Adaptive Compress-and-Forward Relaying in Fading Environments with or without Wyner-Ziv Coding

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***Abstract*—Compress-and-Forward is a protocol for transmission over relay networks in which the relay forwards a compressed version of the signal it observes. The compression method used by the relay is source coding with side information, i.e. Wyner-Ziv coding, since the destination can use the signal it receives directly from the source as side information.**

This paper addresses the case of a wireless relay network with orthogonal transmissions from the source and the relay terminals; we show that when the transmitters have no instantaneous channel state information the optimal compression parameters often make Wyner-Ziv coding reduce to conventional source compression, i.e. compression that does not take into account the side information available at the destination.

This result simplifies the implementation of the CF protocol in the case we consider, since it shows that in several situations one can use more convenient compression methods without significant performance loss.

I. Introduction

Communication in a wireless network can be improved by letting the terminals cooperate. Cooperation helps providing diversity, can enable higher transmission rates and offer a better coverage. These promises of cooperation have drawn a lot of interest and research in recent years; contributions most related to this paper are [1]–[3].

Three relaying techniques are at the core of cooperative communication. The first typical approach is to make the relay decode, re-encode and forward the signal; this is the so-called *Decode-and-Forward* (DF) strategy. The second approach consists in making the relay simply amplify the signal it receives and forward it to the destination; this is the *Amplify-and-Forward* (AF) technique. And finally, in the third approach the relay compresses the signal it receives, then encodes compressed version and sends it to the destination; this is termed *Compress-and-Forward* (CF).

This paper considers a hybrid protocol using DF when the relay can decode successfully, and CF otherwise. The focus is on the CF part of the protocol.

In the CF technique, Wyner-Ziv coding is used by the relay because the destination uses the signal received directly from the source as side information [4], [5]. A practical CF strategy with Wyner-Ziv coding is presented in [6], for fixed channels known to all terminals. However other contributions as [7] have simplified the protocol by using, instead of Wyner-Ziv coding, conventional source compression that does not take into account the side information available at destination.

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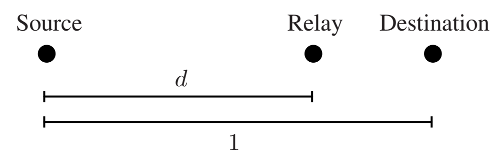


Fig. 1. Relay network and geometric configuration.

In this work we investigate Wyner-Ziv coding in the case of fading channels unknown to the transmitters and observe that, in certain conditions, the compression parameters minimizing outage make Wyner-Ziv coding reduce to conventional source compression. The importance of this observation is that conventional source compression is simpler than Wyner-Ziv coding, that many CF schemes developed in the literature have adopted conventional source compression, and that the situations for which conventional source compression is optimal can be rather frequent.

The paper is organized as follows. The system model, the protocol used and the relevant information theoretic quantities are presented in II. Section III seeks the optimal compression parameters and section IV presents an upper bound on the probability that the optimal compression method would effectively be Wyner-Ziv. Section V illustrates the results and section VI concludes the paper.

II. System model

We consider a simple wireless relay network consisting of a source terminal, a relay and a destination as in fig. 1. Transmissions suffer from frequency-flat block-fading and additive noise, which is deemed appropriate for a narrow-band low-mobility scenario.

A. Medium Access

The relay operates in half-duplex mode, to get round the technical difficulty of receiving and transmitting at the same time in the same frequency band. Moreover, in order to keep the receiver at the destination simple, we allocate orthogonal channels to the source and the relay. Bandwidth and time are equally shared out among these.

Instantaneous channel state information (CSI) is available at the receivers, whereas the transmitters can obtain and use average CSI only.

B. Transmission models

We model the transmissions by their discrete-time baseband equivalent models. The sequence $\boldsymbol{X_s}$ transmitted by the source is received by the relay and the destination as, respectively:

$$\boldsymbol{Y_{sr}} = h_{sr}\boldsymbol{X_s} + \boldsymbol{Z_{sr}} \quad (1)$$

$$\boldsymbol{Y_{sd}} = h_{sd}\boldsymbol{X_s} + \boldsymbol{Z_{sd}} \quad (2)$$

and is followed by the transmission of a sequence $\boldsymbol{X_r}$ from the relay to the destination, which receives

$$\boldsymbol{Y_{rd}} = h_{rd}\boldsymbol{X_r} + \boldsymbol{Z_{rd}}. \quad (3)$$

The input sequences $\boldsymbol{X_s}$ and $\boldsymbol{X_r}$ are codewords of length $n/2$. We choose to use a random code with complex Gaussian symbols, thus all elements of these sequences are mutually independent, identically distributed (i.i.d.) with zero mean and variances P_s and P_r respectively. We write the code rates R_s and R_r respectively. The factors h_{ij} are the channel fading coefficients from terminal i to terminal j and the $\boldsymbol{Z_{ij}}$ are sequences of additive noise, with $i \in \{s, r\}, j \in \{r, d\}$. Statistically, we model the h_{ij} and $\boldsymbol{Z_{ij}}$ as zero-mean, mutually independent, circularly symmetric complex Gaussian random variables. The noise samples in $\boldsymbol{Z_{ij}}$ have a variance normalized to $N_{ij} = 1$. Finally, we also define the shorthand notations $\gamma_{sj} = |h_{sj}|^2 P_s$ and $\gamma_{rd} = |h_{rd}|^2 P_r$. Given the modelization above, these are exponential random variables with mean $\sigma_{ij}^2 \triangleq \mathrm{E}[|h_{ij}|^2]P_i$.

C. Cooperation protocol

Our cooperation protocol extends over two slots; the source transmits in the first slot and the relay forwards in the second one. The processing at the relay depends on the quality of the signal received from the source. If the relay is able to decode the signal, it forwards it using DF, otherwise it uses CF. The reason for using this hybrid strategy is to focus our analysis of the CF protocol only on situations in which DF is not possible.

Achievable rates with these protocols were derived in [4]; in the following we present them for the particular case of Gaussian orthogonal relay channel.

1) DF protocol: If the relay is able to decode $\boldsymbol{X_s}$ from $\boldsymbol{Y_{sr}}$, that is when

$$R_s \le \log_2(1 + \gamma_{sr}), \quad (4)$$

then the DF protocol is used and the sequence $\boldsymbol{X_r}$ is taken from a code with rate $R_r = R_s$ and length $n/2$. The destination jointly decodes the signals from the source and the relay. Achievable spectral efficiencies R for the whole cooperative transmission are those satisfying the constraint

$$R \le \log_2\left((1 + \gamma_{sd})(1 + \gamma_{rd})\right). \quad (5)$$

Note that we obviously have $R_s = R_r = 2R$.

2) CF protocol: When the relay cannot decode the signal from the source it uses the CF protocol. In this protocol the relay performs Wyner-Ziv coding, i.e. it compresses the sequence $\boldsymbol{Y_{sr}}$ and sends a corresponding codeword $\boldsymbol{X_r}$; then the destination calculates the estimates $\hat{\boldsymbol{Y}}_{\boldsymbol{sr}}$ using $\boldsymbol{X_r}$ as well as the sequence $\boldsymbol{Y_{sd}}$ from the source as side information.

The level of compression of $\hat{\boldsymbol{Y}}_{\boldsymbol{sr}}$ is controlled by two parameters, namely the code rate R_r chosen for the forwarding on the relay-to-destination channel and the quantization noise variance N_q. With our Gaussian assumptions on the channels and their inputs, and with compression of $\boldsymbol{Y_{sr}}$ so as to minimize the mean square error on the estimates $\hat{\boldsymbol{Y}}_{\boldsymbol{sr}}$, these can be modeled as

$$\hat{\boldsymbol{Y}}_{\boldsymbol{sr}} = \boldsymbol{Y_{sr}} + \boldsymbol{Z_q}, \quad (6)$$

where $\boldsymbol{Z_q}$ is a sequence of i.i.d. circularly symmetric complex Gaussian quantization noise samples of variance N_q.

At the destination, the receiver first considers $\boldsymbol{Y_{rd}}$ and tries to decode $\boldsymbol{X_r}$. The event $\mathcal{C}$ of *correct decoding* is given by

$$\mathcal{C}: \quad R_r \le \log_2(1 + \gamma_{rd}). \quad (7)$$

Then, from $\boldsymbol{X_r}$ and $\boldsymbol{Y_{sd}}$ the receivers tries to obtain $\hat{\boldsymbol{Y}}_{\boldsymbol{sr}}$; the event $\mathcal{D}$ of *correct decompression* is written

$$\mathcal{D}: \quad R_r \ge \log_2\left(1 + \frac{1 + \frac{\gamma_{sr}}{1+\gamma_{sd}}}{N_q}\right). \quad (8)$$

If both $\mathcal{C}$ and $\mathcal{D}$ occur, the achievable spectral efficiencies for the cooperative transmission are those satisfying

$$R \le \frac{1}{2}\log_2\left(1 + \gamma_{sd} + \frac{\gamma_{sr}}{1 + N_q}\right) \triangleq I_{CF}. \quad (9)$$

Otherwise the signal from the relay is unusable and the destination uses the signal from the source only; the achievable rates are then limited to

$$R \le \frac{1}{2}\log_2\left(1 + \gamma_{sd}\right) \triangleq I_{sd}. \quad (10)$$

D. Comments on the compression

We give here some comments on the constraint (8) that links the compression parameters N_q and R_r.

First, the range of appropriate R_r for a given N_q extends as follows:

$$\log_2\left(1 + \frac{1}{N_q}\right) \le R_r \le \log_2\left(1 + \frac{1 + \gamma_{sr}}{N_q}\right), \quad (11)$$

where the limits correspond to the cases where γ_{sd} would be, respectively, very large or equal to 0. The relay can thus choose any R_r in this range, depending on the assumption it makes on the (unknown) γ_{sd}.

Second, the most conservative choice of R_r, i.e. the upper limit in (11), reduces to using conventional source compression at the relay instead of Wyner-Ziv coding: decompression is possible (i.e. (8) is satisfied) whatever the value of γ_{sd}. In the sequel we show that this most conservative choice of R_r is often optimal in usual configurations.

III. Optimal parameters for CF

A relay using CF has to choose the values of the parameters R_r and N_q. This can be done on a frame-by-frame basis after reception of $\boldsymbol{Y_{sr}}$, to take advantage of the knowledge of γ_{sr}.

This section addresses the calculation of these optimal parameters so as to minimize the outage probability for known γ_{sr}. This outage probability is developed in subsection III-A; then the optimal value of R_r for fixed N_q is derived in subsection III-B. Finding the optimal N_q however, has to be done numerically.

A. Outage probability

In the CF case, an outage event occurs when either (9) or (10) are not satisfied, depending on whether the events $\mathcal{C}$ and $\mathcal{D}$ occur. More precisely, if the decoding fails ($\bar{\mathcal{C}}$), or if it succeeds but the decompression fails ($\mathcal{C}, \bar{\mathcal{D}}$), the appropriate constraint on the spectral efficiency is (10); if both decoding and decompression succeed ($\mathcal{C}, \mathcal{D}$) then (9) is the right constraint. This yields the following decomposition of the outage probability for a spectral efficiency R and given γ_{sr}:

$$\begin{aligned} &P_{\text{out}}(R|\gamma_{sr}) \qquad (12)\\ &= P(R > I_{CF}|\mathcal{C}, \mathcal{D}, \gamma_{sr}) \cdot P(\mathcal{D}|\mathcal{C}, \gamma_{sr}) P(\mathcal{C}|\gamma_{sr}) \\ &+ P(R > I_{sd}) \cdot \left(P(\bar{\mathcal{C}}|\gamma_{sr}) + P(\bar{\mathcal{D}}|\mathcal{C}, \gamma_{sr}) P(\mathcal{C}|\gamma_{sr})\right) \end{aligned}$$

The probabilities appearing in (12) are:

- The probability of not satisfying the rate constraint (9), given that the destination has been able to decode and decompress the signal from the relay:

$$\begin{aligned} &P(R > I_{CF}|\mathcal{C}, \mathcal{D}, \gamma_{sr}) \\ &= 1 - \exp\left(\frac{-1}{\sigma_{sd}^2}\left(2^{2R} - 1 - \frac{\gamma_{sr}}{1 + N_q}\right)\right). \end{aligned} \quad (13)$$

  This is valid only if $N_q > \frac{\gamma_{sr}}{2^{2R}-1} - 1$; this inequality always holds since we use CF only when the relay is not able to decode, thus when the right-hand member of the inequality is negative.
- The probability of not satisfying the rate constraint (10):

$$P(R > I_{sd}) = 1 - \exp\left(-\frac{2^{2R} - 1}{\sigma_{sd}^2}\right). \quad (14)$$

- The probability of successfully decoding the signal from the relay:

$$P(\mathcal{C}|\gamma_{sr}) = \exp\left(-\frac{2^{R_r} - 1}{\sigma_{rd}^2}\right). \quad (15)$$

- And finally the probability of successfully decompressing the signal from the relay:

$$P(\mathcal{D}|\mathcal{C}, \gamma_{sr}) = \exp\left(\frac{-1}{\sigma_{sd}^2}\left(\frac{\gamma_{sr}}{(2^{R_r} - 1)N_q - 1} - 1\right)\right) \quad (16)$$

  which is valid for pairs (R_r, N_q) satisfying (11).

B. Code rate R_r minimizing outage

This section addresses the optimal choice of the relay code rate R_r. For fixed N_q, an analytical expression of the optimal R_r is obtained by simply finding the zero of the partial derivative of (12) with respect to R_r.

The partial derivative $\frac{\partial P_{out}}{\partial R_r}$, not explicitely written here due to lack of space, can be transformed into a polynomial function of the variable 2^{R_r} after several simplifications that conserve its zeros and its sign. This polynomial is

$$2^{2R_r} N_q^2 - 2^{R_r} 2N_q(N_q + 1) + (N_q + 1)^2 - N_q \frac{\gamma_{sr}\sigma_{rd}^2}{\sigma_{sd}^2}. \quad (17)$$

For $N_q < \frac{\gamma_{sr}\sigma_{sd}^2}{\sigma_{rd}^2}$ the polynomial (17) has one root in the range (11), equal to

$$R_r^\star(N_q) = \log_2\left(1 + \frac{1}{N_q}\left(1 + \sqrt{\frac{N_q \sigma_{rd}^2 \gamma_{sr}^2}{\sigma_{sd}^2}}\right)\right). \quad (18)$$

This root corresponds to a minimum of the probability of outage, as can be seen from (17).

On the contrary if $N_q \geq \frac{\gamma_{sr}\sigma_{sd}^2}{\sigma_{rd}^2}$, the polynomial (17) is negative for all R_r in (11), thus the outage probability decreases for increasing R_r. The optimal R_r is then the largest R_r allowed by (11), i.e.

$$R_r^\star(N_q) = \log_2\left(1 + \frac{1 + \gamma_{sr}}{N_q}\right). \quad (19)$$

Among these two solutions, (18) corresponds to Wyner-Ziv coding, whereas (19) uses conventional source compression.

C. Quantization noise variance N_q minimizing outage

The optimal solution for R_r can be substituted in the outage probability (12), which can then be minimized over N_q. There is however no explicit expression for the optimal value of N_q, so that one has to resort to numerical optimization. Furthermore, the outage probability is not convex in N_q, even if we have never observed any case in which there are multiple local minima. After a thorough examination of the function, we conjecture the following:

Conjecture 1: The outage probability (12) has only one minimum, that we write $(R_r^\star(N_q^\star), N_q^\star)$.

IV. Bound on the usage of Wyner-Ziv coding

The aim of this section is to assess how often the optimal compression parameters $(R_r^\star(N_q^\star), N_q^\star)$ correspond to Wyner-Ziv coding, and to conventional source compression.

To do so, we first observe the derivative $\frac{dP_{out}}{dN_q}$ at the border between the regions of Wyner-Ziv coding and conventional source compression, i.e. for $N_q = \frac{\gamma_{sr}\sigma_{sd}^2}{\sigma_{rd}^2}$. The sign of this derivative tells on which side the N_q minimizing outage is, and thus which compression method is optimal. From this observation, we identify a range of values of γ_{sr} in which the optimal solution $N_q^\star$ never corresponds to Wyner-Ziv coding. Finally this yields an upper bound on the usage of Wyner-Ziv coding.

We start with the outage probability for values of $N_q < \frac{\gamma_{sr}\sigma_{sd}^2}{\sigma_{rd}^2}$, and substitute the corresponding optimal R_r given by (18). The derivative $\frac{dP_{out}}{dN_q}$ can be transformed into the following function, after several simplifications not detailed here that conserve its zeros and its sign:

$$\left[\exp\left(\frac{-\gamma_{sr}}{\sigma_{sd}^2(1+N_q)}\right)-1\right]\left[\frac{1+\sqrt{\frac{\sigma_{rd}^2\gamma_{sr}}{\sigma_{sd}^2}N_q}}{\sigma_{rd}^2N_q^2}\right]+\frac{\gamma_{sr}}{\sigma_{sd}^2(1+N_q)^2} \tag{20}$$

Assuming that conjecture 1 holds, the value of (20) when N_q gets close to the border of the Wyner-Ziv region, i.e. for $N_q \to \frac{\gamma_{sr}\sigma_{sd}^2}{\sigma_{rd}^2}$, tells in which region the optimal N_q lies:

- If (20) is positive, then $\frac{dP_{out}}{dN_q} > 0$ and the minimum $N_q^\star$ is such that $N_q^\star < \frac{\gamma_{sr}\sigma_{sd}^2}{\sigma_{rd}^2}$. In that case the relay uses Wyner-Ziv coding.
- If (20) is negative or zero, then $N_q^\star > \frac{\gamma_{sr}\sigma_{sd}^2}{\sigma_{rd}^2}$ and the relay uses conventional source compression.

We now find a value $\hat{\gamma}_{sr}$ such that for every $\gamma_{sr} \in [0, \hat{\gamma}_{sr}]$ the outage probability is minimized with conventional source compression. An upper-bound of (20) is obtained by using $e^{-x} \leq 1-x+\frac{x^2}{2}$. After substituting $N_q = \frac{\gamma_{sr}\sigma_{sd}^2}{\sigma_{rd}^2}$, the function can be transformed into the following second-order polynomial in γ_{sr}:

$$\gamma_{sr}^2\left(1+\frac{\sigma_{rd^2}}{2\sigma_{sd}^6}-\frac{1}{\sigma_{sd}^2}\right)+\gamma_{sr}\left(-\frac{\sigma_{rd}^2}{\sigma_{sd}^4}+\frac{\sigma_{rd}^2}{2\sigma_{sd}^6}-\frac{1}{\sigma_{sd}^2}\right)-\frac{\sigma_{rd}^2}{\sigma_{sd}^4}. \tag{21}$$

Conventional source compression is always used when this polynomial is negative, this happens:

- If the coefficient of the first term is negative, since in that case one can check that the polynomial is negative for every γ_{sr}.
- If the coefficient of the first term is positive, the polynomial is convex and has one positive root written $\hat{\gamma}_{sr}$. The polynomial is negative for $\gamma_{sr} \in [0, \hat{\gamma}_{sr}]$ thus conventional source compression is always used in that range of γ_{sr}.

Now we can calculate an upper-bound on the usage of Wyner-Ziv coding. As discussed above, Wyner-Ziv is never used if $\gamma_{sr} < \hat{\gamma}_{sr}$, and CF in general is never used if $\gamma_{sr} \geq 2^{2R}-1$. Thus, at most, CF with Wyner-Ziv coding can be used for $\gamma_{sr} \in [\hat{\gamma}_{sr}, 2^{2R}-1[$. The statistics of the source-to-relay channel then determine how often this happens. This yields the following upper bound on the probability of using Wyner-Ziv compress-and-forward:

$$P(\hat{\gamma}_{sr} < \gamma_{sr} < 2^{2R}-1) = \exp\left(-\frac{\hat{\gamma}_{sr}}{\sigma_{sr}^2}\right)-\exp\left(-\frac{2^{2R}-1}{\sigma_{sr}^2}\right). \tag{22}$$

Note that increasing the rate R does not change the lower limit of the Wyner-Ziv region $\hat{\gamma}_{sr}$ but increases the upper limit; thus Wyner-Ziv coding is more often used for higher rates R.

V. Simulations and discussion

This section illustrates the results developed above with an investigation of the usage of Wyner-Ziv coding for several choices of the transmission powers and spectral efficiency. We show that for low or moderate spectral efficiencies R, being limited to conventional source compression does not have a significant impact on the outage probability.

The relay network is depicted in fig. 1: all three terminals are lined up, the relay is at a distance d from the source and the distance between the source and the destination is normalized to 1. Path loss between the terminals determines the power levels at the receivers. With a path loss exponent chosen equal to $\alpha = 3.5$ we have $\sigma_{sd}^2 = P_s$, $\sigma_{sr}^2 = P_s/d^\alpha$ and $\sigma_{rd}^2 = P_r/(1-d)^\alpha$.

The relay uses DF if it is able to decode, otherwise it uses CF. The parameters of CF are optimized, and correspond either to Wyner-Ziv coding or to conventional source compression.

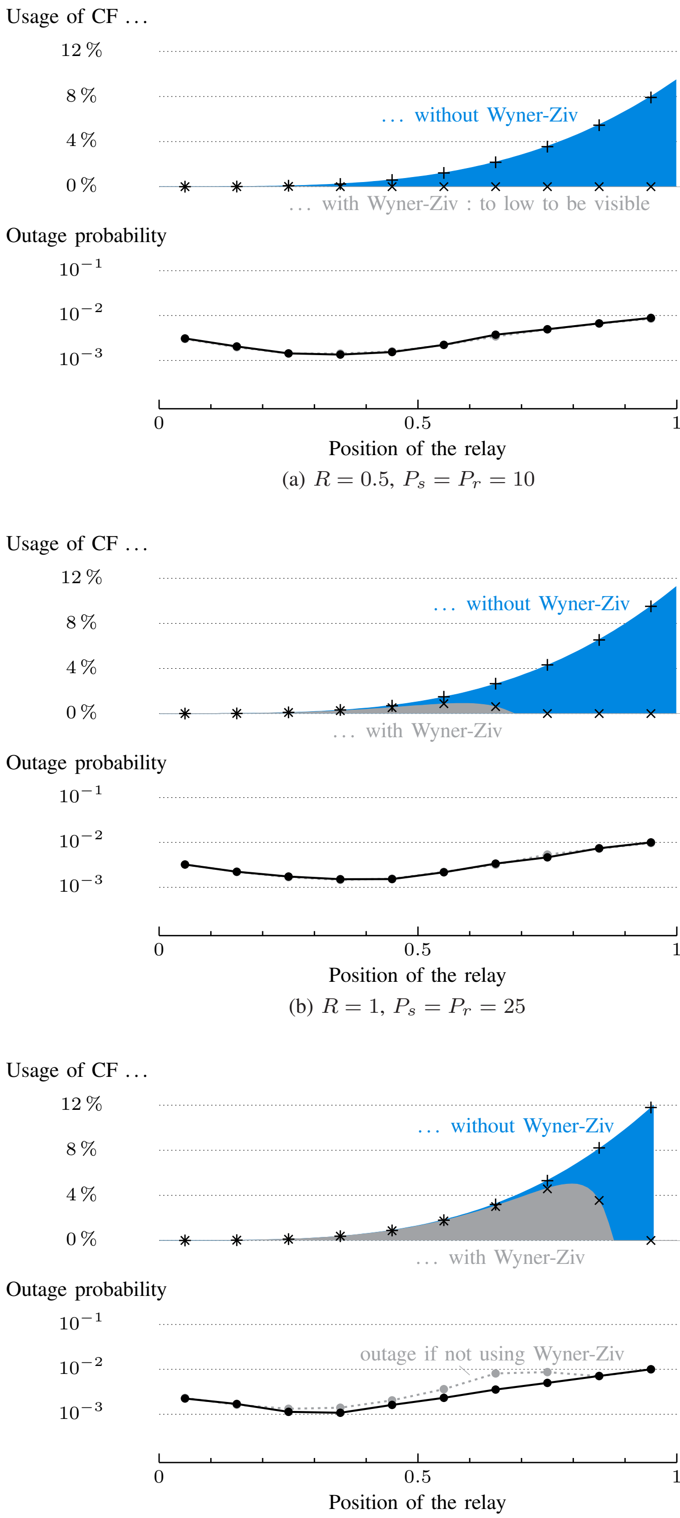
Based on the results of section IV, we evaluate for each position d of the relay the percentage of situations in which DF and CF are used; then among situations requiring CF, we evaluate the upper bound (22) on the proportion of them requiring Wyner-Ziv coding.

Figure 2 presents three situations with different spectral efficiencies $R = 0.5$, 1 and 2 b/s/Hz respectively, with a choice of transmission powers P_s and P_r such that the overall outage probability is below or around 10^{-2} in each case. The upper sub-graphs show the usage of each CF method as a function of the position of the relay d, both theoretically (filled areas) or as observed in Monte-Carlo simulations (crosses + and $\times$). Lower sub-graphs show the corresponding outage probability as obtained by simulation. The dashed curves are obtained when limiting the optimization of relay parameters to conventional source compression.

In figure 2(a), for $R = 0.5$ b/s/Hz and $P_s = P_s = 10$ J/symbol, the optimal compression method is almost never Wyner-Ziv coding (usage in less than $0.02\,\%$ of the frames at its maximum). Note that this case corresponds to $R_s = 1$ b/s/Hz. Figure 2(b) shows that for $R = 1$ b/s/Hz and $P_s = P_s = 25$ J/symbol, Wyner-Ziv is used in up to $1\,\%$ of the cases, for some positions of the relay. However, the outage curves show that forcing the use of conventional compression instead of Wyner-Ziv coding does barely have any impact on the outage. Finally, figure 2(c) shows that for $R = 2$ b/s/Hz and $P_s = P_s = 100$ J/symbol, Wyner-Ziv coding is more often used and brings a performance gain.

These results highlight first that Wyner-Ziv is beneficial only if the source-to-relay and source-to-destination signals are received with a good signal-to-noise ratio, so that their correlation can be exploited. For the same reason, we have seen in section IV that Wyner-Ziv coding is used only if γ_{sr} is larger than a threshold $\hat{\gamma}_{sr}$, whereas conventional source compression is used for smaller values of γ_{sr}.

Second, these results show that the use of Wyner-Ziv coding decreases when the relay gets close to the destination; this is because the rate R_r can be chosen large since the relay-to-destination channel is expected to be strong. The availability



(a) $R = 0.5,\ P_s = P_r = 10$

(b) $R = 1,\ P_s = P_r = 25$

(c) $R = 2,\ P_s = P_r = 100$

Fig. 2. Usage of the CF protocols for three different sets of parameters. In (a), optimal compression does almost never require Wyner-Ziv (usage lower than $0.02\,\%$). In (b), Wyner-Ziv coding is optimal for up to $1\,\%$ of the frames, but using conventional source compression instead does barely have any impact on the outage (dotted curve in lower graph). In (c), Wyner-Ziv coding is more often used and not using it has an impact on the outage.

of a high transmission rate R_r makes Wyner-Ziv coding less appealing.

Our final comments concern the fundamental reasons in the CF coding scheme for the behavior observed above. First, as opposed to AF and DF, CF does not use a joint decoding of the signals from the source and the relay. The destination has instead to decode successively the signal from the relay, then the signal from the source. The performance gain is thus limited by the success of the transmission on the point-to-point relay-to-destination channel. Second, for obtaining a significant gain when using Wyner-Ziv coding the relay must be confident that the side information, i.e. the direct source-to-destination signal, has a good signal-to-noise ratio. This causes the success of the decompression at the reception to be dependent on the point-to-point source-to-destination signal. And finally, since in our case the signal to compress at the relay is Gaussian, the AF protocol yields the same distortion at the destination as the CF protocol with conventional source compression would do if it knew the fading coefficient of the relay-to-destination link. When the relay transmitter has no CSI, the AF protocol is thus expected to perform better. This latest conclusion is however particular to the choices made in this paper and does not extend to, for instance, situation where the time/bandwith are not equally shared between the source and the relay, or in practical (not Gaussian) transmission schemes.

VI. Conclusion

This paper addresses the optimization of the Wyner-Ziv coding parameters of the CF protocol, and shows that for a range of transmission rates and powers the compression method minimizing outage is simply conventional source compression. Being able to resort to this simpler compression method without significant performance gain is particularly interesting for the design and implementation of practical transmission systems with CF relays.

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