion by $D(C_2)$. For the Gaussian relay channel, C_1,C_2 are given as

$$\begin{aligned} C_1 &= 1/2\log(1+(1-\xi^2)(1+\alpha)P_1), \\ C_2 &= 1/2\log(1+P_1+\beta P_2+2\xi\sqrt{\beta P_1P_2}),\end{aligned}$$

where ξ is the correlation between the channel inputs X_1 and X_2. Then we can lower bound the achievable distortion as

$$\begin{aligned} D_{min} \ge \min_{0\le\xi\le1} \max\{&\sigma_1^2(1-\rho^2)(1+(1-\xi^2)(1+\alpha)P_1)^{-1}, \\ &\sigma_1^2(1+P_1+\beta P_2+2\xi\sqrt{\beta P_1P_2})^{-1}\}.\end{aligned}$$

V. Comparison of the Results

In this section, we compare the average end-to-end distortion achieved by the above proposed strategies for various source correlations and link qualities, assuming $\sigma_1^2=1$. In the first scenario, we consider a small correlation coefficient ($\rho=0.2$), that is the quality of the relay side information is low. We assume that the S-D link has SNR 0 dB, while the R-D link has SNR 10 dB. In Fig. 2, we plot the achievable average distortion with respect to the S-R link quality. For clarity, we include two types of strategies only: DF and CF, where relay terminal is used only for relaying the channel code (channel cooperation); and uncoded and hMAC strategies, where the relay is only used as a helper utilizing its side information for source coding (source cooperation). We include DT and the lower bound curves for comparison. Due to the low correlation coefficient, we observe that source cooperation does not bring much improvement over DT. On the other hand, CF performs close to the lower bound since the S-D SNR is low and R-D link has high quality. We also observe that DF performance gets very close to the lower bound as the S-R link quality improves. These observations are in accordance with the achievable rate performances of these relaying strategies [4]. We conclude that, as expected, for a low correlation coefficient, the main improvement is obtained by using the relay for channel cooperation.

Next, we fix both S-D and S-R SNRs to 0 dB, and consider a high quality side information ($\rho=0.9$). In Fig. 3, we see

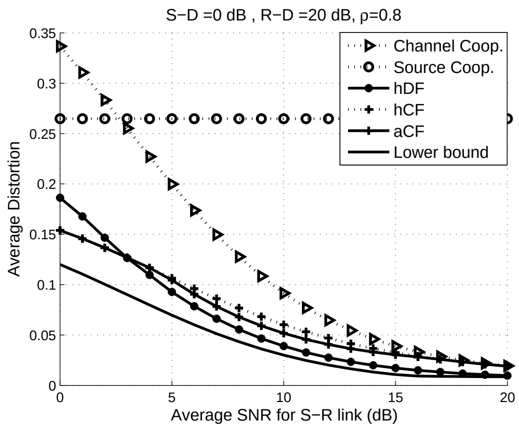

Fig. 4. Average distortion vs. S-R link quality.

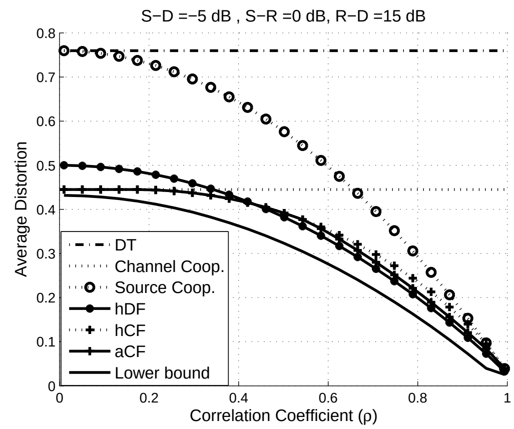

Fig. 5. Average distortion vs. correlation coefficient (ρ) for fixed links.

that source cooperation performs much better than channel cooperation. Due to high correlation and the relatively weak S-R link, it is more important to transmit the side information of the relay to the destination directly. For low R-D link qualities, we see that the best performing strategy is uncoded transmission. This agrees with the observation of [10] where uncoded transmission is shown to be optimal for transmitting correlated sources over a MAC up to an SNR threshold. We can suggest that, for low power applications, uncoded transmission can be viable, although it may not be optimal.

Now, we want to see the improvement due to the hybrid and advanced schemes. Along with helper-CF (hCF), helper-DF (hDF) and advanced-CF (aCF) schemes, Fig. 4 shows channel cooperation (CF-DF) and source cooperation (uncoded-hMAC), which illustrate the best performance achieved by any of the source or channel cooperation schemes under each category. For fixed S-D (0 dB) and R-D (20 dB) links, and for $\rho = 0.8$, we observe that channel cooperation outperforms source cooperation as the S-R link quality improves. Hybrid strategies provide considerable improvement over channel or source cooperation. We observe some improvement by aCF over hCF for certain S-R link qualities. While aCF performs reasonably well over a wide range of S-R link qualities, the distortion of hDF starts to dominate as the S-R link improves.

Finally, we fix the average received SNRs for S-D, S-R and R-D links to -1, 2 and 15 dB, respectively, and compare achievable distortions for varying correlation coefficients. We observe that source cooperation starts to dominate channel cooperation as the correlation increases. Hybrid strategies always improve the performance with respect to their channel cooperation counterparts, and the improvement becomes substantial for high correlation coefficients. The advanced CF scheme improves upon hCF for a range of correlation coefficient values. We observe that, as correlation increases, hDF surpasses hCF and aCF. This is due to the fact that in the hybrid scheme, as more relay power is allocated for source cooperation with increasing correlation, the effective R-D link quality for channel cooperation decreases, and DF relaying becomes preferable.

VI. Conclusion

We consider transmitting a Gaussian source over a Gaussian relay channel where the relay has correlated side information. We propose several source-channel coding schemes, and compare achievable distortion performances with the lower bound based on cut-set arguments. We propose three basic types of strategies: channel cooperation, source cooperation and hybrid schemes. In channel cooperation, the relay is used only for channel coding and its side information is ignored; in source cooperation, the relay is only used for its side information ignoring its received signal; and hybrid strategies combine these two. The strategy that achieves the best performance depends on the correlation coefficient and average channel qualities. In particular, we observe that source cooperation performs well when correlation is high and the source relay link has low quality, while channel cooperation performs well for low correlation cases. Hybrid schemes extend the benefits to a wide range of correlation and channel conditions, and for most cases perform very close to the lower bound.

References

[1] E. C. van der Meulen, "Three-terminal communication channels," Adv. Appl. Prob., vol. 3, pp. 120-154, 1971.

[2] T. M. Cover, A. El Gamal, "Capacity theorems for the relay channel," IEEE Trans. Info. Theory, IT-25(5):572–584, Sept 1979.

[3] M.Khojastepour, A.Sabharwal, B.Aazhang, "Lower bounds on the capacity of Gaussian relay channel," CISS, Princeton, NJ, March, 2004.

[4] G. Kramer, M. Gastpar, and P. Gupta, "Cooperative strategies and capacity theorems for relay networks," IEEE Trans. Inform. Theory, Sept. 2005.

[5] T.M. Cover, A.El Gamal, M. Salehi, "Multiple access channels with arbitrarily correlated sources," IEEE Trans. Info. Theory, 1980.

[6] D. Gündüz and E. Erkip. "Source and channel coding for cooperative relaying," SPAWC, June 2005.

[7] D. Gündüz, E. Erkip, "Source and channel coding for cooperative relaying," Submitted to IEEE Trans. on Info. Theory, August 2006.

[8] Y. Oohama, Gaussian multiterminal source coding, IEEE Trans. Inf. Theory, vol. 43, pp. 19121923, Nov. 1997.

[9] M. Gastpar and M. Vetterli, "Power, spatio-temporal bandwidth, and distortion in large sensor networks," Sel. Areas in Comm, April 2005.

[10] A. Lapidoth, S. Tinguely, "Sending a bi-variate Gaussian source over a Gaussian MAC," ISIT, Seattle, WA, July 2006.

[11] T. Cover, J. Thomas, *Elements of Information Theory,* NY, 1991.

[12] M. Gastpar, "Cut-set arguments for source-channel networks," In Proc. of IEEE Int. Symp. Info. Theory, Chicago, IL, June 2004.