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A Framework for Cooperative Communications at the System Level

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Abstract

In order to improve the communication efficiency without using multi-antennae terminals, cooperative communications implement one or several single antenna relays to assist the transmission between a source and a destination. The design of such a cooperative network, involves several layers of the OSI model. Transmission and multiplexing techniques are addressed at the physical layer whereas the management of the cooperative network (activation of a cooperative mode, selection of relays) is done at the Medium Access Control (MAC) layer and the layers above. After an overview of protocols that have been designed in this domain, we propose an original framework of a cooperative network, at the system level. Inspired from models of the ITU normative organization, our cooperative network model is based on two planes: a data plane and a control plane. A validation of the framework is given by modeling an existing cooperative MAC protocol.

1. Introduction

Multiple-Input Multiple-Output (MIMO) techniques are used widely to combat the effects of fading in wireless communications [1][2]. These multi-antennae techniques work properly only if the antennae of the wireless terminals are sufficiently spaced. Hence, when several antennae cannot be installed on a wireless terminal, alternate solutions are required.

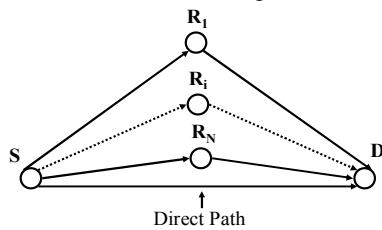


Figure 1. Cooperation with N relays

Cooperative communications propose an attractive answer to that problem. They provide the same properties as the MIMO techniques without requiring multi-antennae terminals. In cooperative scenarios, one or several relay terminals R_i ($1 \leq i \leq N$) assist the transmission between a source terminal S and a destination terminal D (see Figure 1.). In this context, the performance of a cooperative transmission can be expressed in terms of bit error rate (BER). Without cooperation, the BER on a typical wireless link decreases as SNR^{-1} when using a BPSK modulation, where SNR denotes the signal to noise ratio at terminal D. With cooperation methods such as “amplify and forward” or “selective forwarding” [6], the BER decreases as $\text{SNR}^{-(N+1)}$ (see our simulations in Figure 2.).

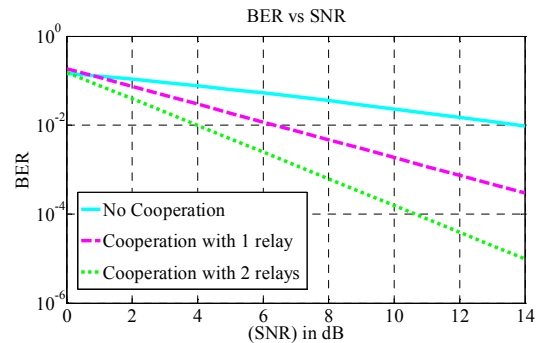


Figure 2. BER for cooperative communications

The design of a cooperative network involves several layers of the OSI model. Transmission and multiplexing techniques are addressed at the physical layer [3]-[6][14] whereas the management of the cooperative network (activation of a cooperative mode between terminals, selection of relays) is done at the MAC layer and the layers above. Several methods and protocols have been already designed to tackle this issue [7]-[13][15]. However, the comparison of the existing approaches is difficult since there are no

common criteria adopted in this domain and, to our knowledge, a common framework of description does not exist yet.

The goal of this paper is to propose a unified framework of a cooperative network, at the system level. The proposed framework is independent of cooperative transmission schemes. The network model is based on two planes: a data plane and a control plane. The proposed network model will help both the comparison of existing protocols and the design of future cooperative protocols. Furthermore, our network model identifies four main tasks that should be implemented to set cooperative network: cooperative mode activation, cooperation data acquisition, relay selection algorithm, and relay notification. We believe that this model can facilitate the design and updating of existing and future propositions in this domain.

The rest of the paper is organized as follows. In section II, we review some of the existing cooperative protocols at the MAC layer. Section III is devoted to the description of the proposed cooperative network model. In section IV, we use our model to describe an existing cooperative protocol at the MAC layer. We conclude the paper in section V.

2. Cooperative Communications at the MAC Layer

As the MAC layer is in charge of the physical resources allocation among user terminals, some requirements have to be stated. First, a dynamic resource allocation scheme is recommended for wireless networks since radio channels are rather accessed in a random fashion than in a static one. Second, radio channels are slowly time-varying. This implies that the results of a relay selection procedure remain valid only within the duration of few MAC frames. Hence, the relay selection process has a given lifetime and that the selection must be updated. Third, the relay selection induces a non negligible traffic load that could possibly counterbalance the benefits provided by cooperative communications. So, the relay selection process must achieve a trade-off between the quality of the selected relay(s) and the amount of bandwidth consumed to process the selection.

Several MAC protocols have been designed to address these issues. We briefly present some of them [7]-[13][15]. They are all based on the MAC layer protocol of the IEEE 802.11 standard. In order to facilitate the presentation, we have chosen to classify the methods according to the node in charge of the relay selection process.

2.1. Relay selection at the source terminal

In [7], the source terminal invites its neighboring nodes. Relaying data are sent back by Potential Relay Terminals (PRTs). These data are processed by the source terminal and a notification is sent to the selected PRTs. The data frame is then sent cooperatively by the source terminal and the selected relay terminals upon the reception of a frame initiated by the destination terminal.

In [11], each terminal maintains a cooperation table of PRTs. Whenever a terminal has to transmit data, it searches for the best PRT in its cooperation table. When a PRT has been successfully found, a modified RTS/CTS handshake is performed between the source terminal, the destination terminal and the selected PRT.

2.2. Relay selection at the PRTs

In [8], the destination node asks for the cooperation of PRTs when it fails in decoding the message sent by the source terminal. Then, the neighboring nodes that have been able to decode the data frame, forward the message using a classical RTS/CTS handshake.

In [9][15], the PRTs overhear the RTS/CTS handshake between the source terminal S and the destination terminal D . Then, each PRT R_i computes a timer T_i that is inversely proportional to the quality of the links (S,R_i) and (R_i,D) [9]. Hence, the most appropriate relay has its timer reduced to zero first. This relay transmits a short duration flag signaling its presence. As soon as all the PRTs hear the best relay to flag its presence, they back off. This completes the relay selection process. Note that the PRTs can also compute additional parameters in order to decide whether they can contribute efficiently to the (S,D) communication or not [10].

2.3. Relay selection at the source node and the destination node

In [13], virtual Multiple Input Single Output (MISO) links are established between the source S and its neighbors. Similar links are established between the destination D and its neighboring nodes. To send a frame, terminal S (resp. D) sends first a local frame toward its neighbors. Then the neighbors cooperatively send the frame toward terminal D (resp. S).

As we can see in previously described MAC protocols, several functions can be identified such as cooperative mode activation, relaying data acquisition, relay selection process, and relay notification. In the following section, we put forward the basic

cooperative functions and their interactions within a cooperative network.

3. Cooperative network model

The objective of the proposed model is to analyze and classify the basic solutions that may be designed for multi hop relay network, named cooperative networks in the paper. Considering that nodes are able to achieve cooperative transmission, the next step is to set up a cooperative network that deals with the control of the relay nodes. The problem is to answer questions such as: how many relays are needed? How and when relays are selected? Who selects the relay?

To answer, we propose a design model for cooperative systems that is composed of two planes: the control plane and the data plane (see Figure 3). The control plane is in charge of the cooperative transmission set up. The data plane sends, receives, or forwards data in case of cooperation. This approach is similar to the one used to represent the functions related to the services in Public Switched Telephone Networks (PSTNs). In PSTNs, the control plane is in charge of the voice path set up, while the data plane is in charge of the voice transport.

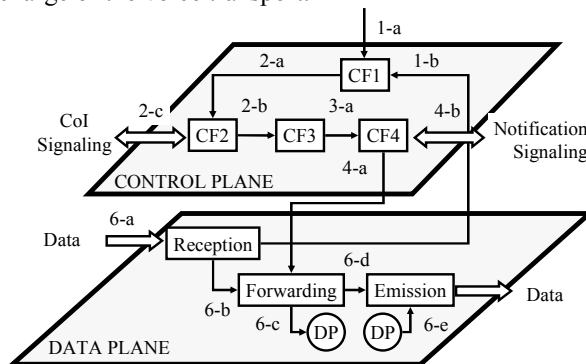


Figure 3. Cooperative Network Model

As we focus on the plane modeling, the figure does not reflect the protocol layering. In fact, data received by the data plane belong to the physical layer and have to be processed by the upper layer protocols. This is represented on the figure by the circle labeled DP for Data Process. Functional processes and interactions between the two planes are described in the next paragraphs.

3.1. Control plane

The main objective of the control plane is to determine the relay nodes that should forward the data and then to activate their respective forwarding blocks

in their data plane. We put forward four functions that are

- CF1: Cooperative mode activation
- CF2: Cooperation data acquisition
- CF3: Relay selection algorithm
- CF4: Relay notification

3.1.1. CF1: Cooperative mode activation. We consider that nodes are not always in a cooperative mode. Rather, the cooperative mode has to be activated. It is done either in a proactive mode or in a reactive mode. The cooperation process can be initiated by an upper process (1-a) when cooperation is activated proactively. The triggering process may be a configuration process that manages the power consumption, or a transport layer process that manages the packet error rate. The cooperation process can be activated when needed, upon the data reception (1-b) when cooperation is activated reactively. Once the cooperation mode is activated, the process that selects the relays is started. Note that the activation may be parameterized with a pre-determined set of relays [11][13].

3.1.2. CF2: Cooperation data acquisition. The cooperation data acquisition function is under the control of the line (2-a). Its output (2-b) contains data that will be used by the relay selection algorithm. Data are labeled CoI (Cooperation Information) in the figure. When cooperation data are already available at the node, CF2 transmits them to CF3; otherwise CF2 has to obtain them by a signaling protocol, named CoI signaling (2-c).

CoI is used by the relay selection algorithm. CoI may include parameters related to the quality of the radio channel, sometimes referred to as channel state information (CSI). The parameters can be estimates of the Rayleigh gain g_{ij} between terminal i and terminal j [9], or estimates of the SNRs between both terminals [10]. CoI may also be constituted by data present in the fields of the received frames such as the RTS/CTS frames [10][11].

CoI signaling solutions are characterized by their type and their level. When out-band signaling is implemented, a specific protocol is designed for the control plane. It induces extra resources consumption. When in-band signaling is considered, the data protocol is used to transmit signaling information. It may be a standardized protocol with minor modifications, or a new protocol. The signaling level may be at the physical, PLCP (Physical Layer Convergence Protocol), MAC, routing level or at a cross-layer level.

3.1.3. CF3: Relay selection algorithm. The CF3 block processes the CoI. Classical selection criteria are best source-to-relay and relay-to-destination channels, and maximum achievable data rates. The result of CF3 (3-a) is constituted by the selected relay nodes based on information obtained by signaling (2-b) or by administrative configuration (1-a, 2-a, 2-b). We assume that the node in charge of this process is also in charge of the relay notification function (CF4). According to the chosen algorithm, it may be the source, the destination or the relay itself.

When CF3 can get data from several potential relays, a true selection process can be done because the respective merits of each potential relay can be compared. So CF3 can determine the best relay (or a set of best relays). At the end of the selection process, CF3 delivers the chosen relays. It may also compute some additional parameters such as the transmit power allocated to each cooperating relay [7][11]. Otherwise, when CF3 can only get CoI from a single terminal, it simply decides whether the current terminal could be a relay or not [9][10].

3.1.4. CF4: Relay notification. Once a terminal has been selected for cooperation, all participating terminals (the source terminal S, the destination terminal D, the selected terminals and all other PRTs) should be informed of it. In particular, the selected terminals should know the result of the selection process in order to achieve the forwarding in the data plane. Two outputs are noted. There are an internal one (4-a) and an external one (4-b). The internal one refers to plane interactions inside a node while the second concerns the interaction between peer entities inside the control plane. Depending on the chosen design of the CF3 function, either the PRT is support of CF3 or not. In the first case, the PRT obtains its status (relaying or not relaying) through internal notification (4-a) between the control plane and the data plane. In the second case, the node in charge of the relay selection is also in charge of the relay notification and thus it sends the notification to the concerned nodes. These ones will receive signaling (4-b) and then will obtain their status through internal notifications. As previously stated concerning the CoI signaling, there are several types and levels of signaling solution. Note that when a node is always relaying, the CF4 function will be empty.

3.2. Data plane

The main function of the data plane consists of receiving the data, and, possibly, of forwarding them.

The terminal processes the received data (6-a) with the reception block. This block may trigger CF1 through 1-b. The reception block sends the received data to the forwarding block through 6-b. This block transmits the data to the emission block (6-d) or sends them to a basic data process (6-c). The DP block is used when there is no cooperative mode. In this mode, data are processed by the basic protocols of the upper layers. Otherwise, when the cooperative mode is chosen, the data enter the emission block to achieve a cooperative transmission. Note that the emission block is usually activated by the basic emission request (6-e).

The set up of the cooperative mode is specified by the control plane model. Thanks to the CF4 function, a node is aware of its relaying capacity. At the same time, to effectively achieve the forwarding, the relay has to recognize the data on which the cooperation mode has to be activated. More precisely, through the control plane, the node R should know that it has to relay data from a specific pair of terminals (S,D).

There are two ways to answer the question: the first one consists in answering on a per data basis, the second one consists in answering on a per flow basis. The first method considers that cooperation is decided for each data frame transmission. It is like a connectionless mode. The second method decides on cooperation for a set of data packets; it memorizes the relay selection result in a cooperative table for a time which is the connection time. It is like a connection-oriented mode. The interest of using a given mode depends on the channel time variability and the overhead control. If the channel does not change significantly over a time period greater than the connection time, thus the connection oriented mode is usable. It would generate less control overhead than the connection less mode, because the CF4 function would be activated less frequently. Otherwise, the connection less mode would be recommended.

3.2.1. Connectionless method. Cooperative MAC protocols act in a connectionless mode. Basically, for each frame, the protocol allocates time for relaying. A relay node knows that it will have to forward the data that it will overhear, after some frame exchanges. Many propositions have been made in this context. They are mainly based on IEEE 802.11 standards and on the exchange of RTS/CTS frames with some additional extensions.

3.2.2. Connection-oriented method. A switching table is consulted on data arrival. The table contains the identity of the received data and the forwarding state (ON,OFF). The identity value is provided by the transmission system or by the MAC protocol through the MAC address. Some cross layer mechanisms are

usable to fill in the table. The routing protocol may be used to fill in both the routing table and the relaying table.

4. Applying the cooperation network model to an existing protocols

In this section, we describe a cooperation protocol implemented at the MAC layer of the IEEE 802.11 standard, using the cooperation network model presented in the previous section. We have chosen a distributed cooperation protocol, referred to as Opportunistic Relaying (OR) [9]. In this protocol, only one relay is selected and the relay selection is done by the PRTs themselves. We shall describe the implementation of the protocol in the three terminals involved in a cooperative communication: the source terminal S, the relay terminal R and the destination terminal D. We begin with the description of the protocol at a PRT R (see Figure 3). Notations have been defined in Figure 2.

4.1. Network model at a PRT R

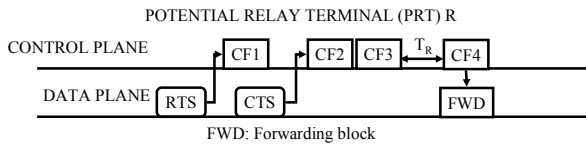


Figure 4. Cooperation at a PRT R

The cooperation process begins at each PRT when the classical RTS/CTS procedure is initiated between terminals S and D. The reception block in the data plane of each PRT is receiving the RTS frame emitted by terminal S. A control (1-b) is then sent to CF1 in order to check whether a cooperative communication is achievable or not. In [9], the cooperative mode is assumed to be always activated. So, we assume that upper layers have enabled the cooperative mode through 1-a. So, when the control 1-b arrives at CF1, this block sends a control 2-a to the relaying data acquisition block CF2. In CF2, the gain g_{SR} of the Rayleigh channel between S and R is estimated. The estimation of g_{SR} relies on the estimation of the SNR observed during the reception of the RTS frame. Similarly, the gain g_{RD} of the Rayleigh channel between R and D is estimated by CF2. The estimation relies on the estimation of the SNR observed during the reception of the CTS frame emitted by terminal D. It has been assumed that the forward and backward channels between R and D are the same due to the reciprocity theorem. Channels RD and DR are using the same frequency band. The CTS frame is received

in the control plane through the signal 2-c. Then, both parameters g_{SR} and g_{RD} are transmitted to the relay selection algorithm CF3 through 2-b. These parameters are used to compute a timer T_R related to the end-to-end channel quality h_R . The timer associated with the PRT R is inversely proportional to the parameter h_R . Therefore, the best relay has its timer reduced to zero first. The control (3-a) is then passed to the relay notification block CF4. This block sends a flag frame to all other PRTs. If no collision occurs, then a control (4-a) activates the forwarding block in the data plane of the best relay terminal. This step terminates the relay selection procedure in the PRTs. In [9], the timers are tuned in order to minimize the collision risk.

4.2. Network model at the source terminal S

At the source terminal S, the reception of the CTS frame activates the control 1-b (see Figure 5).

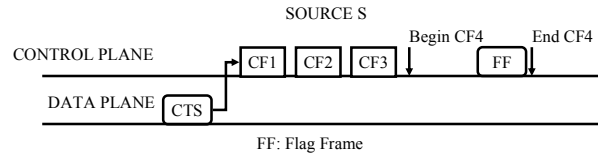


Figure 5. Cooperation at the source node S

Assuming that the cooperative mode is always enabled by upper layers (1-a), the controls (2-a), (2-b), and (3-a) are successively activated (the CF2 and CF3 blocks are empty). In block CF4, the source terminal waits for the flag frame acknowledging the participation of the best relay terminal R. The reception of the flag frame finishes the relay selection process.

4.3. Network model at the destination terminal

At the destination terminal D, the reception of the RTS frame activated the control 1-b (see Figure 6).

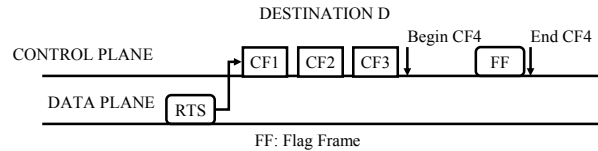


Figure 6. Cooperation at the node D

The rest of the procedure is the same as the one presented for the source terminal S. Note that for the case where all the PRTs are hidden from each other, the destination notifies all relays with a short flag frame. No explicit procedure has been presented in [9] to decide whether all relays can listen to each other or

not. The source S should also wait for this flag frame to finish the relay selection procedure.

5. Conclusion

In the context of wireless communication networks, cooperative communications propose an efficient alternative to the MIMO techniques. They provide the same properties in terms of performance at the physical layer without requiring multi-antennae terminals. To manage cooperative networks, several tasks must be implemented. The cooperative transmission is done at the physical layer whereas supervision processes such as the selection of the relay nodes, are implemented at upper layers. In this context, we have proposed a cooperative network model, at the system level. This framework is independent of the type of cooperative transmission. Our architecture model for cooperative systems is based on two planes: a data plane and a control plane. The main objective of the control plane is to determine the relay nodes that forward the data and then to inform such a node of its forwarding process in its data plane. In the control plane, we have put forward four functions: cooperative mode activation, cooperation data acquisition, relay selection algorithm, and relay notification. The data plane is constituted by three blocks (reception, forwarding, and emission). Note that the decision to forward data can be made on a per data basis or on a per flow basis. The first case corresponds to a connectionless communication principle whereas the second case corresponds to a connection-oriented communication paradigm. We have successfully described an existing cooperative MAC protocol with our model. The new proposed network model will help both the comparison of existing protocols and the design of future cooperative protocols.

Several important issues remain to be addressed. The first one consists in deciding whether a cooperative communication mode could or should be connectionless or connection-oriented. If the radio channel varies very slowly, then a connection-oriented cooperative communication is achievable. Otherwise, connectionless communications are recommended. In any case, this issue must be solved to complete the design of a cooperative network. Another important issue is the activation and shutdown of the cooperative mode in a network. Decision criteria should be developed to decide whether a cooperative communication should be implemented or not.

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