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Hybrid Cooperation Techniques

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1. Introduction

A major challenge in the design of next generation wireless communication systems is to achieve both reliable and spectral efficient communication with large coverage range. To tackle this problem, advanced diversity techniques combined with adaptive mechanisms have to be designed in order to combat or even exploit the variability of the radio propagation medium across time, frequency and space. Diversity techniques create signal redundancy, by repeating the information across multiple, independent channel realizations. This is accomplished by allowing the receiver to experience the average channel effect rather than an instantaneous fade. As a consequence diversity techniques improve the link reliability at the expense of the system spectral efficiency. By adjusting the transmission parameters to the momentary link quality, adaptive mechanisms aim at improving both spectral efficiency and link reliability. Nevertheless, in order to guarantee the Quality of Service (QoS) constraints from the upper layers, adaptive mechanisms implement a sub-optimal trade-off between link robustness and bandwidth efficiency (Calvanese Strinati E., 2006). Therefore in this chapter we propose and analyze a novel cooperation protocol, *the hybrid cooperation protocol* and we combine it with link adaptation techniques such as Adaptive Modulation and Coding (AMC) and power allocation. Our task is to minimize the outage probability and maximize the spectral efficiency of transmission, while limiting the cooperation cost in terms of MAC signalling overhead.

The scientific content of this chapter is based on some innovative results presented in three conference papers (E. Calvanese Strinati and S. Yang and J-C. Belfiore, 2007) (E. Calvanese Strinati and Luc Maret, 2008) (M. Baydar and E. Calvanese Strinati and J. C. Belfiore, 2008) presented in 2007 and 2008.

The goals of this chapter are for the reader to have an understanding of cooperative communication issues and challenges and, to be well informed of the state-of-the-art research development. Eventually, the chapter will present what we have done to improve the performance of currently proposed cooperation techniques, comparing performance of our proposed approaches with state-of-the-art one. A critical discussion on advantages and weakness of the proposed approaches, including future research axes, will conclude the chapter.

The innovative contribution in this chapter is threefold.

First, in this chapter we introduce and details challenges and possible solutions for the so-called cooperative diversity (E. Erkip A. Sendonaris and B. Aazhang: Part I, 2003; E. Erkip A. Sendonaris and B. Aazhang: Part II, 2003) techniques where a source terminal cooperates with several relays to exploited the spatial diversity in a distributed manner. From a physical

layer viewpoint, cooperation drives to improved transmission diversity and consequent improved outage probability performance. Nevertheless, from a MAC layer viewpoint, fixed cooperation requires to probe the network and acquire channel state information (CSI) about all active relays at least with a channel coherence time frequency. This cooperation probing makes fixed cooperation expensive in terms of signalling overhead, battery consumptions of active relays and protocol delay. Recently, researchers showed that cooperating is not always the best solution in terms of outage probability minimization (D. Gunduz and E. Erkip, 2005). For instance in AF cooperation, when the noise is large, cooperative relays can amplify the noise instead of helping. Alternatively to *fixed* cooperation, we propose to introduce a *cooperation controller* that can decide when and how to cooperate. The basic idea is to cooperate when it is advantageous (*cooperative mode*), and not cooperate otherwise (*non-cooperative mode*). The problem in such approach is how the source-destination pair can decide if it is worth to cooperate for a given channel instance? In fixed topology networks an heuristic approach is to analyze the geometry of the network and determine areas where cooperation can help. In a wireless mobile communication scenario the cooperation protocol should use the momentary channel state information to make its decision. This feedback information introduces a large processing delay and signalling overhead and it is impractical for the destination to acquire full CSI about all active relays. In this chapter we present the innovative approach proposed in (E. Calvanese Strinati and S. Yang and J-C. Belfiore, 2007) of introducing a cooperation controller which makes its decision on non-cooperative/cooperative mode based only on the momentary direct link quality information. This information is directly available at the cooperation controller each time the source sends a request to send (RTS). More precisely, for a selected transmission rate R and direct link channel instance (σ_n^2, f, etc.), the cooperation controller can check if direct non-cooperative transmission will be certainly in outage. If an outage is forecasted, the receiver can switch to cooperative mode trying to avoid transmission outage improving the overall link quality with cooperative diversity. This protocol is called *hybrid cooperation*.

Second, the chapter presents how hybrid cooperation protocol and AMC mechanism can be jointly designed. Eventually, we detail the *hybrid cooperative AMC* mechanism (E. Calvanese Strinati and S. Yang and J-C. Belfiore, 2007) in which adaptation is designed for the hybrid link quality and cooperation is activated only when the instantaneous direct source-destination link quality is not good enough to support the aimed spectral efficiency.

Third, we face the problem of optimal power allocation between source and relay in a cooperative network. We present the interesting results proposed in (M. Baydar and E. Calvanese Strinati and J. C. Belfiore, 2008). The authors succeed in finding a close form power allocation algorithm which can only be applied to OAF cooperative transmission. At a first glance, this solution can be not of interest due to the worse performance of the OAF cooperation strategy. We verify that classical NAF outperforms classical OAF also if an optimal power allocation is done for the OAF cooperation and sub-optimal power allocation is done for NAF. This is due to the suboptimal performance of classical OAF. To solve this problem we further investigated the *hybrid* AF protocol that we propose.

2. Preliminaries on Cooperative transmission techniques

The core topic investigated in this chapter is the improvement of outage probability performance in a cooperation network. In the literature (see, e.g., (H. Bölcskei and R. U. Nabar and F. W. Kneubühler, 2004; H. El Gamal K. Azarian and P. Schniter, 2005; S. Yang and J-C. Belfiore, 2006)), three main cooperative transmission protocols have been proposed:

the amplify-and-forward (AF), the decode-and-forward (DF) ((D. N. Tse J. N. Laneman and G. W. Wornell, 2004) (H. Bölcskei and R. U. Nabar and F. W. Kneubühler, 2004) (H. El Gamal K. Azarian and P. Schniter, 2005)) and the compress-and-forward (CF) for which there has been, recently, a grown interest. Nevertheless, most prior works focused on two principal classes of protocols. The first is the class of AF protocols, where the relay simply amplifies and re-transmits the observed signal. The second is the class of DF protocols, where the relay decodes, re-encodes and re-transmits the message it receives. The DF protocols offer good performance but have clearly a higher complexity compared to the AF protocols which are used in practice, due to their low complexity and low relay power consumption. Actually, for most *ad hoc* wireless networks, it is not realistic for other terminals to decode the signal from a certain user, because the codebook is seldom available and the decoding complexity is unacceptable in most cases.

The second topic treated in this chapter is the design of hybrid cooperation protocol combined with an AMC mechanism. Design of cooperation protocol and AMC algorithms have been extensively investigated separately. Nevertheless, joint design of advanced cooperation protocols with AMC algorithms has not been intensively investigated yet. Aiming at maximizing the physical layer throughput, in (Z. Lin and E. Erkip and M. Ghosh, 2005) the authors study adaptive modulation performance for one relay coded cooperative protocols. In the paper the authors find that coded cooperation combined with adaptive modulation offers better physical layer throughput performance than non-cooperative mode. The authors suggest that cooperative mode MCS selection should be decided based on all direct and relays link quality. However, if the cooperative protocol includes more than one relay, this approach can be complex and catastrophic adaptation can occur as for frequency selective block fading channels (M. Lampe and H. Rohling and W. Zirwas, 2002) since it is hard to obtain a reliable predicted packet error rate (PER_{pred}). In (E. Yazdian and M. R. Pakravan, 2006) the application of adaptive modulation to one relay AF cooperation is investigated. The authors aim at evaluating the energy saving achieved through cooperation due to the improvement in average bit/symbol transmission. Furthermore, the authors study the performance improvement as a function of cooperating user's location to identify areas where cooperation is useful. However, in the paper the possible occurrence of detrimental cooperation is not considered.

The third topic investigated in this chapter is the combination of cooperative diversity techniques with power control algorithms. Optimal power allocation between source and relay in a cooperative network has been studied in (M. Hasna and M-S. Alouini, 2004) (Q. Zhang and C. Shao and Y. Wang and P. Zhang and J. Zhang and Z. Zhang, 2004). A total amount of transmit power over the two slots required for relaying is shared between the source and relay. In (I. Hammerstrom and A. Wittneben, 2006), an iterative joint power allocation method is presented for two-hop communications schemes using OFDM modulation. This method is based on the Karush-Kuhn-Tucker (KKT) conditions. Power allocation optimization for NAF cooperative transmissions is classically done using *waterfilling* techniques. Its effectiveness depends on the *a priori* choice of the power allocated to the relay (P_r). Unfortunately, the optimal selection of P_r can be a challenging task. An iterative search may improve the power allocation algorithm performance at the expense of both search latency and algorithm complexity. Alternatively, the power allocation problem can be faced for OAF schemes for which the a priori knowledge of P_r is not required. In such case, the complexity of the power allocation algorithm is strongly reduced at the expense of performance.

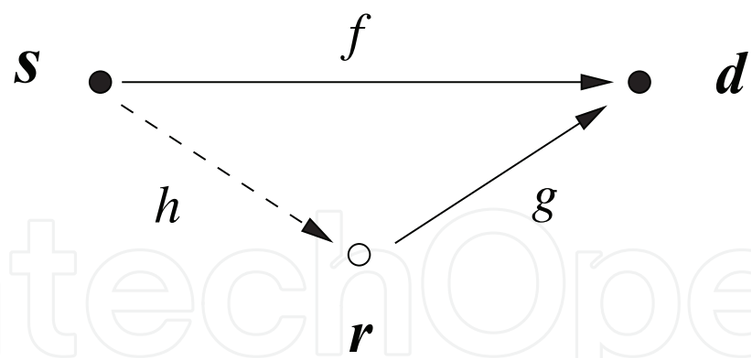

Fig. 1. A relay channel with one source **s**, one destination **d** and one active relay **r**.

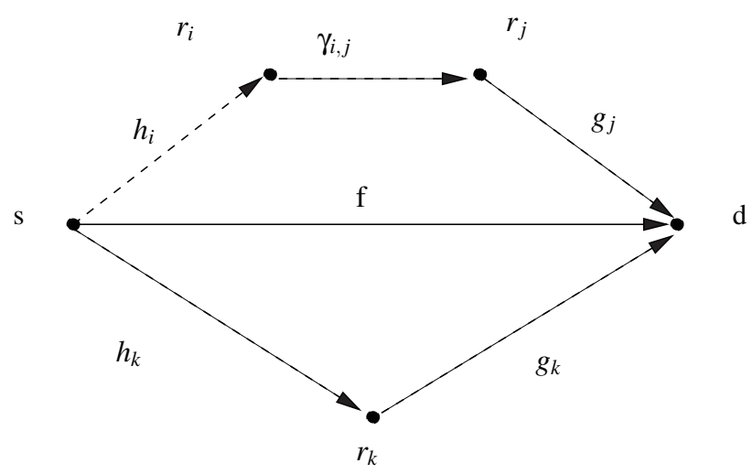

Fig. 2. A relay channel with one source **s**, one destination **d** and N active relays r_i.

3. System model

The considered system model consists of one source s, one destination d and N relays (cooperative terminals) $\mathsf{r}_1, \ldots, \mathsf{r}_N$. The physical links between terminals are slowly faded and are modelled as independent quasi-static Rayleigh channels, *i.e.*, the channel gains do not change during the transmission of a cooperation frame. This assumption implies that we assume the channel coherence time to be much larger than the maximum delay that can be tolerated by the application. All the terminals (source, relay and destination) are equipped with only one antenna and work in half duplex mode, *i.e.*, they cannot receive and transmit at the same time. Two simple illustrations of the channel model are given in Fig. 1 and Fig. 2 respectively for a cooperative network with only one and N active relays per frame transmission.

The gain of the channel connecting s and d is denoted by f. Similarly, g_i and h_i respectively denote the channel gains between r_i and d and the ones between s and r_i. γ_{ij} is used to denote the channel gain between r_i and r_j. Channel quality between terminals is parameterized by the variance of the channel gains. We assume that the receiver can gain perfect knowledge of the channel gains for the whole network activating the relay probing procedure (S. Yang and J-C. Belfiore, 2006). We consider two cases for the power allocated to source and relays.

First, we impose a total average transmit power constraint and no power control is allowed in our scheme. In this case, in order to simplify the analysis, we consider a suboptimal power allocation scheme where the source transmits at full power in the non-cooperation mode and both the source and the relays transmit at half power in the cooperation mode. Then, we refine this assumption proposing a power allocation algorithm for hybrid OAF cooperative protocols with only one active relay per transmission frame (see section 4.3). Also, we suppose that the terminals are subject to the half-duplex constraint, *i.e.*, they cannot transmit and receive simultaneously. We also assume using the capacity achieving code so that the outage analysis holds. The PER prediction is based on the computation of a link quality metric (LQM) that is linked to the predicted PER by means of a look up table (LUT). Ideally, we consider perfect PER prediction. In our work we consider the Amplify-and-Forward (AF) protocol (orthogonal and non-orthogonal) where the relay simply scales and forwards the received signal. We study half-duplex slotted amplify-and-forward (SAF) cooperative schemes proposed in (S. Yang and J-C. Belfiore, 2006). For an N-relay M-slot scheme, the cooperation frame, composed of M slots of l symbols, is of length Ml. During any slot i, $i = 1, \ldots, M$, the source s transmits a sub-frame of l symbols, denoted by a vector $\mathbf{x}_i \in \mathbb{C}^l$ and the relay r_j, $j = 1, \ldots, N$, can transmit $\mathbf{x}_{r_j,i} \in \mathbb{C}^l$, a linear combination of the vectors it received in previous slots. Under the half-duplex constraint, a relay does not receive while transmitting. For example, the NAF scheme (H. El Gamal K. Azarian and P. Schniter, 2005) is an N-relay $(2N)$-slot scheme and the non-orthogonal relay selection scheme (D. P. Reed and A. Bletsas and A. Khisti and A. Lippman, 2005) is an N-relay two-slot scheme. Obviously, the transmission of a cooperation frame with any SAF scheme is equivalent to l channel uses of the following vector (MIMO) channel

$$\mathbf{y} = \sqrt{\mathsf{SNR}}\,\mathbf{H}\mathbf{x} + \mathbf{z}$$

where $\mathbf{x}$ is the transmitted signal, $\mathbf{z} \sim \mathcal{CN}[\mathbf{\Sigma_z}]$ is the equivalent additive coloured noise with covariance matrix $\mathbf{\Sigma_z}$ and $\mathbf{H}$ is an $M \times M$ lower-triangular matrix representing the equivalent "space-time" channel between the source and the destination. Moreover, we have $H_{ii} = c_i f$ with c_i being a constant related to the transmission power. Let $\mathbf{H}$ denotes the equivalent channel matrix (S. Yang and J-C. Belfiore, 2006) for a Non-Orthogonal AF scheme[1]

$$\mathbf{H} = \begin{pmatrix} f & 0 \\ \frac{\sqrt{P_r} bgh}{\sqrt{1+P_r\|bg\|^2}} & \frac{f}{\sqrt{1+P_r\|bg\|^2}} \end{pmatrix}.$$

The matrix coefficients, $h_{i,j}$ are functions of f, g, h, P_r the relay transmission power and the normalization factor b which verifies $b^2 = \frac{1}{1+P_s\|h\|^2}$. The input covariance matrix is a diagonal matrix, denoted $\mathbf{Q}$ and whose diagonal elements are P_{s1} and P_{s2}, the source transmission powers in the first and the second slot, respectively.

4. Improving Cooperative transmission protocols effectiveness

This section will be divided in three parts. First we will present and explain the *Hybrid Amplify and Forward Cooperation Protocol* proposed in (E. Calvanese Strinati and S. Yang and J-C. Belfiore, 2007) which has been designed to overcome the suboptimal error rate performance of AF cooperative schemes in the low SNR region. Second, we will describe the Adaptive

[1] An Orthogonal AF scheme is a particular case of the NAF scheme in which the source does not transmit simultaneously with the relay in the second slot (*i.e.*,$h_{2,2} = 0$)

Modulation and Coding Combined with the Hybrid Cooperation protocol proposed in (E. Calvanese Strinati and S. Yang and J-C. Belfiore, 2007; E. Calvanese Strinati and Luc Maret, 2008). In a third part of the section, we will present the Power Allocation Optimization for Hybrid Cooperation Protocols which has been proposed in (M. Baydar and E. Calvanese Strinati and J. C. Belfiore, 2008).

4.1 Improving amplify and forward Cooperation protocol: Hybrid amplify and forward

We present in this section the novel cooperative protocol proposed in (E. Calvanese Strinati and S. Yang and J-C. Belfiore, 2007). The protocol is named *hybrid cooperation* and it has been designed to overcome the suboptimal error rate performance of AF cooperative schemes in the low SNR region. The protocol proposal is based on the observation that cooperating is not always the best solution in terms of outage probability minimization (D. Gunduz and E. Erkip, 2005). For instance in AF cooperation, in the low SNR regime, the relays amplify the noise instead of helping. Alternatively to *fixed* cooperation, a *cooperation controller* can decide when and how to cooperate. The principle of the hybrid cooperation protocol is simple: based on the direct source-destination link quality, a cooperation controller decides if and how to run cooperation. Indeed, cooperation is activated only when the instantaneous direct source-destination link quality is not good enough to support the aimed spectral efficiency. The problem in such approach is how the source-destination pair can decide if it is worth to cooperate for a given channel instance? In fixed topology networks an heuristic approach is to analyze the geometry of the network and determine areas where cooperation can help. In a wireless mobile communication scenario the cooperation protocol should use the momentary channel state information to make its decision. This feedback information introduces a large processing delay and signalling overhead and it is impractical for the destination to acquire full CSI about all active relays. In (E. Calvanese Strinati and S. Yang and J-C. Belfiore, 2007) the authors propose that the cooperation controller makes its decision on non-cooperative/cooperative mode based only on the momentary direct link quality information. This information is directly available at the cooperation controller each time the source sends a request to send (RTS). More precisely, for a selected transmission rate R and direct link channel instance (σ_n^2, f, etc.), the cooperation controller can check if direct non-cooperative transmission will be certainly in outage. If an outage is forecasted, the receiver can switch to cooperative mode trying to avoid transmission outage improving the overall link quality with cooperative diversity.

Classical NAF outperforms classical OAF also if an optimal power allocation is done for the OAF cooperation and sub-optimal power allocation is done for NAF. This is due to the suboptimal performance of classical OAF. To solve this problem we further investigated the *hybrid* AF protocol. Calvanese Strinati *et al.* first propose an OAF hybrid cooperation protocol under the same power constraint adopted above: impose a total average power constraint and no power allocation is considered. If P denotes the total power constraint, in case of NAF cooperation, we impose $P_{s1} = P/2$ for the power allocated to the source in the first slot and $P_{s2} = P_r = P/2$ the power allocated to the source and the relay respectively in the second slot. In the OAF scheme, the authors propose to fix $P_s = P_r = P/2$. The mutual information of the direct channel, the cooperative channel[2] and the OAF channel are respectively:

[2] Factor $\frac{1}{2}$ comes from the fact that two time slots (*i.e.*, two channel uses) are needed to transmit symbols

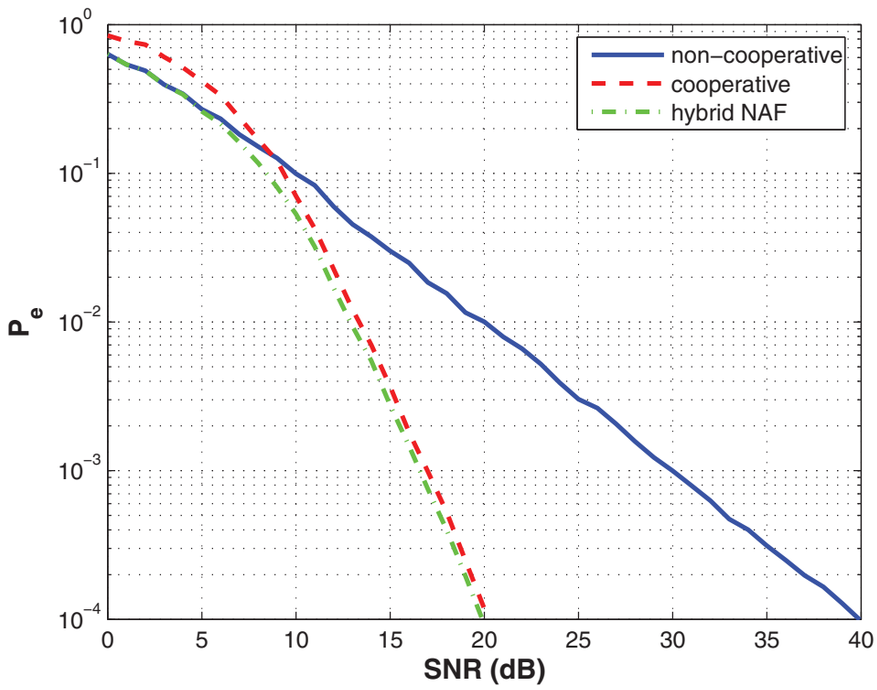

Fig. 3. Outage probability for Cooperative/non-cooperative/hybrid NAF cooperative transmission with $N = 2$, $M = 5$

$$I_d = \log_2(1 + \frac{P}{2}\,|f|^2)$$
$$I_{NAF} = \frac{1}{2}\log_2\,\det(I + \mathbf{H}\,\mathbf{Q}\,\mathbf{H}^{\dagger})$$
$$I_{OAF} = \frac{1}{2}\,\log_2(1 + P_s|f|^2 + \frac{P_s P_r |bgh|^2}{1 + P_r|bg|^2})$$

Based on these mutual information expressions, in (E. Calvanese Strinati and S. Yang and J-C. Belfiore, 2007) the authors propose to numerically compare non-cooperative, NAF cooperative, hybrid NAF cooperative and hybrid OAF cooperative protocols in terms of outage probability versus average SNR. Let $\mathcal{O}_d$ denotes the direct channel outage event, $\mathcal{O}_d = \{I_d < R\}$, and $\mathcal{O}_c$ denotes the cooperative channel outage event, $\mathcal{O}_c = \{I_c < R\}$. The equivalent channel is in outage if both events, $\mathcal{O}_d$ and $\mathcal{O}_c$, are realized.

4.1.1 Simulation results

We report here some significant simulation results to evaluate effectiveness of the proposed hybrid cooperation protocol when applied to NAF cooperation on Fig 3.

Next, we extend the study of the hybrid cooperation protocol to OAF schemes and we introduce a power allocation algorithm well designed for OAF hybrid cooperative transmission. We find out that transmission outage is slightly smaller adopting hybrid cooperation for OAF scheme than for NAF one. Nevertheless, there are other important

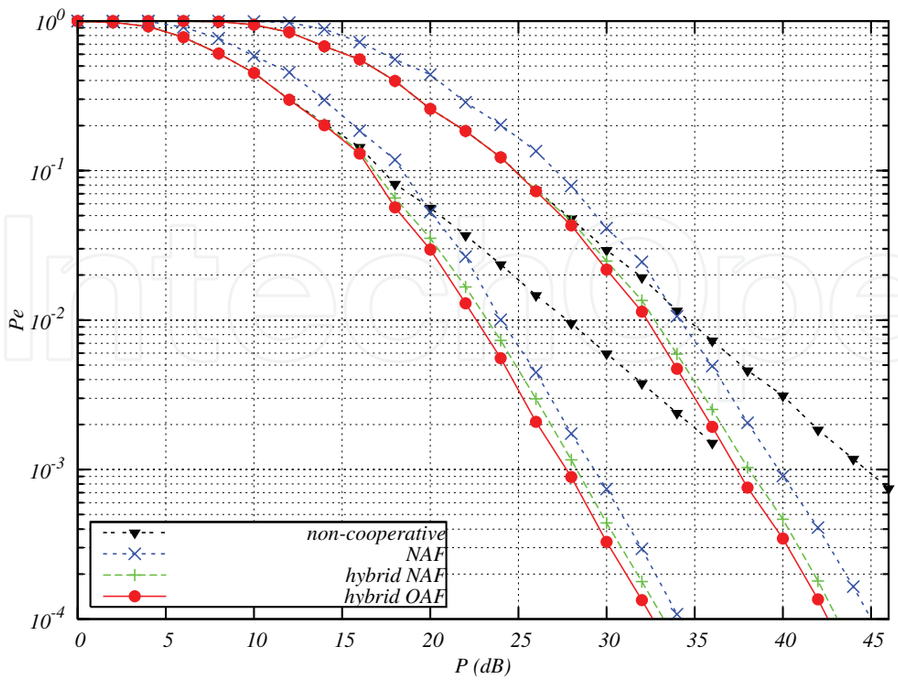

Fig. 4. Outage probabilities for the non-cooperative, NAF, Hybrid-NAF and Hybrid OAF scheme. Considered information rates: 2 and 4 BPCU.

advantages in adopting an OAF hybrid cooperation protocol. First, the cooperation complexity and cost are reduced. Second, the hybrid strategy reduces significantly the complexity of the algorithm implemented to determine the outage probability. This is the key reason for which we succeeded in finding an optimal power allocation algorithm for OAF hybrid cooperation schemes. We now show some simulation results for hybrid cooperative transmission without power allocation. Performance is compared in terms of average outage probability versus average SNR.

Based on these mutual information expressions, we numerically compare non-cooperative, NAF cooperative, hybrid NAF cooperative and hybrid OAF cooperative protocols in terms of outage probability versus average SNR. Let $\mathcal{O}_d$ denotes the direct channel outage event, $\mathcal{O}_d = \{I_d < R\}$, and $\mathcal{O}_c$ denotes the cooperative channel outage event, $\mathcal{O}_c = \{I_c < R\}$. The equivalent channel is in outage if both events, $\mathcal{O}_d$ and $\mathcal{O}_c$, are realized.

Other simulation results are shown in Figure 4 for the case of one active relay and transmission rate of 2 and 4 bits per channel use (BPCU). We find out that, adopting the proposed OAF hybrid cooperation protocol, transmission outage performance is better than for both non-cooperative and NAF hybrid cooperation transmissions. This result confirms our choice of using an orthogonal scheme: since the channel is assumed to be quasi-static, if the direct link is in outage in the first slot, it will remain in outage in the second one. The outage performance improvement is not our major achievement. Combining hybrid cooperation with OAF scheme, we obtain a cooperation protocol with both reduced complexity and cooperation cost. Furthermore, the proposed hybrid strategy permits to reduce the complexity of the outage probability computation. This is the key reason for which we succeeded in finding an optimal power allocation algorithm only for OAF hybrid cooperation schemes.

The Orthogonal AF strategy, sub-optimal in a full time cooperation scheme, is optimal with the hybrid strategy. In fact, since the channels are assumed to be slow fading, if the direct link is in outage in the first slot of the frame, it will be the case in the second. So it is better not to transmit in the second slot, and thus economize power, since we are sure that the reliability of the information is not guarantied. The mutual information is in this case

$$I_{OAF} = \frac{1}{2}\ \log_2(1 + P_s|f|^2 + \frac{P_s P_r |bgh|^2}{1 + P_r |bg|^2}) \tag{1}$$

4.2 Proposed Adaptive Modulation and Coding Combined with the Hybrid Cooperation Protocol

In this section we present the mechanism proposed in (E. Calvanese Strinati and S. Yang and J-C. Belfiore, 2007) in which the authors propose to combine the *hybrid* cooperation protocol with an AMC mechanism. The protocol is named *hybrid cooperative AMC* mechanism. A flow chart of the proposed algorithm is shown in Fig. 5. $I_{non-coop}$ is the instantaneous mutual information when transmission is done in non-cooperative mode and R is the transmission rate.

The algorithm is summarized as follows:

Step 1: S sends a RTS each time it wants to transmit new data.

Step 2: After receiving a RTS, the AMC mechanism (in D) selects R for next data transmission. R is selected from the set of LUT of PER versus LQM for hybrid cooperation transmission performance, given the LQM computed at previous received packet.

Step 3: D estimates the instantaneous channel conditions of the direct source-destination link (σ^2,f, etc.) and computes $I_{non-coop}(f, \sigma^2)$

Step 4: The *cooperation controller* in D decides if cooperate or not:

- if $I_{non-coop} < R$, non-cooperative transmission is forecasted to be in outage: the cooperation controller starts cooperation (go to step 5)
- otherwise, cooperation mode is not activated (go to step 9)

Step 5: D checks if the *relay probing* is up to date:

- YES (go to step 9)
- NOT (go to step 6)

Step 6: relay probing: D probes the relays available for cooperation and estimates the channel coefficients of the cooperation links.

Step 7 and 8: Each relay calculates the product gain $|g_i h_i|$ and reacts by sending an availability frame after t_i time which is anti-proportional to $|g_i h_i|$. Therefore, the relay with the strongest product gain is identified as relay 1, and so on.

Step 9: D sends a clear to send (CTS) that includes information on transmission rate R, M, relay identifiers, etc.

Step 10: S starts data transmission at rate R

Step 11: After receiving data from S, D derives PER_{pred} from the LUT of hybrid cooperation and selects R for next transmission of S.

Summarizing, based on the direct source-destination link quality, a cooperation controller decides if and how cooperate. We call this cooperation protocol as *hybrid cooperation*. The rate

R is chosen after each received packet by the AMC that aims at maximizing the throughput performance of the hybrid transmission mode meeting the QoS constraints imposed by the upper layers.

Note that the AMC mechanism selects R based on a set of pre-computed AMC switching points that depends on N, M, PER_{target}, transmission scenario, etc. Such switching points are chosen based on the average PER versus average performance of the hybrid cooperation protocol. Given N, M and R, there is a *crossing point* (PER_{cross}) between non-cooperative and cooperative average performance. For $PER \leq PER_{cross}$ cooperation outperforms non-cooperative mode. Hence the gain of hybrid cooperation is high since the direct link results more often in outage that cooperative transmission. When $PER > PER_{cross}$, non-cooperative transmission outperforms cooperation. In such case the gain of hybrid cooperation is reduced and asymptotically (for $PER_{cross} \rightarrow 0$) hybrid cooperation performs as non-cooperative transmission since cooperation is never activated. In order to fully exploit the proposed hybrid cooperative AMC to improve the average system performance, AMC mechanism and hybrid cooperation protocol have to be designed jointly. As an example, given our system model, we computed the minimum values of M (M_{min}) for which hybrid cooperative AMC outperforms both classical non-cooperative and cooperative AMC. A selection of our results are shown on table 1 for maximum transmission rates R_{max} at which the system can operate and typical PER_{target} values imposed to the AMC. Indeed, given

N	M_{min}	PER_{target}	R_{max}
2	9	10^{-1}	10
2	5	10^{-2}	10
2	7	10^{-1}	8
2	3	10^{-2}	8
2	5	10^{-1}	6
2	3	10^{-2}	6
2	5	10^{-1}	4
2	3	10^{-2}	4
2	3	10^{-1}	2
2	3	10^{-2}	2

Table 1. Minimum values of M (M_{min}) for typical PER_{target} values

PER_{target} and R_{max}, we can define an M_{min} from which hybrid cooperation is beneficial. Note that the larger M is the more complex the cooperation protocol is. There is indeed a trade off between cooperation performance and cooperation complexity.

4.2.1 Simulation results

In this section, we show by means of numerical simulations the effectiveness of combining the hybrid cooperation protocol with the AMC mechanism. Results first show how the proposed mechanism drives to improved average system throughput performance. Then, we outline the advantage introduced by the hybrid cooperation protocol in terms of reduction of cooperation signalling overhead, cooperation protocol delay and average power consumed by the active relays. Simulation results are given here for the system model presented in section 3. In the system both AMC and ARQ are implemented. The simulated AMC algorithm selects the MCS which maximizes the throughput while meeting the PER_{target}

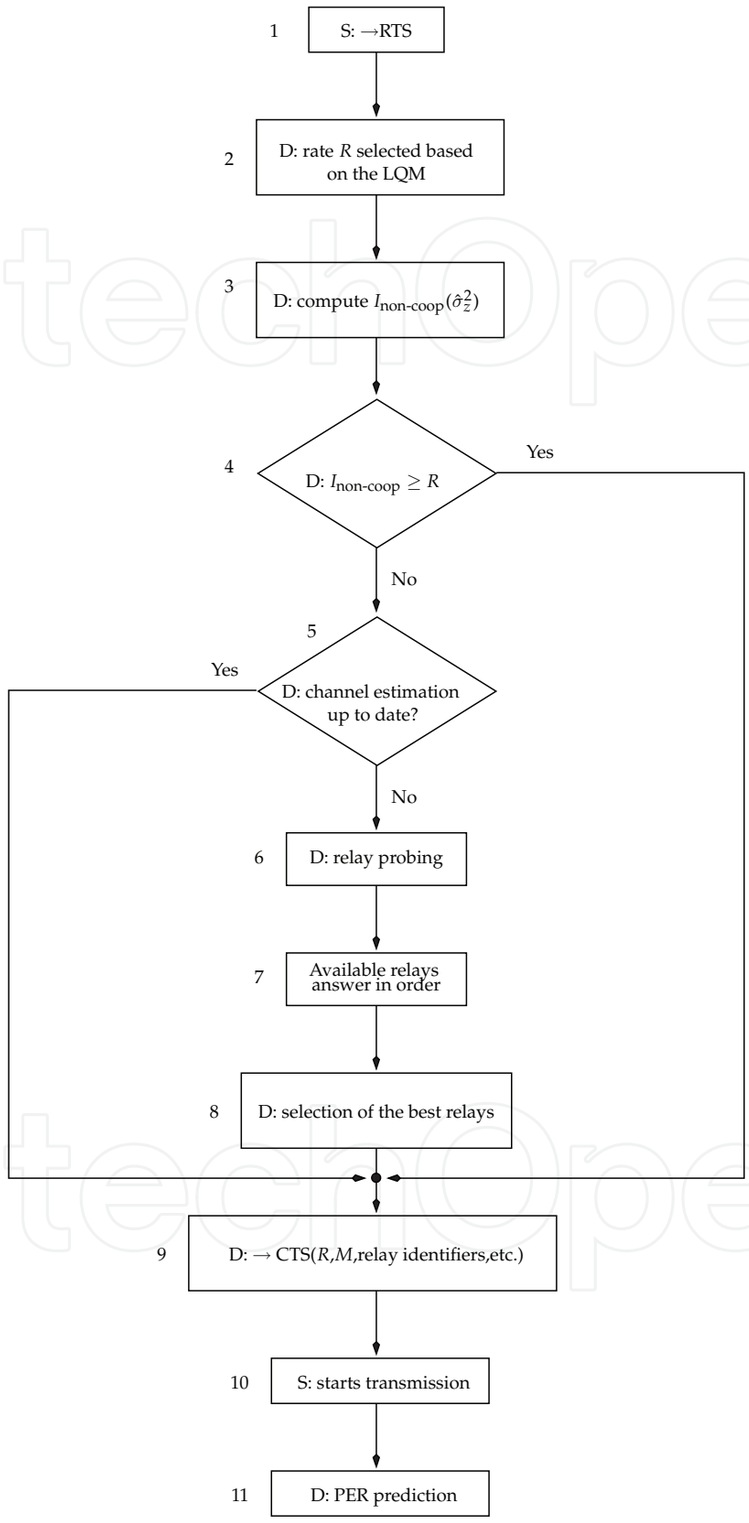

Fig. 5. Flow chart of the proposed hybrid opportunistic cooperation combined with AMC

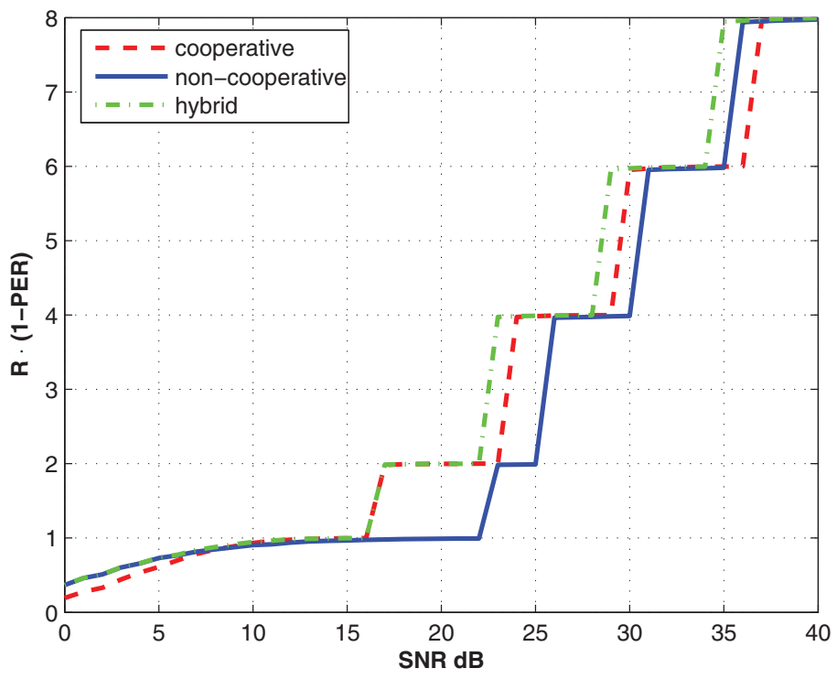

Fig. 6. Cooperative/non-cooperative/hybrid cooperative transmission with $N = 2$, $M = 3$ and $PER_{target} = 10^{-2}$

QoS constraints. The set of MCS corresponds to the transmission rate set $\underline{\mathbf{R}}$=1, 2, 4, 6, 8. We fix the $PER_{target} = 10^{-2}$. Moreover, a total average power constraint is imposed and no power allocation is considered here. We access the average physical layer throughput of a system that can perform data transmission with three different transmission modes: non-cooperative, cooperative and hybrid. Performance is compared in terms of average throughput versus average SNR. The link between source, destination and relays are assumed to be symmetric and with independent fading coefficients.

On Fig. 6 we show the performance of the AMC algorithm combined with cooperation for $N = 2$ and $M = 3$. From these results, we observe three regions for the SNR : the *low*, *medium* and *high* SNR regions. At low SNR, the non-cooperation mode outperforms cooperation mode since the noise power dominates the received power at the relays. In the medium SNR region, the cooperative scheme outperforms the non-cooperative scheme with a gain up to 6 dB. This gain is due to the better diversity-multiplexing trade-off (DMT) of the cooperative scheme. However, this gain decreases for increasing SNR since we fix $PER_{target} = 10^{-2}$ while $R_{max} = 8$ and $M = 3$ (hence $M < M_{min}$, see table 1). Therefore, when $M < M_{min}$, the cooperative scheme is not preferable at high SNR.

On Fig. 7 the performance of the case $N = 2$ and $M = 5$ is shown. As demonstrated in (S. Yang and J-C. Belfiore, 2006), the DMT is improved with the number of slots M. This improvement translates into a better performance in both cases. We observe that the decrease of SNR gain at medium to high SNR is slower than the previous case. Cooperation is always better than the non-cooperation since $M \geq M_{min}$. Best performance is always reached when using *hybrid cooperation*. We remark that the hybrid scheme alleviates the performance loss of cooperation

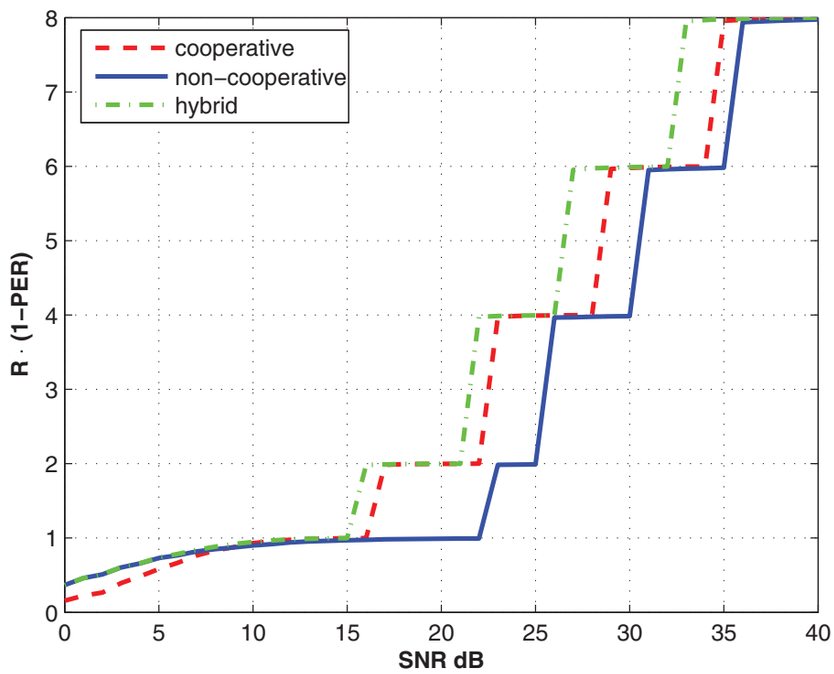

Fig. 7. Cooperative/non-cooperative/hybrid cooperative transmission with $N = 2$, $M = 5$ and $PER_{target} = 10^{-2}$

in both the low SNR and the high SNR regions. In case of $M = 3$ and $M = 5$, we observe respectively up to 5 and 7.5 dB of gap from fixed-cooperation and 1.5 and 2 dB of gap from non-cooperative transmission.

Hereafter we enlarge the investigation on *hybrid* cooperation protocols performance for a realistic communication scenario such as, OFDMA based wireless mobile communication transmission which employs limited modulation alphabets and real FEC codes. We access the effectiveness of *hybrid* cooperation protocol in real communication scenarios in terms of average PER versus average SNR, average system throughput enhancement and average cooperation cost reduction. The set of parameters used in this simulations are chosen according to the IEEE 802.16e standard . The mobile wireless channel is modelled according to (Spatial Channel Model Ad Hoc Group, 2003).

We propose to use an OAF hybrid cooperation protocol under the following power constraint: we impose a total average power constraint and no power allocation is considered. If P denotes the total power constraint, we impose $P_s = P/2$ for the power allocated to the source in the first slot and $P_r = P/2$ the power allocated to the relay in the second slot. Hereafter we adopt the following graphical notation: we represent respectively with the solid blue line, dashed red line and solid green line, non-cooperative, persistent cooperative and hybrid cooperative transmission mode performance.

Simulation results are given here for the system model presented in section 3. We use as Forward Error Correcting (FEC) code the LDPC codes as specified by the standard IEEE 802.16e (IEEE Standards Department, 2005) for the different coding rates.

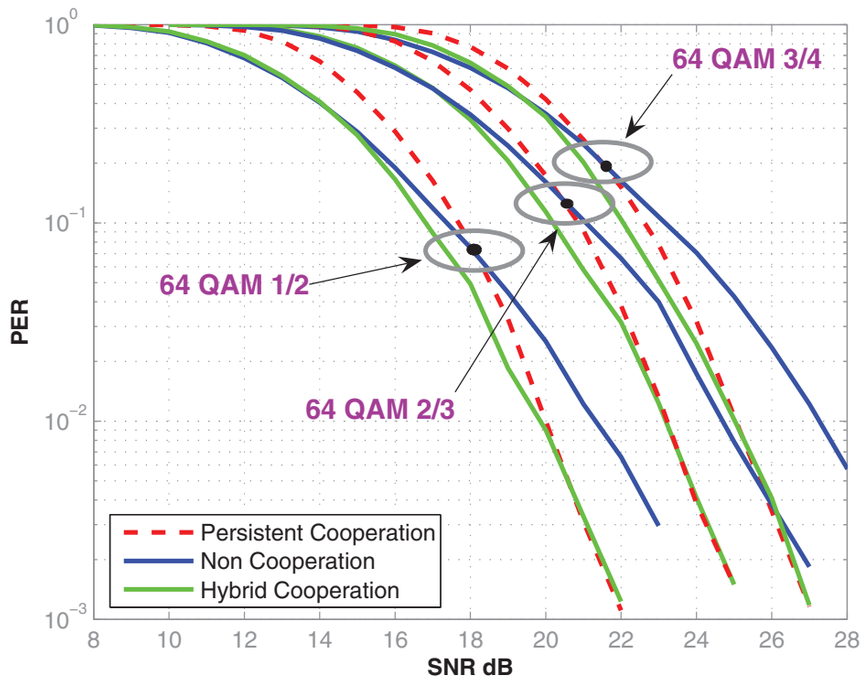

Fig. 8. Cooperative/non-cooperative/hybrid cooperative transmission

On figure 8 we compare the three transmission mode performance in terms of average PER performance versus average SNR. Results are reported here only for 64-QAM modulation with coding rates $R_c = 1/2,\ 2/3,\ 3/4$. From these results, we observe that there is a *crossing point* (PER_{cross}) between non-cooperative and cooperative average performance. For $PER \leq PER_{\text{cross}}$ cooperation outperforms non-cooperative mode. Hence the gain of hybrid cooperation is high since the direct link results more often in outage that cooperative transmission. Note that the PER that corresponds to this *crossing point* depends on the code correcting power: stronger codes present the *crossing point* at higher PER. For sake of simplicity we impose same codeword length for each MCS. Therefore, the information block length is larger for higher coding rate which results in a stronger correcting code. This is verified on figure 8. When $PER > PER_{\text{cross}}$, non-cooperative transmission outperforms cooperation. When $PER_{\text{cross}} \rightarrow 0$, hybrid cooperation performs as non-cooperative transmission since cooperation is never activated. Hybrid cooperation notably outperforms both cooperative and non-cooperative transmissions for PER values close to PER_{cross}. Note that in the present simulation we also introduce a feedback delay between $MI_{non-coop}$ estimation and cooperation controller action. Due to this delay, hybrid cooperation performance is slightly decreased comparing to equivalent results presented in (E. Calvanese Strinati and S. Yang and J-C. Belfiore, 2007).

In order to show the effectiveness of hybrid cooperative AMC mechanism, which combines AMC with hybrid cooperation, we compare the three transmission modes in terms of average system throughput versus average SNR. The simulated AMC algorithm selects the MCS which maximizes the throughput while meeting the PER_{target} QoS constraints (Calvanese

Strinati E., 2006). Typical values for the target PER is a few percent. For instance, imposing $PER_{target} \leq 10^{-1}$ results in a residual PER below 10^{-5} after 4 retransmissions.
The set of MCS corresponds to the transmission rate set defined by the IEEE 802.16e standard. In our simulation results we show the per-user performance, having one data region of 24 sub-carriers (in frequency) and 16 data OFDM symbols (in time). Under this assumption, the set of MCS schemes and the related nominal throughputs r_{mcs} and information block lengths N_{Info} are given in table 2.

Modulation	**Code Rate**	$\mathbf{N}_{\text{Info}}$	$\mathbf{r}_{\text{mcs}}$
QPSK	1/2	384 (bits)	215 (Kb/s)
QPSK	3/4	576 (bits)	315 (Kb/s)
16-QAM	1/2	768 (bits)	420 (Kb/s)
16-QAM	3/4	1152 (bits)	630 (Kb/s)
64-QAM	1/2	1152 (bits)	630 (Kb/s)
64-QAM	2/3	1536 (bits)	840 (Kb/s)
64-QAM	3/4	1728 (bits)	945 (Kb/s)

Table 2. Modulation and Coding Schemes of IEEE 802.16e

When $PER_{\text{target}} < PER_{\text{cross}}$, then cooperation is always better than the non-cooperation. Otherwise, non-cooperation transmission can outperform persistent cooperation transmission. As an example, we report respectively on figure 10 and 9 our simulation results for $PER_{\text{target}} = 10^{-1}$, $5 \cdot 10^{-2}$.

As it is shown on figure 9, with $PER_{\text{target}} = 5 \cdot 10^{-2}$, persistent cooperation outperforms non-cooperative transmission over all the considered SNR range since, $PER_{\text{target}} < PER_{\text{cross}}$ for all MCS.
In this case, *hybrid cooperation* outperforms *non-cooperative* and *persistent cooperative* transmission respectively with a gain up to 1.75 dB and 0.75 dB. Relaxing the constraint on the PER_{target} to $PER_{\text{target}} = 10^{-1}$, there are some MCS for which $PER_{\text{target}} > PER_{\text{cross}}$. As a consequence, *non-cooperation* outperforms *persistent cooperation* in same parts of the considered SNR range. Again, *hybrid cooperation* outperforms *non-cooperative* and *persistent cooperative* transmission respectively with a gain up to 1.25 dB and 0.9 dB (see figure 10).
We report hereafter also some simulation results aimed at understanding the average relaying activation ratio χ) - which is the ratio between the number of frames were the relay is active over the total number of transmitted frames - versus the average SNR adopting the proposed *hybrid cooperation* protocol. Results are shown on Fig 11 for $PER_{target} = 10^{-1}$. Two working zones of an AMC mechanism can be distinguished. In the first zone, even if AMC selects the minimum MCS at which the system can operate, we have that $PER > PER_{target}$. Therefore, since PER is large, χ is large too. For such link quality conditions the AMC may decide to avoid transmission since AMC cannot assure the QoS constraints imposed by the upper layers. The second zone starts when MCS selected for transmission assures $PER \leq PER_{target}$. In this zone each saw tooth corresponds to a change of MCS. Our results outline that when AMC can assure a $PER \leq PER_{target}$, χ is very small ($\chi \leq PER_{target}$) since the hybrid cooperation protocol activates the cooperative mode only when direct link transmission is in outage. At the end of the second zone transmission is done at the highest MCS and the system operates at $PER \ll PER_{target}$, with consequent $\chi \ll 1$. Note that, contrary to the cooperative AMC protocol case for which $\chi = 1$ over the whole SNR range, when AMC can assure a $PER \leq PER_{target}$ and the proposed hybrid cooperation protocol is adopted, χ is reduced to the same

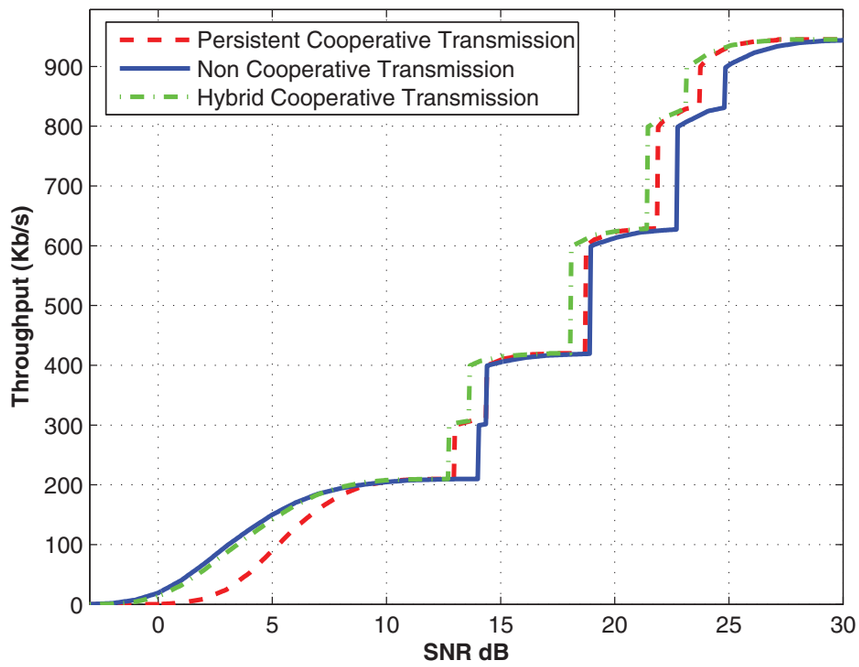

Fig. 9. Cooperative/non-cooperative/hybrid cooperative transmission with $PER_{\text{target}} = 5 \cdot 10^{-2}$

order of magnitude of PER_{target}. Note that the major result in our investigation is reduction of average relaying activation and not the improvement in average system throughput achieved with hybrid cooperative AMC mechanism.

The reduction of average relaying activation ratio achieved with the proposed hybrid AMC protocol presents three main advantages. First, the average power consumed by the active relays is strongly reduced especially when cooperation does not help and consequently cooperation activation results in a waist of relays processing power. Second, the delay caused by the cooperation protocol and consequently the packet delivery delay can be strongly reduced adopting our proposed *hybrid cooperation* protocol. For instance, when direct non-cooperative transmission is not forecasted to be in outage, the destination can immediately send a clear to send (CTS), without waiting for the relay probing process. This is an important attribute for scheduling algorithm with delay QoS constraints. Third, the average computing complexity is reduced by decreasing the number of average operation associated to cooperation.

4.3 An efficient power allocation optimization for hybrid cooperation protocols

In this section we combine the OAF hybrid cooperation protocol presented in section 4.1 with an optimal power allocation algorithm. The goal is to maximize the mutual information of the equivalent cooperative channel via optimal power allocation between the source and the relay. It is well known that the performance of a cooperative scheme is improved by relaying with optimal power values. Hereafter we assume that a maximal overall transmit power is fixed by using, for instance, a suitable power control algorithm in order to minimize co-channel

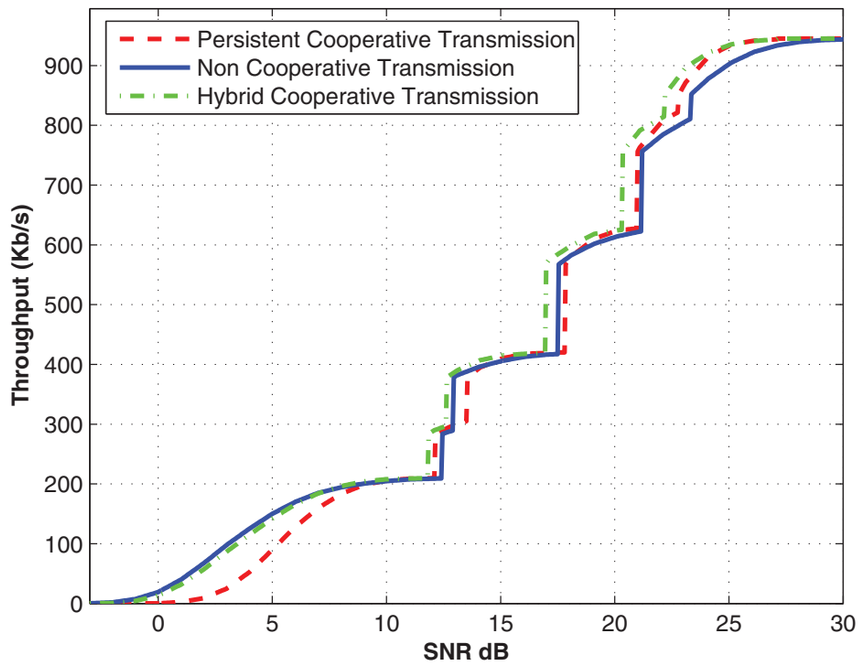

Fig. 10. Cooperative/non-cooperative/hybrid cooperative transmission with $PER_{\text{target}} = 10^{-1}$

interference. The overall total transmitting power should then be optimally shared between the source and the relay. The simplicity of an OAF cooperation scheme leads to an outage probability expression easier to handle than in the NAF case. Basically, we optimize the power allocation by minimizing the outage probability in the high SNR regime.

4.4 Outage probability approximation

First we should find the expression of the outage probability, denoted $\mathbb{P}(\mathcal{O}_c, \mathcal{O}_d)$, and approximate it in the high SNR regime. *Proposition 1:* Let P denotes the total power constraint in the network, $P_s = \alpha P$ and $P_r = (1-\alpha)P$ the fractions of P allocated to the source and the relay, respectively. Let $C_\lambda = \frac{\lambda_g}{\lambda_h}$ and $C_R = \frac{1}{2^R+1}$. Then, the approximation of the outage probability in the high SNR regime is

$$\mathbb{P}(\mathcal{O}_c, \mathcal{O}_d) = 2(2^R-1)^2(2^R+1)\epsilon^2\, \lambda_f \lambda_h \left(\frac{1-\alpha+\alpha C_\lambda}{\alpha(1-\alpha)}\right)\left(1-\alpha C_R\right)$$

Proof: The following *Lemma* will be used in our proof

Lemma 1: Let δ be positive, and let $r_\delta = \frac{vw}{v+w+\delta}$ where v and w are independent exponential random variables and λ_v and λ_w are, respectively, their parameters. Let $h(\delta)$ be continuous with $h(\delta) \to 0$ as $\delta \to 0$. Then

$$\lim_{\delta \to 0} \frac{1}{h(\delta)}\, \mathbb{P}\{r_\delta < h(\delta)\} = \lambda_v + \lambda_w$$

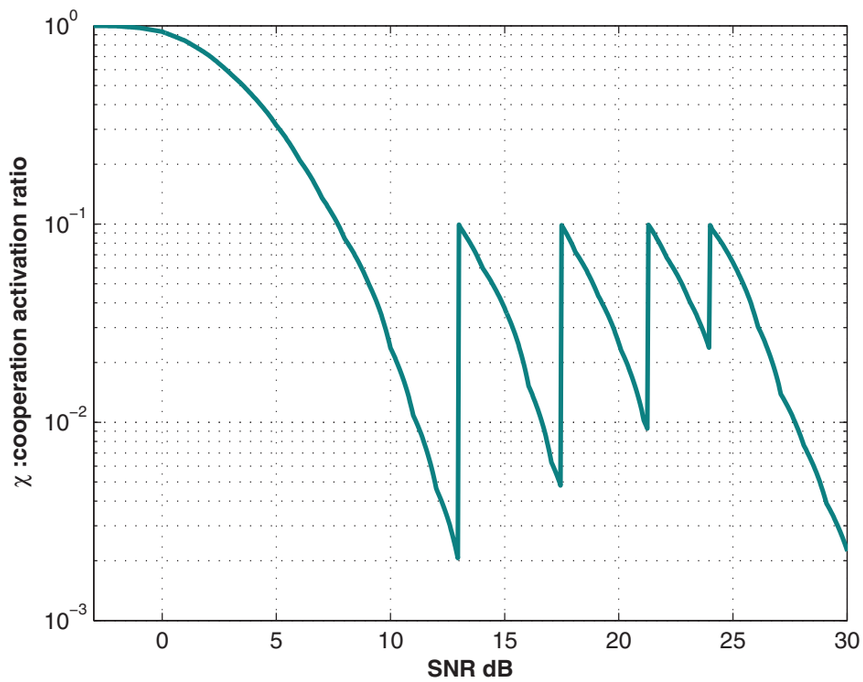

Fig. 11. Average relaying activation ratio for hybrid cooperative transmission with $PER_{\text{target}} = 10^{-1}$

$$\mathbb{P}(\mathcal{O}_c, \mathcal{O}_d) = \mathbb{P}\{\alpha|f|^2 + \frac{\alpha|h|^2(1-\alpha)|g|^2}{\alpha|h|^2 + (1-\alpha)|g|^2 + P^{-1}} < \frac{2^{2R}-1}{P}, \frac{|f|^2}{2} < \frac{2^R-1}{P}\} \tag{2}$$

$$= \mathbb{P}\{u + \frac{vw}{v+w+\epsilon} < (2^{2R}-1)P^{-1}, u < 2\alpha(2^R-1)P^{-1}\} \tag{3}$$

$$= \mathbb{P}\{r_\epsilon < g_1(\epsilon) - u, u < g_2(\epsilon, \alpha)\} \tag{4}$$

$$\mathbb{P}(\mathcal{O}_c, \mathcal{O}_d) = 2(2^R-1)\epsilon^2\lambda_f\left[\frac{\lambda_h}{\alpha} + \frac{\lambda_g}{1-\alpha}\right]\left[(2^{2R}-1) - \alpha(2^R-1)\right] \tag{5}$$

We know that

$$\mathbb{P}(\mathcal{O}_c, \mathcal{O}_d) = \mathbb{P}\{I_c < 2R, I_d < R\}$$

The outage probability can be expressed as in (2), if we define $u = \alpha|f|^2$, $v = \alpha|h|^2$, $w = (1-\alpha)|g|^2$, $\epsilon = P^{-1}$, $g_1(\epsilon) = \frac{(2^{2R}-1)}{P}$, and $g_2(\epsilon, \alpha) = 2\alpha\frac{(2^R-1)}{P}$.
Let λ_u, λ_v and λ_v be the parameters of the exponential random variables u, v and w, respectively. For $i = f, h$, we have

$$\lambda_i = \frac{1}{\alpha\sigma_i^2} = \alpha^{-1}\lambda_i \; and \; \lambda_w = \frac{1}{(1-\alpha)\sigma_g^2} = (1-\alpha)^{-1}\lambda_g$$

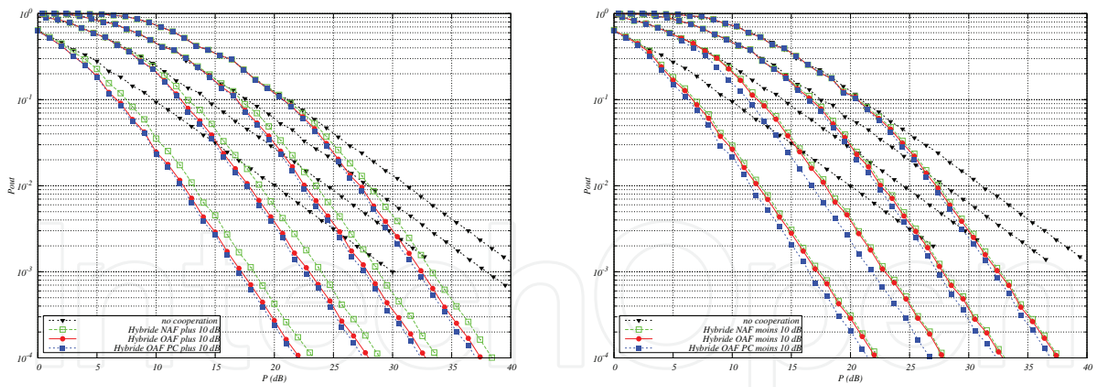

Fig. 12. Outage probabilities for the non-cooperative, Hybrid-NAF, Hybrid-OAF and Hybrid-OAF with power allocation scheme. One relay network. Considered information rates: 1, 2, 3 and 4 BPCU. $C_\lambda = \pm 10$ dB.

Using Lemma 1, we get

$$\mathbb{P}(\mathcal{O}_c, \mathcal{O}_d) = \int_0^{g_2} \mathbb{P}\{r_\epsilon < g_1(\epsilon) - u\} p_u(u) \mathrm{d}u$$

$$= \int_0^{g_2} (\lambda_v + \lambda_w)(g_1(\epsilon) - u) p_u(u) \mathrm{d}u.$$

Knowing the pdf of the exponential variable u, the expression of $\mathbb{P}(\mathcal{O}_c, \mathcal{O}_d)$ is developed (calculation details are omitted due to length constraints). This expression is then approximated in the high SNR regime, using the second order Taylor development of $e^{-a\epsilon}$ when $\epsilon \to 0$, a being positive, which leads to expression (5).

Eventually, define $C_\lambda = \frac{\lambda_g}{\lambda_h}$ and $C_R = \frac{1}{2^R+1}$ which, when substituted in (5), complete the proof.

For a given spectral efficiency R and channels variances, optimizing the power allocation consists in minimizing the outage probability and thus, finding the optimal α, denoted α^*, that verifies

$$(C_\lambda - C_\lambda C_R - 1)\alpha^{*2} + 2\alpha^* - 1 = 0 \tag{6}$$

4.4.1 Simulation results

In order to clarify the impact of the proposed power allocation algorithm we compare non-cooperative, NAF cooperative, hybrid NAF cooperative and hybrid OAF cooperative protocols in two different transmission scenarios. Fist we suppose that both path-loss and shadowing effects are the same between source, relay and destination. This scenario is specified by $C_\lambda = 0$ dB, so that we have $\sigma_h^2 = \sigma_g^2$. In this case α^* is

$$\alpha^* = \frac{1}{1 + \sqrt{1 - C_R}}$$

We observe that minimizing the outage probability leads to almost an equal power allocation between the source and the relay since α^* takes values around 0.5 independently from the transmission spectral efficiency. We evince that, when $C_\lambda = 0$ dB, the algorithm of power

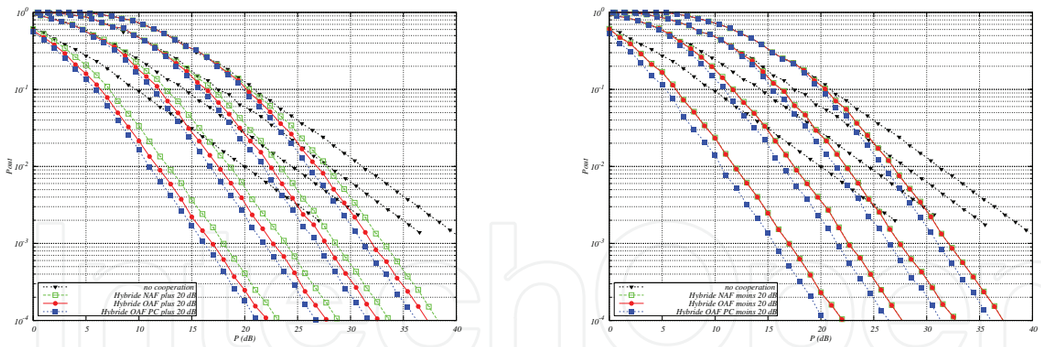

Fig. 13. Outage probabilities for the non-cooperative, Hybrid-NAF, Hybrid-OAF and Hybrid-OAF with power allocation scheme. One relay network. Considered information rates: 1, 2, 3 and 4 BPCU. $C_\lambda = \pm 20$dB.

allocation optimization performs as an equal power allocation $P_s = P_r = P/2$. This is obvious since source-relay and relay-destination links have the same link quality.
As a second scenario, we consider the more realistic case where $C_\lambda \lesseqgtr 0$ dB. Actually, having $C_\lambda \lesseqgtr 0$ dB, we assume that one of the links, source-relay or relay-destination, has a better quality, *i.e.*, $(\sigma_h^2 \lesseqgtr \sigma_g^2)$. Optimizing the power allocation becomes more worthy in this situation since allocating more power to the worst channel helps. In this case, α^* can be derived from (6) as follow:

$$\alpha^* = \frac{1}{1 + \sqrt{C_\lambda (1 - C_R)}}$$

On Figures 12 and 13 we consider the case of $C_\lambda > 0$ dB, having respectively, $C_\lambda = 10$ dB and $C_\lambda = 40$ dB. In this scenario, *e.g.*, the attenuation between source and relay is much smaller than between relay and destination. In this case, if the cooperation is activated by the hybrid cooperation controller, our power optimization allocates a higher fraction of the overall transmit power P to the relay.
A more challenging scenario is when $C_\lambda < 0$ dB or equivalently $\sigma_h^2 < \sigma_g^2$. In this case, an optimal power allocation algorithm can drive to notable performance improvement. Mainly, making reliable the transmission between the source and the relay is imperative since the relay amplifies and then forwards the received signal. That is why our optimization technique allocates, in this case, a higher fraction of P to the source. Simulation results for $C_\lambda = -10$ dB and $C_\lambda = -40$ dB are given on Figures 12 and 13.

5. Conclusion

In this chapter we present an effective scheme to improve the system performance of a cooperative system, reduce cooperation complexity, signalling overhead and cooperation protocol delay, while meeting the QoS constraints from the upper layer. For this reason, we looked for a novel AF cooperative protocol, and its combination with adaptive mechanisms such as AMC and power allocation.
First, we propose a novel cooperation protocol for half-duplex AF cooperative networks. We call this protocol *hybrid cooperation*. We prove by simulation that, NAF hybrid cooperation outperforms both non-cooperative and classical full-cooperative transmission. To evaluate the improvement due to this new strategy, we also propose an *hybrid cooperative AMC*

mechanism, which is the combination of AMC mechanism and *hybrid cooperation* protocol. We show that the advantages of *hybrid cooperative AMC* are twofold. First, its average throughput performance is higher than both AMC combined with non-cooperative and with fixed-cooperation transmission for all values of SNR. This results is benchmarked by our simulation results. Second, the proposed algorithm drives to a reduction of both average power consumed by the active relays and cooperation probing cost. This results in a reduced average packet delivery delay since both throughput performance is improved and cooperation probing delay is strongly reduced. Moreover, we showed how the proposed *hybrid cooperative AMC* mechanism drives to a reduction of cooperation signalling overhead that from a MAC layer point of view, may result in an additional throughput enhancement at the top of the MAC layer.

We further investigate the proposed hybrid AF cooperation protocol. We compared hybrid OAF and hybrid NAF protocols. Imposing a total average power constraint and no power allocation, we showed that the orthogonal strategy (OAF), suboptimal in the case of a classical amplify-and-forward scheme, outperforms both classical NAF cooperative and hybrid NAF schemes. Moreover, we pointed out that from an implementation point of view, the hybrid OAF protocol reduces significantly the cooperation complexity.

Furthermore, we profit of the simplicity of the outage probability expression for the OAF cooperation scheme to derive an optimal power allocation algorithm. The proposed algorithm optimizes the system performance by minimizing the outage probability of the channel at high SNR. We underlined that the need of such an optimization increases with the increasing quality difference within the links (source-relay and relay-destination). Indeed, we succeeded in finding a low complexity algorithm that optimizes the power allocation in the case of a hybrid-OAF schemes.

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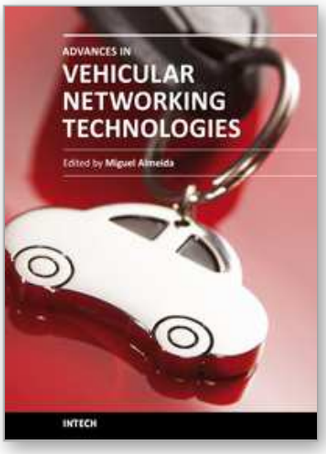

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This book provides an insight on both the challenges and the technological solutions of several approaches, which allow connecting vehicles between each other and with the network. It underlines the trends on networking capabilities and their issues, further focusing on the MAC and Physical layer challenges. Ranging from the advances on radio access technologies to intelligent mechanisms deployed to enhance cooperative communications, cognitive radio and multiple antenna systems have been given particular highlight.

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