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Research Article

How to Solve the Problem of Bad Performance of Cooperative Protocols at Low SNR

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We propose some new adaptive amplify-and-forward (AF) and decode-and-forward (DF) protocols using a selection. The new selection criterion is a function of the instantaneous capacities of all possible transmission schemes (with or without cooperation). Outage probabilities and simulation results show that the adaptive cooperation protocols solve the problem of bad performance of cooperation protocols at low SNR. Moreover, they improve the asymptotic performance of their corresponding AF and DF protocols.

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1. INTRODUCTION

Diversity techniques have been developed in order to combat fading on wireless channels and improve the reliability of the received message. Recently, cooperation has been proposed as a new mean to obtain "space-time" or "cooperative" diversity [1, 2]. Different nodes in the network cooperate in order to form a virtual MIMO system and exploit space-time diversity even if their hardware constraints do not allow them to support several antennas. Many cooperative protocols have been proposed [3–6] which can be classified in three main families: amplify-and-forward (AF), decode-and-forward (DF), and compress-and-forward (CF).

In this paper we are interested in the two first families, which are the more natural ones. AF protocols have been studied the most due to their simplicity. Indeed, the relays just amplify the received signals and forward them. DF protocols require a bit more processing: this strategy consists in decoding the received signals at the relays and then forwarding them. They have interesting performance, however, and are even essential for multihop systems. Asymptotically, both protocols bring diversity and give better performance than SISO which only uses the direct link. However, it does not match noncooperation at low SNR.

We propose here a new strategy named adaptive cooperation which can be applied either to AF or to DF protocols. This new strategy consists in choosing the best transmission scheme, based on a new selection criterion, a function of the instantaneous capacities of all these possible transmission schemes. Selection between cooperation and noncooperation has already been proposed in literature for DF protocols [5, 7], as well as relay selection [8], but never adapted to AF protocols. Moreover, the usual selection criterion of DF protocol is based only on the source-relay outage probability, while the proposed selection takes all the channel links into account. Outage probability calculations and simulation results prove that the new adaptive AF and DF protocols perform asymptotically better than their corresponding AF and DF protocols, and more interesting, solve the problem of poor performance of cooperation protocols at low SNR.

2. SYSTEM MODEL

We consider $N+1$ terminals who want to transmit messages to the same destination D. The channel is shared in a TDMA manner, so each terminal is allocated a different time slot and the system can be reduced to a relay channel with one source, N relays, and one destination (Figure 1). The $N+1$ terminals play the role of the source in succession while the others are used as relays.

In the next sections, we will use the notation given in Figure 1. The channel coefficient of the link between source

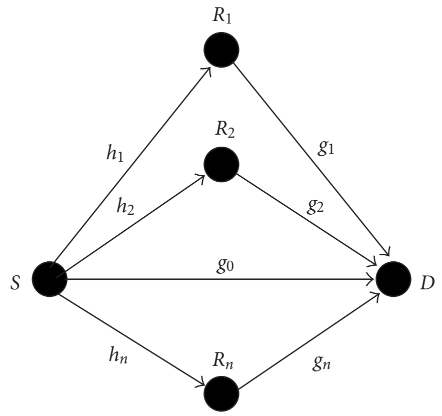


Figure 1: System model : a relay channel with one source, N relays, and one destination.

S and destination D is g_0, the one between source S and relay R_i is h_i, and the one between relay R_i and destination D is g_i.

We consider a half-duplex channel; each terminal, and in particular the relays, cannot receive and transmit at the same time. The channel links are Rayleigh, slow fading, so we can consider their coefficients as constant during the transmission of at least one frame.

We suppose that all terminals are equipped with only one antenna; the MIMO case is not considered in this work. We focus here on the protocol. So, for simplicity, we assume a uniform energy distribution between source and relays, with the total power kept constant.

We will see in the following (see Sections 3.3 and 6.2) that channel state information needs to be known only at destination.

3. NEW SELECTION FOR AF PROTOCOLS

AF protocols proposed in literature [3, 4, 6] bring diversity at high SNR, but their performance at low SNR is poorer than that of the noncooperative scheme. To solve this issue, we introduce the adaptive AF strategy where the choice of a transmission scheme is based on the channel links quality.

3.1. Presentation of the adaptive AF

The idea leading to the definition of the adaptive AF strategy is to consider all possible transmission schemes and decide which one to select. In order to better understand this strategy, the one-relay case is detailed, before the generalization to the N-relay case.

One-relay case

There are only three possible transmission schemes as follows (Figure 2).

(a) AF case: full cooperation scheme is used, symbols are sent using the AF protocol. In case of a full rate protocol (NAF [9]), the symbol rate is 1 symbol per channel use (1 symb. pcu).

(b) SISO case: only direct link is used, symbols are sent over the source-destination link in a noncoded manner, at a rate of 1 symb. pcu.

(c) NLOS case: only nonline-of-sight (NLOS) link is used, in a first phase symbols are sent over the source-relay link in a noncoded manner and forwarded by the relay in a second phase. The rate is then 1/2 symb. pcu. Therefore in order to have the same spectral efficiency of 1 symb. pcu case as in the other cases, we need to use a larger constellation. For example, if the other protocols use a 16-QAM constellation, the NLOS scheme must use a 256-QAM.

The principle of this new adaptive AF strategy is to evaluate the qualities of the three schemes (SISO, AF, and NLOS) and to select the best of them.

Generalization to the N-relay case

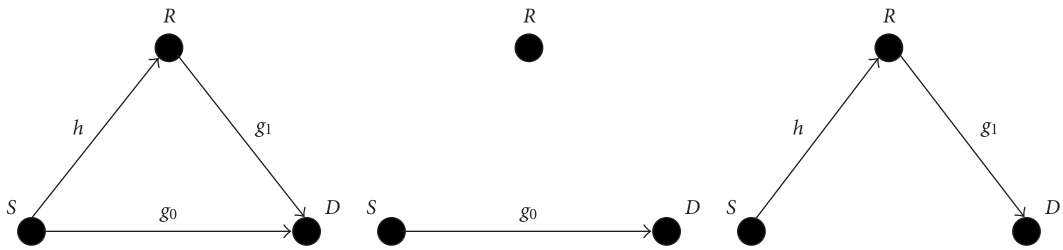
This selection can be generalized quite easily to a higher number of relays.

For example, for 2 relays R_1 and R_2, the number of possible schemes is 7:

(1) full cooperation: symbols are sent using the AF protocol for 2 relays. With a full rate protocol, the symbol rate is 1 symb. pcu;
(2) cooperation with only relay R_1: symbols are sent using the AF protocol for only 1 relay. With a full rate protocol, the symbol rate is still 1 symb. pcu;
(3) cooperation with only relay R_2;
(4) noncooperation: symbols are sent in a noncoded manner over the direct link: the symbol rate is 1 symb. pcu again;
(5) NLOS link using only relay R_1: symbols are sent in a noncoded manner and the symbol rate is 1/2 symb. pcu;
(6) NLOS link using only relay R_2;
(7) both NLOS links: the symbol rate is 1/2 symb. pcu.

The number of cases grows with the number of relays. In the N-relay case, there are $\sum_{k=0}^{N}\binom{N}{k} = 2^N$ different cooperation cases from the noncooperative one (no relay, $k = 0$) to the full cooperation one (N relays, $k = N$). If $K > 2$ terminals are transmitting simultaneously, the signal power has to be divided by K, which makes the signals too difficult to decode. That is why we consider only the NLOS cases with one or two relays, which corresponds to $\binom{N}{1} + \binom{N}{2} + N(N+1)/2$ cases. We can remark as well that, in cooperation schemes, even if several relays are used, at each time slot, only two terminals transmit simultaneously. So finally, there are $2^N + N(N+1)/2$ different transmission schemes to consider.

However, this high number of cases does not increase complexity that much. Indeed, only a simple test is necessary to determine the best one. As some schemes are identical except for exchanging coefficients (e.g., NLOS with relay R_1 or relay R_2), the decoding complexity reduces to only $(N + 1) + 2 = N + 3$ different algorithms. So the complexity of this new selection protocol increases linearly with the number of relays, which is quite reasonable.



(a) AF scheme (b) SISO scheme (c) NLOS scheme

Figure 2: Three possible schemes in the 1-relay case.

Moreover, we will show in the example of Section 4 that depending on the chosen AF scheme, some cases can be omitted, which reduces the complexity even more.

3.2. Selection criterion

In the previous subsection we have listed all the $2^N + N(N+1)/2$ possible transmission cases. The question is now which criterion to use to select the best one.

We propose to study all these schemes and to select the one which has the largest instantaneous capacity.

Let us number the possible transmission schemes from 1 to $N_S = 2^N + N(N+1)/2$ and note $C_i(H)$ the instantaneous capacity of the ith scheme. The selected transmission scheme is the one offering the maximum instantaneous capacity

$$\arg \max_{i\{1,\ldots,N_s\}} \{C_i(H)\} \tag{1}$$

with

$$C_i(H) = \log_2(1 + \text{SNR} H^H H). \tag{2}$$

3.3. Implementation constraints

To implement the new adaptive AF strategy, a node in the network has to decide which transmission scheme to use. We suppose that this node is the destination. So it has to estimate the channel coefficient g_0 of the direct link and the product channels $g_i\beta_i h_i$ for each relay R_i, calculate the instantaneous capacity of each possible transmission scheme, and determine the one to be used. Then it broadcasts no more than $\lceil \log_2(2^N + N(N+1)/2) \rceil = N+1$ bits at both source and relays in order to inform them about its decision.

As we consider a slow fading channel, an estimation is made for several frames and so the transmission strategy remains the same. When a new estimation is made and if the strategy has to change, it is effective after a delay of one frame during which the strategy is not optimal.

4. EXAMPLE OF THE ADAPTIVE NAF PROTOCOL

In order to better understand this new selection strategy and its possible simplifications, we develop in this section the example of the adaptive NAF protocol.

Table 1: NAF protocol.

S	x_{11}	x_{12}	x_{21}	x_{22}	$\cdots$	x_{N1}	x_{N2}
R_1	y_{r1}	$\beta_1 y_{r1}$					
R_2			y_{r2}	$\beta_2 y_{r2}$			
$\vdots$					$\ddots$		
R_N						y_{rN}	$\beta_N y_{rN}$
D	y_{11}	y_{12}	y_{21}	y_{22}	$\cdots$	y_{N1}	y_{N2}

4.1. NAF protocol

We consider the nonorthogonal AF (NAF) protocol proposed in [4] for the one-relay case and generalized in [5] to $N > 1$ relays.

This protocol is schematized in Table 1 where x_{i1}, x_{i2} are the signals to be transmitted, y_{ri} is the received signal at the ith relay, y_{i1},y_{i2} are the received signals at destination, and β_i is the scale factor of the ith relay. The source keeps transmitting: x_{11} during the first time slot and x_{12} during the second one, and so on. During the first time slot, the first relay listens y_{r1}, and, during the second time slot, retransmits a scale version of the signal $\beta_i y_{r1}$.

The optimum value of each scale factor β_i has been calculated in [9]:

$$\beta_i = \frac{1}{\sqrt{1 + \text{SNR}|h_i|^2}}, \tag{3}$$

where SNR stands for the signal-to-noise ratio.

An equivalent model of the form $Y = HX + W$ can be calculated for any number of relays. After vectorization and separation of real and imaginary parts of complex expressions, we obtain a lattice representation of the system. So decoding can be performed by using ML lattice decoders, such as the sphere decoder or the Schnorr-Euchner algorithm.

It has been proven in [9] that this protocol is optimal when used with the distributed Golden code [10] for the one-relay case, or a distributed $2N \times 2N$ perfect code [11] for the N-relay case.

4.2. Adaptive NAF protocol

As can be seen immediately in Table 1, the NAF scheme is a parallel protocol. Indeed, the N relays of the NAF scheme play exactly the same role and are never used in the same time. By studying the instantaneous capacities of the cooperation schemes using NAF protocol with different number of relays, we can see easily that the greatest instantaneous capacity will be associated to a one-relay case.

So we can avoid to study all the NAF strategies with several relays, which reduces considerably the complexity. Indeed, the adaptive NAF protocol is then the result of the selection of the best transmission scheme between the SISO scheme, the NAF schemes using only one relay, and the NLOS schemes using either 1 or 2 relays. Finally, we have only $1+N+N(N+1)/2 = (1+N)(1+N/2)$ possible transmission cases to study and 4 corresponding decoding algorithms; and so, we can remark that the decoding complexity does not increase with the number of relays.

5. PERFORMANCE OF THE ADAPTIVE AF STRATEGY

5.1. Outage probability

The outage probability can be expressed as a function of the instantaneous capacity. For each scheme numbered from 1 to $N_S = 2^N + N(N+1)/2$ as in Section 3.2:

$$P_{\text{out}}^{(i)} = P\{C_i(H) < R\}, \tag{4}$$

where R is the spectral efficiency in bits per channel use (bits pcu).

The principle of the adaptive AF protocol is to choose the transmission scheme that maximizes the instantaneous capacity $C_i(H)$ over i. So the instantaneous capacity of the new adaptive AF protocol is larger than each $C_i(H)$ for a fixed-channel realization H. Thus, the selection scheme is in outage if and only if the N_S possible transmission schemes are all in outage. So we get

$$P_{\text{out}}^{(\text{AAF})} \leq P_{\text{out}}^{(i)} \quad i \in \{1, \ldots, N_S\}. \tag{5}$$

We can calculate and plot the outage probabilities of these different protocols as functions of the SNR thanks to Monte Carlo simulations.

In Figure 3, we plot the outage probabilities of the SISO, NAF, and adaptive NAF protocols for a one-relay scheme and a spectral efficiency of 4 bits pcu. We can note that the adaptive NAF performs better than the NAF protocol. Indeed, we obtain a 4 dB asymptotic gain. Even more interesting is the fact that the adaptive NAF always performs better than SISO, even at low SNR, which was the main weakness of the NAF protocol without selection.

In Figure 4, we plot the outage probabilities of the SISO, NAF and adaptive NAF protocols for a two-relay scheme and a spectral efficiency of 4 bits pcu. Here again, the enhancement of the adaptive NAF over the NAF protocol is verified, as we obtain a 5 dB asymptotic gain and solve the problem of bad performance at low SNR.

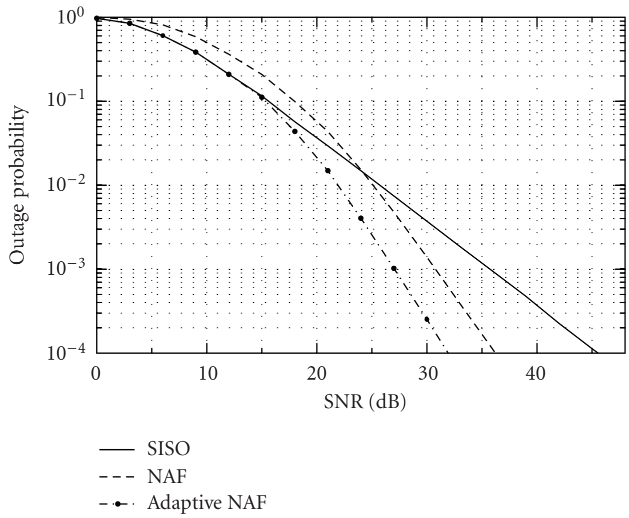


FIGURE 3: 1-relay scheme: comparison of the outage probabilities of the noncooperative case, the NAF protocol, and the adaptive NAF for 4 bits pcu.

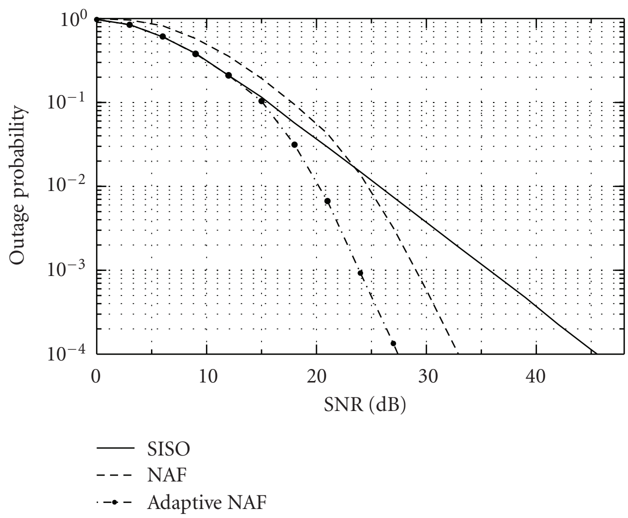


FIGURE 4: 2-relay scheme: comparison of the outage probabilities of the noncooperative case, the NAF protocol, and the adaptive NAF for 4 bits pcu.

5.2. Simulation results

In Figures 5 and 6, we plot the frame error rate of the SISO, NAF, and adaptive NAF protocols as functions of the SNR for a spectral efficiency of 4 bits pcu.

In Figure 5, the curves for a one-relay scheme are represented. The NAF protocol is implemented with a distributed Golden code [10] and a Schnorr-Euchner decoding. Simulation results confirm theoretical ones obtained by outage probability calculations. We can observe that the a3daptive NAF performs better asymptotically than the NAF protocol, with a 5 dB gain. Moreover, we can check that it solves the problem of bad performance at low SNR.

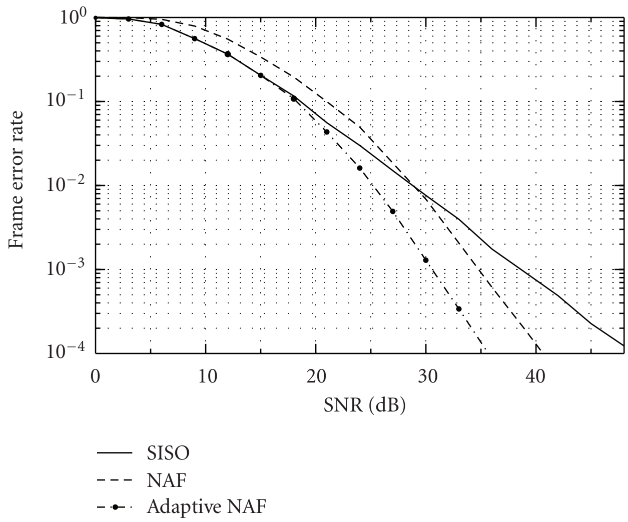


Figure 5: 1-relay scheme: comparison of the performance of the noncooperative case, the NAF protocol, and the adaptive NAF for 4 bits pcu.

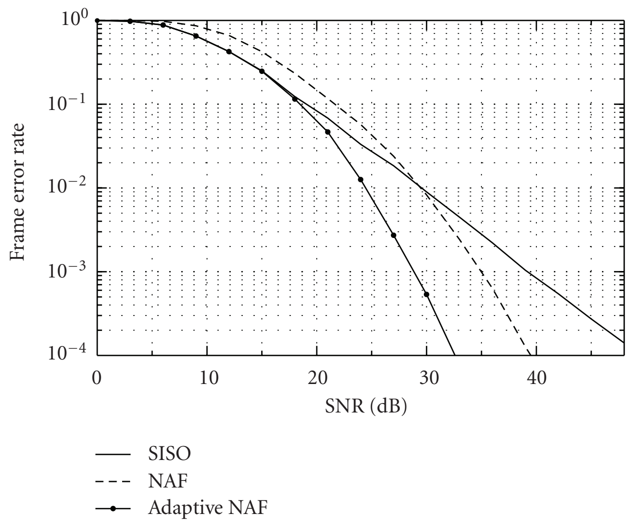


Figure 6: 2-relay scheme: comparison of the performance of the noncooperative case, the NAF protocol, and the adaptive NAF for 4 bits pcu.

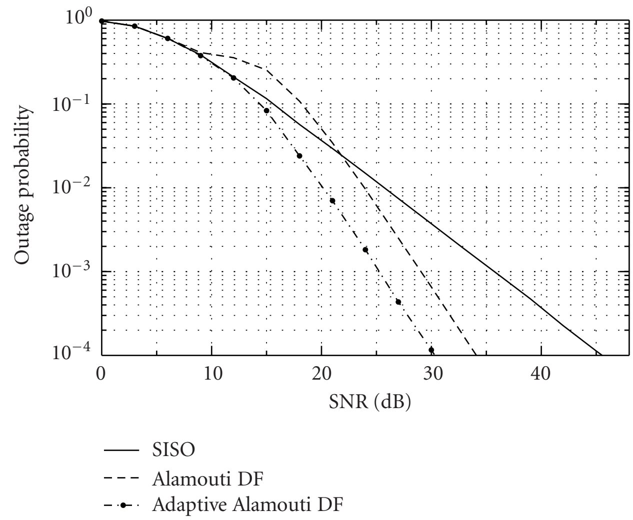


Figure 7: 1-relay scheme: comparison of the outage probabilities of the noncooperative case, the Alamouti DF protocol, and the adaptive Alamouti DF for 4 bits pcu.

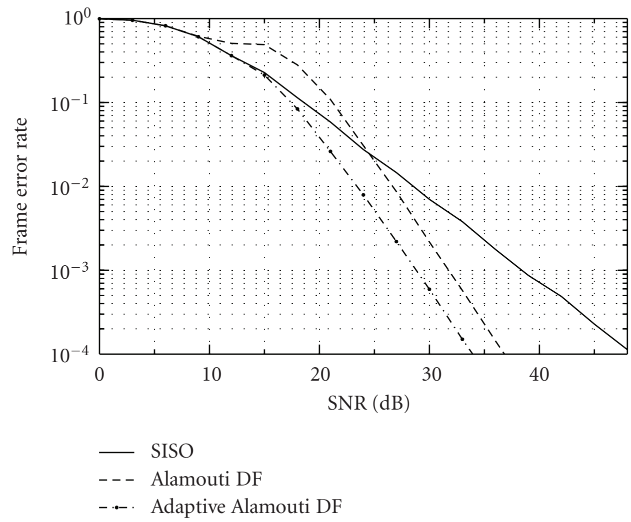


Figure 8: 1-relay scheme: comparison of the performance of the noncooperative case, the Alamouti DF protocol, and the adaptive Alamouti DF for 4 bits pcu.

In Figure 6, the curves for the two-relay scheme are represented. The NAF protocol is implemented with a distributed 4×4 perfect code [11] and a Schnorr-Euchner decoding. The improved performances of the adaptive NAF are here again confirmed with a 7 dB gain over the NAF protocol. Besides, the problem of bad performance of the NAF at low SNR is solved with two relays too, since the adaptive NAF curve is always under the SISO curve.

6. NEW SELECTION FOR DF PROTOCOLS

This new selection working quite efficiently on AF protocols, we propose to adapt it to DF protocols, which have the same problem as the AF protocols: poorer performance at low SNR than SISO.

6.1. Presentation of the adaptive DF

The adaptive DF strategy is based on the same principle than the adaptive AF strategy. However, relays do not amplify the signals but decode them for both DF and NLOS protocols. So there is one more criterion to take into account. Indeed, a DF or NLOS protocol is efficient only if signals are correctly decoded at relays.

According to Shannon theorem, if a source-relay link is in outage, signals cannot be decoded without error at this relay. On the contrary, if a source-relay link is not in outage, detection without error is possible and we can use either a DF or a NLOS protocol using this relay by assuming that no error occurs during detection.

So a first selection step has to be added to the protocol. In the N-relay case, the strategy of an adaptive DF protocol is as follows:

(1) select only the K relays whose source-relay link is not in outage,
(2) select the best transmission scheme in the $2^K + K(K+1)/2$ possible ones in term of instantaneous capacity.

6.2. Implementation constraints

As in the adaptive AF strategy, it is the destination who has to select the best transmission scheme. However, before considering the possible transmission schemes, it has to know which relays are usable, that is, which source-relay links are not in outage. We propose that each relay estimates its own source-relay link and transmits a single bit to the destination indicating whether it is in outage or not.

Then, the steps are the same as for the adaptive AF: the destination estimates the direct link g_0 and the relay-destination links g_i for all K relays which are not in outage. Estimations of the source-relay links are not necessary as the relays decode the signals. Thanks to these estimations, it can calculate the instantaneous capacities of all possible transmission schemes and determine the best one. $N+1$ bits are then necessary to broadcast the information on the chosen scheme to the source and relays.

7. EXAMPLE OF THE ADAPTIVE ALAMOUTI DF PROTOCOL

7.1. Alamouti DF protocol

The Alamouti DF protocol is a DF protocol designed for a 1-relay channel and based on the Alamouti space-time code [12]. It requires 4 channel uses to send 2 symbols: the symbol rate is 1/2 symb. pcu.

As schematized in Table 2, in the first phase, the source sends the first line of the Alamouti codeword: x_1 and x_2, while the relay listens. In the second phase, the relay sends a decoded version of the first line of the codeword, while the source sends the second line of the Alamouti codeword: $-x_2^*$ and x_1^*. The destination keeps listening during the whole transmission.

Assuming x_1 and x_2 have been correctly decoded, the received signals can be written in the form $Y = \sqrt{\text{SNR}}HX + W$ with an equivalent channel matrix H being orthogonal. So, linear decoding can be performed as for the original Alamouti ST code.

However, the Alamouti DF protocol can be used only if the signals are correctly decoded at the relay, which, according to Shannon's theorem, is possible only if the source-relay link is not in outage. In the other case, we can not use the relay, so signals are sent in a noncoded manner over the direct link.

Table 2: Alamouti DF protocol.

S	x_1	x_2	$-x_2^*$	x_1^*
R	y_{r1}	y_{r2}	$\widetilde{x_1}$	$\widetilde{x_2}$
D	y_1	y_2	y_3	y_4

7.2. Adaptive Alamouti DF protocol

The first test is on the source-relay link. Two cases can occur:

(1) either it is in outage, then signals cannot be decoded without error at relay, so we only use the direct link;
(2) or it is not in outage, then three different transmission schemes can be considered:
   (a) SISO scheme;
   (b) Alamouti DF scheme;
   (c) NLOS scheme.

According to the same selection criterion as in Sec ure ??, we choose the one with the greatest instantaneous capacity.

8. PERFORMANCE OF THE ADAPTIVE DF STRATEGY

8.1. Outage probability

The outage probability of the adaptive DF protocols can be proven to be lower than the outage probability of the corresponding DF protocols in the same manner than for the adaptive AF protocols. It comes directly from the selection criterion which minimizes the instantaneous capacity.

In Figure 7, we plot the outage probabilities of the SISO, Alamouti DF, and adaptive Alamouti DF protocols as functions of the SNR, obtained through Monte Carlo simulations. We can see that for the DF protocols too, the new selection criterion brings a great improvement in asymptotic performance with a 4 dB gain, and solves the problem of bad performance at low SNR.

8.2. Simulation results

We plot the performance simulations of the SISO, Alamouti DF, and adaptive Alamouti DF protocols as functions of the SNR in Figure 8. The improvements due to the new selection criterion are here again confirmed with a 3 dB asymptotic gain, and better or same performance as SISO for low SNR.

9. CONCLUSION

We proposed adaptive amplify-and-forward (AF) and decode-and-forward (DF) protocols based on a new selection criterion derived from the calculations of the instantaneous capacities of all possible transmission schemes (SISO, cooperative schemes, NLOS schemes). For the adaptive DF protocol, an additional selection on the source-relay links is necessary to ensure an efficient decoding at relays. Both outage probability and performance from simulation results prove that the adaptive cooperation enhances the performance of the initial cooperation schemes at high SNR, and solves the problem of poor performance at low SNR.

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