Cooperative networks: overview of state-of-the-art and trends toward green cooperative networks

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***Abstract*—This paper gives a general overview of a cooperative network (CN), which allows single-antenna mobiles to reach some of the advantages of multi-input multi-output (MIMO) systems. The idea is that single-antenna mobiles in a multi-user scenario can share their antennas so as to create a virtual MIMO system. Several important results in this area have been reached through an important research activity. However, most of them focused on performances of a CN such as rates and outage probability, with little consideration to the energetic aspect of this technology. This paper aims to cover most of what researchers all over the scientific community have achieved regarding this technology, with special regard to energy-aware CN schemes involving other new radio technologies.**

Keywords- Cooperative communication; Relaying; Network coding; Green radio, Amplify-and-forward; Decode-and-forward; Femtocells.

I. INTRODUCTION

Multiple-input multiple-output (MIMO) is a system based on the use of multiple antennas at both the transmitter and the receiver so as to improve communication performances. There are many advantages of this system, such as interference reduction, spectral efficiency and coverage. Moreover, it allows an error rate reduction since it mitigates fading through spatial diversity. However, there are many obstacles to MIMO implementations. Hardware costs are more important since multiple antennas means multiple RF chains. Moreover, the MIMO technology signal processing requires more power and energy consumption.

Cooperative networks (CN), based on virtual MIMO system concept, seem to be better solutions to achieve partial advantages of MIMO systems. In fact, fundamental research have demonstrated the great potential of cooperative wireless networking in increasing system capacity and coverage as well as enhancing quality of service (QoS). In [1], authors have studied a scheme of two users cooperating with each other for uplink transmission over a code division multiple access (CDMA) system and noticed better performances in terms of rate, outage capacity, and error probability. Thus, CN has become one of the recent recognized features for IEEE802.16j, ad-hoc networks and LTE-Advanced. Many works focus on CN analysis and strategies. Recently, a cross-layer approach of this technology has been studied [2]. Physical layer play a vital role since diversity and multiplexing across multiple cooperation links are extremely important. Many works addressed problems related to this layer, especially with space time coding (STC) [18]. Given that the number of cooperative terminals grows, a certain resources competition has been identified. Therefore, it was highly required to involve higher layers for best routing. Furthermore, some routing strategies that will be covered in this paper had achieved the same performance as STC and with less complexity.

This paper aims first to cover almost big results achieved in CN area, including different transmission schemes and different routing strategies, with a great focus on the best schemes in terms of performances. Furthermore, we give a special attention the energetic aspect of CN and focus on new schemes aiming more energy saving. Thus we first present in section II the concept of cooperative communication and the most popular methods namely, amplify-and-forward (AF) and decode-and-forward (DF). In section III, we investigate advantages and limitations of different cooperative routing strategies and focus on the best routing strategy. In section IV, we consider the case of bidirectional schemes, where terminals communicate simultaneously with each other over a shared relay. This scheme has involved another promising technology called network coding (NC). In section V, we focus on the "green" aspect of CN and point out open issues that need further research. Finally, we summarize some of the most important future research directions in section VI. This paper is concluded in section VII.

II. BASIC CONCEPTS OF COOPERATIVE COMMUNICATIONS

Under a CN system, single antenna user shares its antenna with other users in order to increase system

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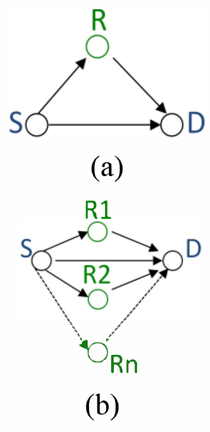
capacity and coverage [32]. Users are here empowered with a new role as cooperating nodes or more properly "relays", in contrast to their traditional role as consumers. Contrarily to MIMO technology, antennas in a CN scheme do not belong to the same terminal. Thus, transmission in CN involves a preliminary coordination phase, prior to the second phase called cooperation phase [5]. The coordination phase is to decide on the best method for source to broadcast its signals to both destination and relay. In this work, we consider the broadcasting method based on orthogonal transmissions to avoid interferences. The cooperation phase is to decide to involve further signal processing and the method of forwarding them to the destination among the methods we will describe in (section II. B).

Regarding the communication model scheme, we focus on the two most popular schemes, namely one-relay scheme and dual-hop scheme.

- **One-relay scheme (fig 1.a):** This represents the simplest relaying scheme, where only one relay assists the communication between the source and the destination.
- **Dual-hop scheme (fig 1.b**): under this scheme the source exploits the presence of all potential relays to communicate with the destination. Although this scheme is more complex than one-relay scheme, it has shown better performances, especially with opportunistic relaying (OR) which will be covered in next section.



(a) one-relay scheme (b) dual-hop scheme
Figure 1. One-relay and dual-hop schemes

A. Channel transmission types

Two types of channel transmission are defined:

- **Full-duplex links:** using this transmission, relays are able to receive and transmit at the same time. However, this scheme presents a big interference problem. Thus, we consider only the second channel transmission type; i.e., half-duplex links which is the most used for cooperative wireless networks.
- **Half-duplex links:** under this link type, relay could not listen and transmit at the same time. This scheme is simple and does not show a great interference problem. However, better performances have been shown using a bidirectional communication scheme. This scheme, called also two-way relaying allows two terminals to communicate simultaneously using a shared relay. This scheme will be covered in section IV.

B. Cooperation methods

We consider the two most popular cooperation methods: amplify-and-forward (AF) and decode-and-forward (DF). For simplicity, let us explain those schemes under the one-relay scheme (fig 1.a). Under the AF method, the relay amplifies the received noisy signal from the source and then forwards it to the destination. This scheme is the simplest relaying strategy due to its low implementation cost. Under the DF method, the relay decodes the received noisy signal from the source node, re-encodes it and forwards it to the destination. DF and AF methods are also knows in literature as regenerative and non-regenerative methods. The diversity-multiplexing tradeoff of AF and DF relays has been demonstrated in [3][4][6]. However, the performance of AF protocol is limited by the noise amplification especially at low signal to noise ratio (SNR). The DF scheme is limited by the ability of the relay to correctly decode the received signal due to the source-relay channel quality [10]. To get around AF and DF limitations, many schemes have been proposed [3][15]. For instance, authors in [3] proposed that the user decides to cooperate using AF or DF methods only when fading channel shows high SNR values. Otherwise, user decides to not cooperate. However, AF-DF comparison remains an unexplored topic in [3]. In fact, authors stated that the choice depends upon architecture of the network and implementation conditions. In [11], a comparative study in terms of relay location showed that both DF and AF achieve the maximum performance when the relay is located in the middle, i.e., at the same distance from the source and the destination. However, with optimal power allocation, DF is the best for relay located close to the source while AF is the best for relay located close to destination [9]. The comparison in terms of network architecture is different and led to conclude that AF outperforms DF at low transmit power in a dual-hop relay scheme [12].

At the end of this sub-section, we would note that there are other cooperation methods, such as compress-and-forward [21] and coded cooperation [23]. However, these methods are beyond the scope of this paper.

III. COOPERATIVE ROUTING STRATEGIES

In multiple relay cooperative systems, routing strategies play a vital role not only to organize cooperation between users, but also to overcome AF and DF limitations. The classical cooperating strategy is called fixed relaying (FR), where relays use AF or DF to retransmit the signal without using channel information. More performing routing strategies have been proposed using channel conditions feedback either from the source; i.e., selective relaying (SR), or from the destination; i.e., incremental relaying (IR) [4]. In SR, the relay retransmits only when the source-relay link is reliable, meaning the feedback shows little fading problems. This scheme seems to be beneficial especially for DF, since fixed DF relaying is mainly limited by the source-relay link quality. In a cooperative system using SR strategy, DF achieves same performances as fixed AF, especially under rayleigh fading conditions [4]. However, both FR and SR suffer from an inefficient use of bandwidth. The third strategy; i.e., IR is a good solution to this problem. In fact, the IR strategy exploits limited feedback from destination and the relay retransmits only when the direct transmission is not working. Thus, the relay avoids inefficient use of the channel freedom degrees, especially for high rates. Consequently, it is beneficial to use IR strategy upon selective or fixed AF or DF.

Under the dual-hop scheme (fig1.b), the source transmits and all relays listen. Consider the case where more than one relay is able to cooperate based on channel state information (CSI). In that case, routing involving high layers is required. Different metrics were defined in order to select the best relay to cooperate, such as location, outage probability, bit error rate (BER), and end to end performance.

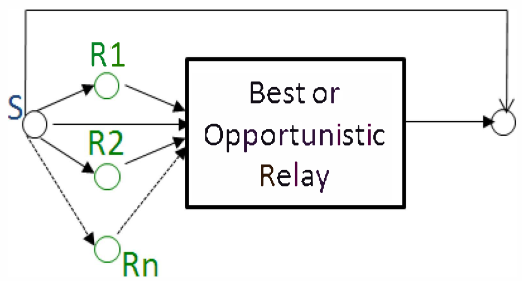


Figure 2. Opportunistic and best relaying schemes.

Among the routing strategies, we notify opportunistic relaying (OR) (fig.2), best relaying (BR) (fig.2) and partial selection (PS). In OR strategy, the relay holding the maximum of the minimum SNR between two hops is selected. The BR strategy selects the relay having the largest global received SNR. The last strategy; i.e., PS, uses only CSI of the second hop. In fact, PS selects the relay offering the best instantaneous SNR on the first-hop among relays showing a second-hop instantaneous SNR above the predefined threshold. Based on analytic performances such as outage performance, the recent developments have shown that OR strategy is the most interesting solution [13]. Indeed, cooperative relays can be useful even when they do not re-transmit, but just cooperatively listen and give priority to a single opportunistic relay. Furthermore, it has been shown in [13] that opportunistic DF relaying is the same as DF strategy using all potential relays. Moreover, the diversity-multiplexing tradeoff of OR is the same as space time coding (STC), with less complexity and only one extra time utilization [7]. Furthermore, a more developed scheme was proposed in [6] to avoid the extra time slot consumption. The performance of OR was not limited to Rayleigh or Rice fading, but also proved over m-Nakagami channel using a closed form of outage probability [8]. These performances are not the same under AF strategy. Indeed, AF remains outage-optimal in case of a single relay selection, and performs better with (equal power) multiple-relay transmissions. However a scheme with multiple selected relays is less practical for real implantations since it presents more complexity and less energy efficiency. The OR strategy is instead a practical scheme for real networks. In fact, existing cheap radios could be employed for CN under OR strategy employing simple packet level feedback [14].

IV. TWO-WAY RELAY NETWORKS

The use of half-duplex links lead to some losses in throughput compared to the direct communication. This is due do the fact that relays cannot transmit and receive at the same time. A two-way or a bidirectional communication is potentially useful to overcome this loss. A Two-way communication consists of a pair of terminals trying to exchange messages over a shared half-duplex relay. Firstly developed by Shannon in [19], this scheme was generalized to multiple pairs communicating over several half-duplex relays [20]. Furthermore, it has been shown that the conventional relay selection methods proposed for one-way or unidirectional schemes may be applied to two way communications after some modifications [27].

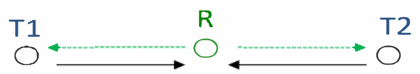


Figure 3. Two terminals (T1) and (T2) using a two-way scheme

The AF strategy is similar to that in one-way relay. However, the DF strategy is quite different and might require the concept of network coding (NC). Consequently, hybrid schemes combining NC and DF CN systems presents an interesting research area and have shown better rates and a better outage probability [22][25][26]. The performance of this hybrid schemes has also been shown upon schemes using OR. Indeed, authors in [25] have shown performances of NC over a CN using selective DF with multiple source-destination pairs, where the selected relay performs NC on the correctly decoded information from all the sources. However, in a recent work [24], it has been asked if the integration of NC is always beneficial for CN, and demonstrated that NC can affect negatively CN. This is related especially to AF schemes, where a non negligible noise at destination was identified.

V. GREEN COOPERATIVE COMMUNICATIONS

It is undeniable that cooperative communication is an energy efficient technology compared to MIMO systems. Authors of [2] have demonstrated a significant reduction in energy consumption when a cooperative link, with a relay, is used. The energy efficiency is more seen in low rates where the energy consumption gain achieves 8 compared to direct transmission [17]. For high rates, IR and NC two-way scheme are useful, to decrease the number of retransmissions. The choice of the solution to adopt depends upon network constraints and implementation conditions. The OR scheme is also a good energy-aware scheme, since cooperative relays can just listen and give priority to the selected opportunistic relay. This efficient use of relays in OR points out the energy efficiency of this scheme. This has been demonstrated especially for an uplink transmission using single carrier frequency division multiple access (SC-FDMA) and AF relays [16]. Almost research works have focused on performances of CN such as throughput, and outage probability. However, several recent works consider energetic aspect of this technology [17]. Recently, it has been shown that the cross layer approach is a good method of energy saving. Authors in [2] showed that cooperative link with a cross layer route can achieve an energy saving average over than 82% with QoS target guaranteed.

Note that even with the use of IR or two-way schemes, or the cross layer approach, energy consumption in high SNR remains still out of expectations. This is due to the fact that increased rate for a source node can comes at the price of the energy consumed by another terminal assisting it as a relay. This open issue led to think about some eventual solutions to have a green cellular network using cooperative nodes. From the base station side, it could be beneficial to use femtocells, as low power base stations [17]. In fig4, an example of a CN using one femtocell is shown. The femtocell is based on one home base station (HBS) deployed by subscribed users and connected to the operator base station with a cheap backhaul.

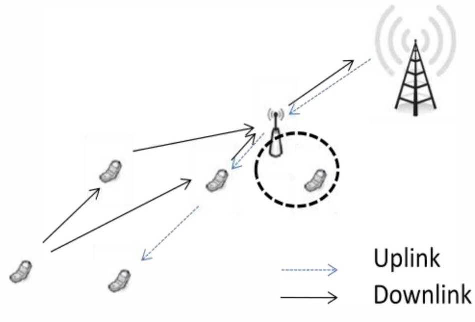


Figure 4. A green cooperative scheme using a femtocell as a relay

In fact, HBS can be used under two operating modes: open-access (OA), where all users can profit of the near HBS, and closed-access (CA) designed to subscribed users. A scheme using HBS under OA mode as a relay has shown good performances in [31]. Regarding the user's side, it is interesting that users act as relays only when they are in idle mode, achieving greater battery lifetime and more energy efficiency. Consequently, note that the solution is to have "selfish" CN where users cooperate only when they would not be very affected in terms of energy efficiency. This area still has many open questions and could be the subject of further research.

VI. CHALLENGES AND RESEARCH DIRECTIONS

A. *Hybrid scheme*

Recently, research focus on better performing schemes called hybrid schemes employing both AF and DF [28][29]. Relays can be divided into two groups: DF group including relays that are able to decode correctly and the AF group including others. A more smart method is based on SNR of received signal. Indeed, relay in [29] uses AF when SNR is greater than the average SNR of the source-relay link, and use DF in the other case. One may think of how we can realize more energy efficiency using those systems. In other terms, realize green CN based on hybrid AF-DF scheme.

B. *Quantize-and-forward*

In an AF scheme, the relay amplifies the signal received from the source and forwards it to the destination. However, as almost of networks consists of half-duplex terminals, relays have to store the received information for a while. A more realistic method is that the stored data is quantized before storage, called the quantize-and-forward (QF) [30]. This concept is recently studied over CN [30], especially concerning channel estimation. This recent promising scheme needs to be developed to become a good energy-efficient channel estimation scheme.

VII. CONCLUSION

In this work, we gave a useful digest of big results under cooperative communication technology, with comparative studies of the two most know methods amplify-and-forward (AF) and decode-and-forward (DF). As a conclusion, performances of AF and DF change when some parameters are varied, thus each of them outperforms the other in specific conditions; there is no case of dominance for the two strategies. The green trend of cooperative networks has also been shown, involving femtocell technology and a new concept of selfish users, which cooperate only when cooperation is favorable for their energy saving.

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