Lossy Transmission of Correlated Sources in a Multiple Access Quasi-Static Fading Channel

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***Abstract*—In this paper, we investigate low-complexity, receiver-driven strategies for the transmission of two correlated sources in a multiple access quasi-static fading channel. We consider two different transmission modes at the physical (PHY) layer depending on the average signal to noise ratio (SNR) of the involved Rayleigh fading channels. The two modes that are allowed are orthogonal transmissions and interfering transmissions with successive interference cancellation (SIC) decoding. Further, we consider the sources are compressed independently while they are jointly decoded with an adaptive linear minimum mean square error (MMSE) algorithm. Hence, the receiver selects the combination of a PHY transmission mode that should be used at the sources, together with the adaptive MMSE-based estimation of each source. We show that in different SNR regimes, a different transmission strategy is optimum, that is in the low SNR regime interfering transmission together with MMSE decoding is better, while in the high SNR regime orthogonal transmission is superior. Both schemes outperform distributed source coding (DSC) based approaches regardless of the degree of the correlation of the two sources.**

I. Introduction

The most well-known example of correlated data sources are sensors that collect observations correlated in space and/or time. The data are typically collected with the help of a wireless sensor network (WSN). In such a system in order to reduce the communication bandwidth, increase robustness to channel errors, and eventually improve the estimation accuracy of the source signal, all the source and channel transmission options should be explored. In this paper, in order to shed light to different practical low-complexity schemes for communicating the correlated sources, we consider a scenario where two continuous random correlated sources are transmitted over a quasi-static Rayleigh fading multiple access channel (MAC).

For continuous correlated sources, the optimal source coding strategy for a given bandwidth is Wyner-Ziv DSC [1], [2] where correlated sources are compressed separately and decoded jointly, i.e., the signal from one source is used as side information at the joint decoder (in Figure 1, we assume that this is source Y). However, the Rate Distortion (RD) function for a quasi-static fading channel is not trivial to characterize since the side information may not be available leading to the need for a lossy RD function. Early works considered the lossy RD function of Wyner-Ziv DSC [3], and modeled the impact of lossy side information from a fading cooperative link [4]. In [5], the authors derived distortion bounds for the case of two correlated sources compressed with DSC. In our previous work, we considered the lossy transmission of two correlated sources compressed with DSC [6]. We investigated the benefits of interfering transmissions for increasing the capacity of the channel allowing thus lower distortion[1].

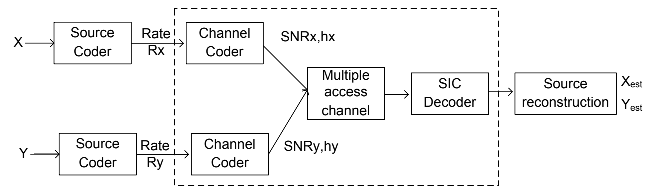


Fig. 1. System model for the transmissions of correlated sources in a MAC. The dashed lines include the MAC which is a channel coding problem. Outside the dashed lines we have two correlated sources.

Even though the previous studies characterized the RD performance of DSC in fading channels [3], [4], [5], or even optimized it [6], this is unfortunately not enough to ensure optimality in this scenario (i.e., Shannon source-channel separation theorem does not hold). Therefore, a joint optimization of source and channel coding (JSCC) strategy is necessary. The optimality of such a choice for *lossless communication* and a Gaussian MAC was proven in the seminal paper of Cover [7] with the design of a simple JSCC scheme. For *lossy communication* that we are interested in this paper, Lim et al. [8] proposed a JSCC communication strategy for the correlated discrete memoryless Gaussian (DM-MAC) according to which the source and channel coders use the same codeword. JSCC and the lossy transmission of a continuous bivariate Gaussian source over a Gaussian MAC is studied by designing a single source-channel coder [9]. In [10], an achievable rate distortion region for lossy transmission of two correlated sources over a discrete memoryless interference channel (DMIC) as well as Gaussian interference channel was derived. Overall most of the results for JSCC in our scenario focus on Gaussian channels, while for the fading case the complexity of the problem limits the related works. In one recent work reported in [11], the authors derived bounds of the distortion exponent for the JSCC problem but for some special cases of the fading MAC and only for a single source. Even though there is definitely a need for obtaining robust bounds

[1]In that work, both sources were not operating under a global power constraint. This is typically the case with multi-user systems and SIC decoding since the purpose is to decode as many source packets as possible.

for the setup considered, there is also a need for practical schemes that can be implemented without the re-design of the source/channel coders.

In this paper, we propose practical low-complexity strategies for the transmission of two correlated sources over a fading MAC under a global power constraint. More specifically, we propose the use of different transmission modes at the PHY depending on the average SNR of the involved Rayleigh fading channels. Regarding source coding, the sources are compressed independently (sources are agnostic) while they are jointly decoded with an adaptive MMSE algorithm. Hence, the complexity is shifted to the receiver that selects the combination of a PHY transmission mode that should be used at the sources, together with the adaptive MMSE-based estimation of each source. The first PHY mode adopts a first stage successive interference canceling (SIC) decoder at the receiver, so that we can allow two sources to transmit simultaneously. The second mode involves orthogonal transmission from the two sources. Our results indicate that for both orthogonal and interfering transmissions, our linear estimator (the source correlation is extracted at the receiver) performs significantly better compared to Wyner-Ziv DSC (the source correlation is extracted at the sender) [6]. Furthermore, for both types of correlation extraction methods (DSC and MMSE), interfering transmissions outperform the orthogonal transmissions for the low SNR regime, whereas orthogonal transmission provides better results for the higher SNR regime. For certain average channel conditions, our scheme is better regardless of the correlation between the two sources.

This paper is organized as follows. We introduce the system model in Section II. We formulate the outage probabilities in Section III and discuss the adaptive MMSE algorithm in Section IV. Section V analyzes the proposed strategies for different source and channel conditions. We conclude the paper in Section VI.

II. SYSTEM MODEL

We consider a system where T_x and T_y are two terminals in a wireless network communicating with a common destination. Each link has flat Rayleigh fading with instantaneous fading levels h_x and h_y, and average received signal to noise ratios SNR_x and SNR_y. The fading levels are accurately measured at the receivers, while the transmitters are only aware of the statistics. We define a packet as a block of N channel uses and assume the fading is constant for multiple packets.

We assume terminals T_x and T_y have access to two correlated sources X and Y respectively, which they wish to transmit to the destination with minimal expected distortion in a squared error sense. Without loss of generality, we can write, $Y = aX + Z$ where $Z \sim \mathcal{N}(0, \sigma_z^2)$ is independent of X with $\sigma_z^2 = \sigma_y^2 - a^2\sigma_x^2$ and $a = \rho\frac{\sigma_y}{\sigma_x}$. The sources are zero-mean jointly Gaussian with the covariance matrix

$$\mathbf{K}_{XY} = \begin{bmatrix} \sigma_x^2 & \rho\sigma_x\sigma_y \\ \rho\sigma_x\sigma_y & \sigma_y^2 \end{bmatrix} \quad (1)$$

where ρ is the correlation coefficient.

For the transmission of the correlated sources, we consider two different options. First, we assume time division multiple access (TDMA) among the terminals where each time slot lasts for one complete packet transmission. At each time slot, we send K source samples, leading to a bandwidth ratio $b = \frac{N}{K}$. For T_x, we assume the number of transmitted information bits (or source bits) per channel use is R_x. This results in a compression rate of $\overline{R}_x = \frac{NR_x}{K} = bR_x$ bits per source sample. The corresponding distortion can then be expressed as:

$$D_x(\overline{R}_x) = \sigma_x^2 2^{-2\overline{R}_x} \quad (2)$$

Second, we let T_x and T_y transmit at the same time, hence, allowing interfering transmission. In the interference cases, both terminals utilize the total number of time slots. Assuming T_x and T_y are each utilizing N channel uses with TDMA, the total number of channel uses for both terminals for the interfering transmission case is $2N$ while the compression rates remains the same. Similar quantities can be defined for T_y as well.

To ensure a fair comparison of all the tested schemes all source transmissions are constrained to a specific power level per each time slot. This means that when orthogonal transmissions are used for example, then the source transmits with power Φ while for the schemes that use interfering transmissions the transmission power for each source is $\Phi_x = \Phi_y = \Phi/2$. Also the transmit SNR for the two sources is defined as $SNR_x = \Phi_x/N_0, SNR_y = \Phi_y/N_0$.

To illustrate the effects of the different transmission modes on the reconstruction of the correlated sources, we consider four transmission schemes.

- *ORT*: Each terminal compresses its own signal, ignoring the source correlation. Each terminal transmits its own source directly to the destination in its own timeslot, i.e. orthogonal transmission.
- *SIC*: Each terminal compresses its own source without considering the correlation as in *ORT*. However, in this mode interfering transmissions are allowed.
- *ORT-MMSE*: Each terminal compresses and transmits its own source directly to the destination in its own timeslot. At the receiver, different from the *ORT*, the source correlation is exploited.
- *SIC-MMSE*: Each terminal compresses and transmits its own source to the destination. In this mode, interfering transmissions are allowed and the source correlation is extracted at the receiver.

III. OUTAGE PROBABILITY COMPUTATIONS

For a given transmission scheme, average channel SNRs, source correlation and bandwidth ratio, the expected distortion is a function of the source rates and the amount of channel coding. We will assume that a complete frame will be discarded if the channel decoder can not correct all the errors.

We define P^i as the average probability of state (i), where i denote whether (X, Y) is received. Here $i \in \{1, 2, 3, 4\}$. For $i = 1$, the compressed bits of both T_x and T_y are received, for $i = 2$ the compressed bits of T_x are received but the bits for T_y are lost, $i = 3$ means the compressed bits of T_y are received but the bits for T_x are lost and finally for $i = 4$ the compressed bits of both T_x and T_y fail to reach the destination.

Next, we will illustrate the computation of the outage probabilities for TDMA orthogonal based transmission as well as interfering transmission.

A. TDMA based transmission

To compute the average probabilities P^i, we consider an information theoretic approach. Considering complex Gaussian codebooks, for a channel code operating at a rate R bits per channel use, information is lost when the instantaneous channel capacity is lower than R, leading to the outage probability $P_{\text{out}} = \Pr\{C(|h|^2 SNR) < R\}$ for a point to point link where $C(x) = \log(1+x)$ is the Gaussian channel capacity and $|h|$ is the fading amplitude.

We will illustrate the computation of P^1 as an example. Using the outage approach the compressed bits of both T_x and T_y are correctly received at the destination if:

$$R_x < C(|h_x|^2 SNR_x), R_y < C(|h_y|^2 SNR_y) \tag{3}$$

Note that we have modeled the transmission of additional parity bits as independent Gaussian codebooks. By taking into account the above, and the fact that the two transmissions are independent, we have:

$$P^{1,\text{ORT}} = \Pr\{R_x < C(|h_x|^2 SNR_x)\} \Pr\{R_y < C(|h_y|^2 SNR_y)\} \tag{4}$$

We can compute the other probabilities $P^{2,ORT}$, $P^{3,ORT}$ and $P^{4,ORT}$ similarly. The average distortion for ***ORT*** can then be expressed in terms of error/success probabilities as:

$$ED_x^{\text{ORT}} = (P^{1,\text{ORT}} + P^{2,\text{ORT}}) D_x(bR_x) + (P^{3,\text{ORT}} + P^{4,\text{ORT}}) \sigma_x^2 \tag{5}$$

$$ED_y^{\text{ORT}} = (P^{1,\text{ORT}} + P^{3,\text{ORT}}) D_y(bR_y) + (P^{2,\text{ORT}} + P^{4,\text{ORT}}) \sigma_y^2 \tag{6}$$

B. Interfering Transmissions and SIC Decoding

While computing the outage probability for the interfering transmissions, we follow a similar approach as in the TDMA case where we modify the SNR expressions such that interfering transmissions are accounted for. The baseband signal model that is used for the case of interference at the receiver is:

$$I = h_x X_d + h_y Y_d + W \tag{7}$$

Note that in the above expression X_d and Y_d are digital compressed signals. We assume an ordered SIC (OSIC) decoder is used which means that the stronger signal is decoded first. For exposition purposes, let us assume that the stronger signal is $h_x X_d$. Then, the instantaneous Signal to Interference plus Noise Ratio (SINR) for X_d can be expressed as:

$$SINR_x^a = \frac{|h_x|^2 \sigma_{x_d}^2}{|h_y|^2 \sigma_{y_d}^2 + N_0} \tag{8}$$

Now, if X_d is successfully decoded, we can decode Y_d with its respective SINR being equal to:

$$SINR_y^a = \frac{|h_y|^2 \sigma_{y_d}^2}{N_0} \tag{9}$$

If $h_x Y_d$ is stronger signal then we have:

$$SINR_x^b = \frac{|h_x|^2 \sigma_{x_d}^2}{N_0}, SINR_y = \frac{|h_y|^2 \sigma_{y_d}^2}{|h_x|^2 \sigma_{x_d}^2 + N_0}.$$

At the SIC decoder the validity of the result is verified with the use of a channel code, i.e., we do not assume perfect decoding. The channel capacity under SIC can be computed by replacing the $h_x SNR_x$ and $h_y SNR_y$ in (3) with the SINR expressions computed above. We can now write the probability of receiving both X_d and Y_d for the case of interfering transmissions as:

$$\begin{aligned} P^{1,\text{SIC}} &= \Pr\{R_x < 2C(SINR_x^a)), R_y < 2C(SINR_y^a))\} \\ &+ \Pr\{R_x < 2C(SINR_x^b)), R_y < 2C(SINR_y^b))\} \end{aligned} \tag{10}$$

We can compute $P^{2,SIC}, P^{3,SIC}$ and $P^{4,SIC}$ similarly. We note that for SIC, we do not use the correlation at T_x, hence the expected distortion can be expressed as:

$$ED_x^{\text{SIC}} = (P^{1,\text{SIC}} + P^{2,\text{SIC}}) D_x(bR_x) + (P^{3,\text{SIC}} + P^{4,\text{SIC}}) \sigma_x^2 \tag{11}$$

$$ED_y^{\text{SIC}} = (P^{1,\text{SIC}} + P^{3,\text{SIC}}) D_y(bR_y) + (P^{2,\text{SIC}} + P^{4,\text{SIC}}) \sigma_y^2 \tag{12}$$

IV. MMSE Reconstruction of Correlated Sources

Now we describe the *estimation algorithm* that is used after the digitally modulated packets are decoded at the receiver. These packets are the result of SIC. In this case, we exploit our knowledge of the data model (correlation between sources X, Y) that was defined to be $Y = \alpha X + Z$.

When both signals are correctly decoded with SIC, the system could then proceed and deliver the packets to the application. However, notice that we have two digital observations contained in X_d and Y_d that are correlated. To exploit this, we define at a finer level the data model of the digital observations:

$$Y_d = \alpha X + Z + q_y \text{ and } X_d = X + q_x, \tag{13}$$

where q_x, q_y are the samples of the quantization noise that have variance equal to $D_x(bR_x)$ and $D_y(bR_y)$. From these two observations, we will jointly estimate X with MMSE estimation. This leads to the distortion of X being equal to:

$$D_x^1 = \frac{\sigma_x^2}{\sigma_x^2 \left(\frac{\alpha^2}{\sigma_z^2 + Dy} + \frac{1}{Dx}\right) + 1}$$

The numerical superscript above indicates the first event, i.e., both packets were decoded. The distortion of Y is:

$$D_y^1 = \min\{D_y(bR_y), \alpha^2 D_x^1 + \sigma_z^2\}$$

The reason for the above expression is because the receiver can estimate Y since it has the digital compressed signal Y_d, that is hampered by quantization noise q_y (with distortion $D_y(bR_y)$). Or it can estimate it as $\hat{Y} = \alpha \hat{X}$ depending which provides the lowest distortion.

Let us now consider the second event that X_d is decoded and Y_d is not. Then, the distortion of X is equal to:

$$D_x^2 = D_x(bR_x),$$

since we cannot avoid the quantization distortion. Similarly as before, we estimate source Y as $\hat{Y} = \alpha\hat{X}$ since now we do not have any other observation of this signal. Thus we have:

$$D_y^2 = \alpha^2 D_x(bR_x) + \sigma_z^2$$

Note that if we did not use the estimated signal $\hat{X}$ at all, the distortion would be equal to $\sigma_y^2 = \alpha^2\sigma_x^2 + \sigma_z^2$ which is clearly the worst case.

Now, we consider the case where Y_d is decoded and X_d is not. The distortion for Y is then equal to:

$$D_y^3 = D_y(bR_y)$$

With MMSE estimation we can also estimate X from our data model in (13) and in this case the distortion is equal to:

$$D_x^3 = \frac{\sigma_x^2}{\sigma_x^2(\frac{\alpha^2}{\sigma_z^2 + D_y}) + 1}$$

What we do in all these cases is that we check the availability specific observations, and then we use the knowledge of the data model to optimally combine the available information leveraging linear estimation principles. We need an adaptive MMSE estimation algorithm since we are not interested in X, Z from our data model, but X, Y where the later is a linear combination.

Now, the average distortion expressions for the case of orthogonal transmissions can be written as:

$$\begin{aligned} ED_x^{\text{ORT-MMSE}} &= P^{1,\text{ORT}} D_x^1 + P^{2,\text{ORT}} D_x^2 \\ &+ P^{3,\text{ORT}}\ D_x^3 + P^{4,\text{ORT}}\ \sigma_x^2 \end{aligned} \qquad (14)$$

$$\begin{aligned} ED_y^{\text{ORT-MMSE}} &= P^{1,\text{ORT}} D_y^1 + P^{2,\text{ORT}} D_y^2 \\ &+ P^{3,\text{ORT}}\ D_y^3 + P^{4,\text{ORT}}\ \sigma_y^2 \end{aligned} \qquad (15)$$

For the case of interfering transmissions, the average distortion expressions can be written as:

$$\begin{aligned} ED_x^{\text{SIC-MMSE}} &= P^{1,\text{SIC}} D_x^1 + P^{2,\text{SIC}} D_x^2 \\ &+ P^{3,\text{SIC}}\ D_x^3 + P^{4,\text{SIC}}\ \sigma_x^2 \end{aligned} \qquad (16)$$

$$\begin{aligned} ED_y^{\text{SIC-MMSE}} &= P^{1,\text{SIC}} D_y^1 + P^{2,\text{SIC}} D_y^2 \\ &+ P^{3,\text{SIC}}\ D_y^3 + P^{4,\text{SIC}}\ \sigma_y^2 \end{aligned} \qquad (17)$$

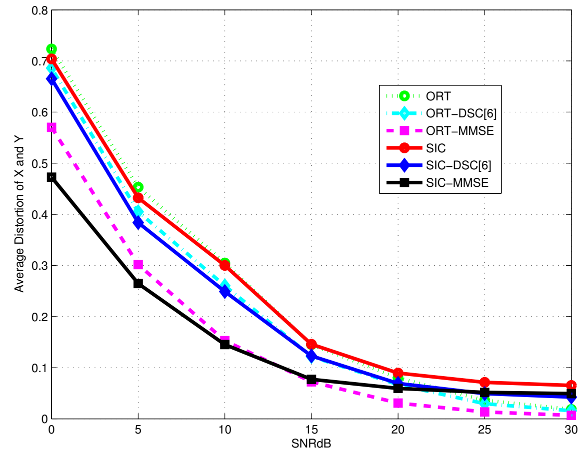
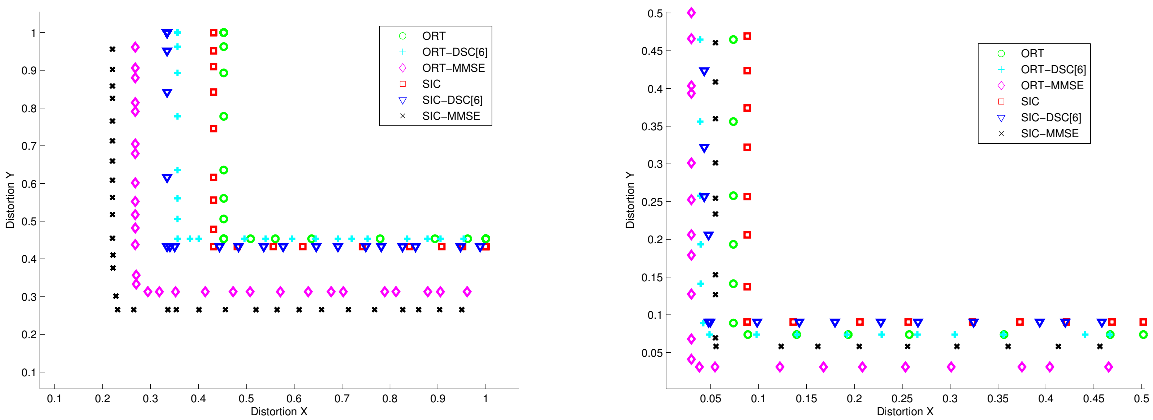


Fig. 2. Average distortion with $\rho = 0.9$, SNR_x = SNR_y = SNRdB

V. Results

In this section, we carry out the minimization of (5), (6), (11), (12), (14), (15), (16), (17) numerically and compare the expected distortions achieved by different modes for various source correlation and channel link qualities. We assume $\sigma_x^2 = \sigma_y^2 = 1$ and $b = 1$. We consider a symmetric scenario where the terminals are at an equal distance to the destination such that $SNR_x = SNR_y = SNR$. We consider the modes that are discussed in Section II: *ORT*, *ORT-MMSE*, *SIC* and *SIC-MMSE*. Furthermore, we present additional results for the case where the source correlation is extracted at the sources using Wyner-Ziv DSC as in [6] with one small modification where we apply the global power constraint as in all the other modes to ensure fair comparison. For DSC, we consider both orthogonal transmission (*ORT-DSC*) and interfering transmission with SIC decoding (*SIC-DSC*).

Note that a chosen rate pair jointly affects both ED_x and ED_y when correlation is extracted. One way to determine an optimal assignment of rates and the distortion tradeoff is to minimize the average distortion of X and Y, $(ED_x + ED_y)/2$. Figure 2 illustrates the achievable minimal average distortion with such optimal allocation over a wide range of channel SNRs for a high correlation coefficient ($\rho = 0.9$). We observe that joint decoding of correlated sources exploits the signal correlation very well, hence, reducing the distortion significantly. Interfering transmission together with joint decoding (*SIC-MMSE*) is more effective in low SNR regime and at high SNR regime, orthogonal transmission with joint decoding (*ORT-MMSE*) provides lower distortion values. Essentially in the high SNR regime interfering signals are stronger which means that they cannot be cancelled so effectively, i.e., the ratio in (8) is relatively low. An important result is that MMSE can extract source correlation better compared to the DSC-based schemes in both orthogonal transmissions as well as interfering transmissions for all SNR regimes. DSC performs poorly especially for low SNR regime compared to MMSE,



(a) SNR_x = SNR_y = 5dB

(b) SNR_x = SNR_y = 20dB

Fig. 3. ED_x versus ED_y for $\rho = 0.9$

however as the SNR gets higher, the performance of *ORT-DSC* approaches to the best performing scheme at high SNR, *ORT-MMSE*.

To observe the individual and joint effects of interference and correlation, for a fixed SNR and correlation coefficient, we vary R_x and R_y, compute the corresponding (ED_x,ED_y) pairs and plot the minimum values. Figure 3 illustrates the ED_x versus ED_y behaviour for a high correlation coefficient (ρ=0.9), for two different channel signal to noise ratios, SNR_x=5dB and SNR_y=20dB. Comparison of *ORT* and *ORT-MMSE* shows how correlation helps to improve the distortion of X and Y using MMSE at the receiver. We observe that the proposed method, *SIC-MMSE*, outperforms all other modes by reducing the distortion of both X and Y significantly in the low SNR regime. The reason is that in the low SNR regime SIC detection ensures better performance for interference decoding which means that at least one packet is decoded with high probability. *SIC-MMSE* also uses joint detection which means that for highly correlated data between X, Y when we have at least one observation we can estimate the other one with high accuracy. On the other hand, in the high SNR regime, orthogonal based transmission outperforms the interference-based transmission both with and without MMSE applied at the receiver.

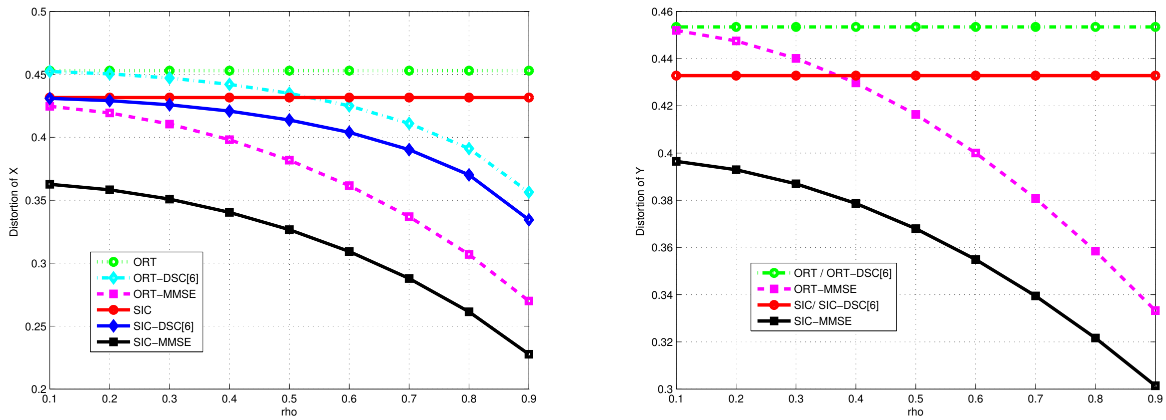
Figure 4 illustrates the minimum distortion of X and Y as a function of correlation coefficient ρ for the low SNR regime (SNR_x=SNR_y=5dB). For *ORT-MMSE* and *SIC-MMSE*, we observe the expected distortion of both X and Y reduce as the correlation increases. Introducing interference (*SIC* and *SIC-MMSE*), reduces the distortion significantly compared to the corresponding non-interference modes (*ORT* and *ORT-MMSE*). Joint decoding (*SIC-MMSE*) provides the lowest distortion values for both X and Y for both low and high correlation coefficients. We also observe that DSC-based schemes (*ORT-DSC* and *SIC-DSC*) the distortion of Y is constant over different ρ values while the distortion of X reduces as ρ increases. This is due to the Wyner-Ziv DSC function that considers lossy side-information. On the other hand, MMSE-based schemes (*ORT-MMSE* and *SIC-MMSE*) are symmetric in a sense where as ρ increases, both distortions of X and Y are reduced since they are jointly decoded at the receiver.

Similarly, in Figure 5 we illustrate the minimum distortion of X and Y as a function of correlation coefficient ρ for the high SNR regime (SNR_x=SNR_y=20dB). Here, in general the behaviour is similar to the low SNR regime except that orthogonal transmission is more beneficial compared to interfering transmission. Still, MMSE estimation performs better than DSC for all different correlation values, hence *ORT-MMSE* provides the best performance by significantly reducing the distortion of both X and Y.

VI. Conclusions and Future Work

In this paper, we proposed practical transmission strategies for correlated sources in quasi-static fading channels. We showed that by compressing each source independently and applying an adaptive MMSE decoding algorithm at the receiver, the expected distortion of correlated sources can be minimized over DSC-based schemes. Even more importantly, allowing interference is the optimal choice in the low SNR regime, while orthogonal transmission is superior in the high SNR regime. Overall, our approach always outperforms DSC-based schemes indicating the unsuitability of this approach for fading channels. The proposed scheme is practical since the sources are agnostic to the use of the proposed scheme, and they do not need to deploy any new source-channel coders. Furthermore, other benefits are expected since the channel access overhead through a MAC protocol is minimized.

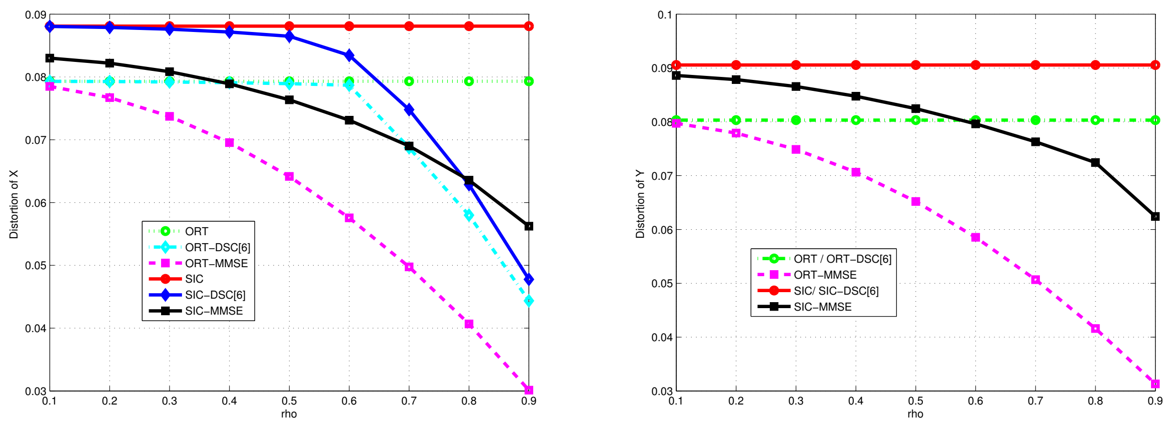
In our future work, we first plan to consider a WSN of several nodes and analyze the performance for such a multi-source system under the assumption of Gaussian sources. Also designing an adaptive communication scheme that uses orthogonal or interfering transmissions depending on the operating regime of the system.



(a) D_x versus ρ

(b) D_y versus ρ

Fig. 4. Distortion of X and Y for SNR_x = SNR_y = 5 dB



(a) D_x versus ρ

(b) D_y versus ρ

Fig. 5. Distortion of X and Y for SNR_x = SNR_y = 20 dB

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