# Cooperative Relaying for Wireless Local Area Networks

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**Abstract.** The concept of cooperation in wireless communication networks has drawn significant attention recently from both academia and industry as it can be effective in addressing the performance limitations of wireless networks due to user mobility and the scarcity of network resources. Future wireless systems are provisioned to be highly heterogeneous and interconnected, motivating cooperative relaying to be applied to future mobile networks. This chapter describes the state of the art in this area classified in different families. The main focus is the Medium Access Control (MAC) layer design, analysis, challenges and how cooperative networks can be designed for highly dynamic networks comprising large number of moving nodes.

**Keywords:** Wireless networks · Cooperative diversity · MAC protocols · Wireless resource management

## 1 Introduction

The growth of wireless networks in the last decades is motivated by their ability of providing communication anywhere and anytime. Because of the importance of this aspect on the modern society, a high proliferation of wireless services and devices, such as mobile communications, WiFi or cordless phones has emerged. This increasing trend is the main motivating factor for development of novel wireless technologies for reliable and cost efficient transmissions, among the cooperative networks.

Cooperative networking can find its niche in diverse applications, from increasing capacity or extending coverage in cellular networks, to enhancing transmission reliability and network throughput in Wireless Local Area Networks (WLANs); from offering more stable links in volatile and dynamic propagation conditions in vehicular communications, to saving energy and extending network lifetime in wireless Ad-hoc networks.

While cooperative networking has a rich theoretical history in the literature, efforts to actually implement cooperative systems have been much more limited. Cooperative networking refers to the sharing of resources and the realization of distributed protocols among multiple nodes in a network. Cooperation in communications is achieved in various ways such as cooperation by relay to forward


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source's data, cooperation among nodes in a cluster and cooperation between source and relay to transmit together to achieve diversity. There are numerous cooperative techniques for physical layer (cooperative communications) but to get the most out of the system it requires the support of MAC layer. Cooperation can be incorporated at MAC layer. This is achieved by cooperative MAC protocols (cooperative relaying).

Over the past decade, Internet access became essentially wireless, with 802.11 technologies providing a low cost broadband support for a flexible and easy deployment. However, channel conditions in wireless networks are subjected to interference and fading, decreasing the overall network performance [6]. Fading effects in a wireless environment can be classified as either fast or slow [29]. While fast fading can be mitigated by having the source retransmitting frames, slow fading, caused by obstruction of the main signal path, makes retransmission useless, since periods of low signal power last for the entire duration of the transmission. Moreover, the interference from other transmitters also affects the communication quality severely. Because of the constant change of the environment and the mobility of the terminals (transmitter or receiver or both) the signal is scattered over many objects in the surroundings. Such channel impairments can be mitigated by exploiting cooperative diversity [22].

In what concerns WLANs, they suffer among other issues from scarcity of bandwidth, which limits the network throughput and requires efficient utilization of this valuable resource. One example of these issues is from the existing WLANs, where the performance of the whole system degrades greatly once low data-rate nodes become dominant. Cooperative relaying may mitigate this problem by allowing low data-rate devices to finish their transmission faster by using a pair of wireless links (relays) that provide better wireless conditions than the direct channel to the destination. High data-rate stations have a high incentive to cooperate by relaying messages from low data-rate stations, since such cooperation may increase their probability to grab the wireless channel faster.

This chapter is organized as follows: Sect. 2 describes cooperative networking in general. In Sect. 3 we explain cooperative relaying and provides analysis of prior art. Section 4 discusses open research issues. Finally Sect. 5 presents the summary.

## 2 Cooperative Networking

Extensive research has been done to achieve better throughput and reliability in wireless networks, being mostly focused on MIMO systems. Recently, cooperative networking techniques have been investigated to increase the performance of wireless systems by using the diversity created by different single antenna devices. In cooperative networking, intermediate nodes (relays) help source-destination transmission forming dual-hop communication. This unique solution provides a response to the majority of the concerns in an efficient way. However, most of the cooperative solutions rely upon Channel State Information (CSI), explicit notifications and additional broadcast information, which incur overheads and complexity.

Current cooperative networking proposals are characterized by their limited focus. Most of the research being done focuses on the physical layer, by exploiting spatial diversity to increase system reliability of cellular networks [22]. In its simplest version, a terminal trying to reach a base station is assisted by a relay terminal. Due to the broadcast nature of the wireless channel, the relay can overhear the sender's transmission, decode it, and, if correctly received, repeat it. The base station combines these two copies of the same transmission, reducing the packet error-rate. This results in larger reliability gains than simple retransmission due to the exploitation of spatial diversity, in addition to time diversity.

From an implementation perspective, cooperative systems can be classified accordingly to different ways of utilizing relays, as shown in taxonomy given in Fig. 1. Cooperative networking can be designed with physical layer approaches (cooperative communications) or with higher layers (relay stages or cooperative relaying). The main focus of this chapter is cooperation at MAC layer (relaying). Since considerable research has been done on physical layer we explain cooperative communication in the following.

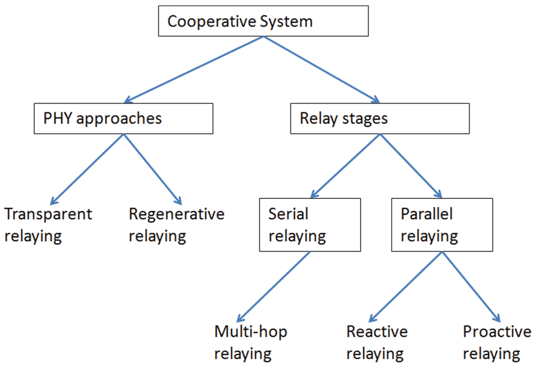


**Fig. 1.** Classification of cooperative systems.

## 2.1 Cooperative Communications

The basic ideas behind cooperative communication can be traced back to the groundbreaking work of Cover and El Gamal [5] on the information theoretic properties of the relay channel. The transmission of different copies of the same signal from different locations, generating spatial diversity allows the destination to get independently faded versions of the signal that can be combined to obtain an error-free signal.

In a cooperative communication system, each wireless user is assumed to transmit its own data as well as acting as a relay for another user. Figure 2 shows single antenna devices able to act as relays of each other by forwarding some version of "overheard" data along with its own data. Since the fading channels of two different devices are statistically independent, this generates spatial diversity.

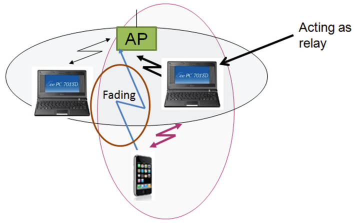


**Fig. 2.** Mitigating fading effects by relaying.

At PHY layer, cooperative diversity is usually modeled as a MIMO system. Some designs aim at full diversity: For N-antenna virtual array, the outage probability decreases asymptotically with $SNR^{-N}$. Other designs set their performance criteria according to the well-known trade-off between diversity and multiplexing gain: for N-antenna array, the multiplexing gain r and the diversity gain d, as defined in [2], are complementary and upper bounded by $d(r) \leq N + 1 - r$.

There are two main categories of PHY relaying approaches, i.e., transparent and regenerative relaying (c.f. Fig. 1). In transparent relaying the relay does not decode data from the signal received from the direct link; examples are Amplify and Forward (AF) and Store and Forward (SF) [25]. In regenerative relaying, relays decode received packets, recode the information and forward it to the destination; example is Decode and Forward (DF) [17].

### 2.2 Cooperative Relaying

The choice of relay stages is very important, because relays can operate either in series or in parallel (see taxonomy in Fig. 1). On the one hand, increasing the number of serial relaying nodes reduces the path-loss along each transmission hop. On the other hand, increasing the number of parallel relaying nodes increases potential diversity gains. Parallel relaying is implemented at PHY/MAC layers (single-hop), while serial relaying can be implemented with combination of both MAC and routing layers (multi-hop). There are two types of approaches for implementing parallel relaying, i.e., proactive and reactive relaying, which are explained in Sect. 3. In case of multi-hop relaying, the relays help more than one transmission requiring routing information.

Recently, the exploitation of link-layer diversity (cooperative relaying) in cellular and multi-hop wireless networks has attracted considerable research attention. The first attempts have been done in cellular networks by devising cooperative relaying systems with single-hop relays: the MAC allows the usage of relays that can help the source-destination transmission with one retransmission. Cellular networks generally suffer from three fundamental problems: interference, limited coverage and capacity shortage. To alleviate these problems, it is proposed that communication between a Base Station (BS) and a Mobile Station (MS) can be performed not only directly but also (or exclusively) via a Relay Station (RS), as shown in Fig. 3. Such a deployment can yield significant gains, which can boost performance of users that are capacity-limited (bottom-left cell in Fig. 3); coverage-limited (top-left cell) or interference-limited (middle-right cell) [24]. The case of multi-hop networks is more complex since such networks are still a challenging target for the design of MAC protocols. The challenge increases when terminals or objects move, resulting in time-selective fading channels.

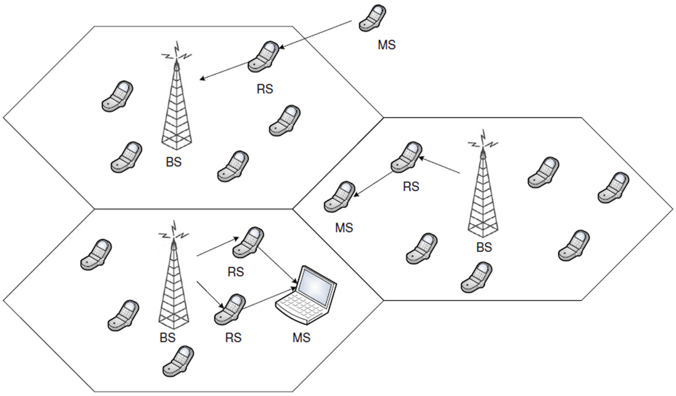


**Fig. 3.** Cooperative relaying in cellular networks.

Relaying can benefit not only the nodes involved, but the whole network in many different aspects. Many MAC protocols have introduced rate adaptation to overcome adverse channel conditions. Due to its distance from the AP, a wireless node can observe a bad channel as compared to other nodes that are closer to the AP, leading to the use of 802.11 rate adaptation schemes. Figure 4 illustrates the transmission characteristics of wireless nodes, as a result of the rate adaptation functionality of 802.11: nodes closer to the AP transmit at high data-rates, while nodes far away from the AP decrease their data-rate after detecting missing frames. Figure 4 also shows the role that relaying may have increasing the performance of the overall wireless network, helping low data-rate nodes to release the wireless medium sooner, helping high data-rate nodes to keep the desirable performance, and the network to achieve a good overall capacity. In this case the total transmission time for the dual-hop transmission is smaller than that of the direct transmission, cooperation readily outperforms the legacy direct transmission, in terms of both throughput and delay perceived by the source S.

Cooperative transmissions require unique features from MAC, which should be distributed and cooperative for a multipoint-to-multipoint environment. There are noteworthy issues that must be taken into account while designing cooperative diversity MAC: relay selection, cooperation decision, cooperation notification and cooperative transmission design [16].

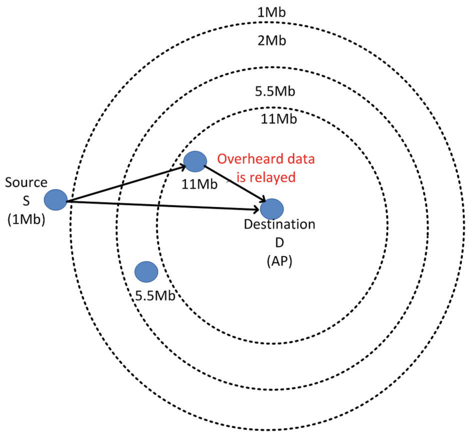


**Fig. 4.** Helping low data-rate nodes by cooperative relaying.

In what concerns the relay selection, there is broad horizon of selection parameters, mostly based on channel information. Such parameters are complex and unstable. Moreover, the selected relay may be the best for the transmission pair that is helped but may be the worst in terms of the overall network capacity. Therefore, there is need to design hybrid techniques that allow simultaneous optimization over several parameter domains. In what concerns the relay failure issues, there are many situations when the relay may fail or when the poor relay is selected.

In what concerns the cooperative transmission design: the first issue is the relay discovery. Most of the protocols require an image of neighborhood implemented in a table, normally based on channel qualities. Most of the protocols use periodic broadcast for this purpose. Such periodic broadcast needs to be very frequent to cope with network variations, in any case it limits the performance of cooperative system. Another issue is coordination with relays; most of the protocols use additional control messages for relay management in a centralized manner. Such explicit notifications affect the gain of cooperation. Yet, in some scenarios, it is infeasible to have such a centralized coordination [23]. The challenge is how to identify the cooperation capabilities of the possible relays in a distributed manner.

### 2.3 Potential Benefits and Limitations of Cooperation

Spatial diversity is the main advantage provided by cooperative communications. This property can be expressed in terms of increased diversity order [17]. As a simple example (c.f. Fig. 5), if the channel quality between source node S and destination node D degrades severely, a direct transmission between these two nodes may experience an error, which in turn leads to retransmissions. Alternatively, S-D can exploit spatial diversity by having a relay R1 overhear the transmissions and forward the frame to D. The source S may also use another relay R2 for helping in forwarding the information, or use both relays together. So, compared with direct transmission, the cooperative approach enjoys a higher successful transmission probability. Therefore, cooperative communications have the ability to mitigate the effects of shadow fading better than MIMO since, unlike MIMO, antenna elements of a cooperative virtual antenna array are separated in space and experience different shadow fading.

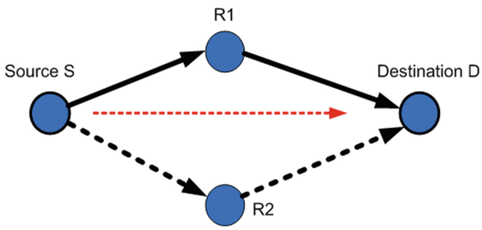


**Fig. 5.** Increasing diversity order.

Cooperative communications also ease the roll-out of a system that has no infrastructure available prior to deployment. For instance, in disaster areas, relaying can be used to facilitate communications even if existing communication systems such as cellular systems are out of order.

Due to relaying, a node can reach to AP even via a relay, extending range and avoiding handovers. In the case of pedestrian mobile networks, mobile devices may perform pendular movements at the edge of an AP with high probability, where devices will spend too much time performing handovers between neighbor APs, leading to performance degradation. To avoid such situation, another device can act as relay allowing the moving node to stay always associated to the same AP, avoiding handovers (c.f. Fig. 6).

The limitations of cooperation can be as significant as the advantages. Therefore, cooperative network design needs to be performed carefully in order to

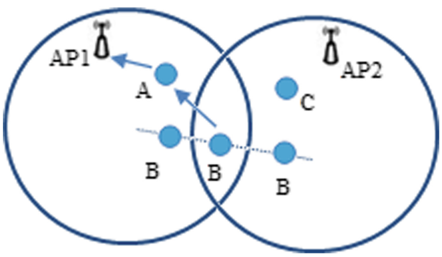


**Fig. 6.** Avoiding unwanted handovers.

achieve the full gains of cooperation and at the same time to ensure that cooperation does not cause degradation of system performance. As cooperative transmissions involve additional transmissions via relays, therefore, it always introduces some additional overhead and interference as compared to non-cooperative transmission. Thus, the benefits brought by cooperation can be diminished if relaying mechanism is not cleverly designed. There are many other constrains such as concurrent transmissions and mobility etc., which can affect the performance of cooperative networks [11]. Therefore, the implementation of cooperative relaying implies additional design constraints so that cooperative transmissions do not interfere with other direct transmissions. In cooperative systems, not only the traffic of different sources but also the relayed traffic needs to be scheduled. Thus, more sophisticated scheduling is required.

## 3 Analysis of Cooperative Relaying

Both the telecommunications operators and the end-users would reject a wireless network with cooperative diversity if the PHY layer requires manual configuration. So the role of the MAC layer is essential. In addition to cooperation control, the MAC layer must support error recovery, dynamic optimization, mobility support, relay selection and cooperation decision [11].

Cooperative relaying at MAC layer comprises two phases: relay selection and cooperative transmission. In the first phase a relay or group of relays are selected, while in the latter phase the transmission via relay(s) takes place. The relays can be selected either by source (source-based), destination (destination-based), or by the relay itself (relay-based). At MAC layer we can classify cooperative protocols as proactive and reactive. In the proactive protocols, the cooperation is based on some pre-arranged optimal or random format. In proactive relaying the source, destination or potential relay replaces the slow direct transmission with a fast, one-hop relayed transmission, aiming to improve the data-rate [27]. These protocols are time critical and incur higher overheads. They require frequent information exchange for timely delivery of data. Whereas, in reactive protocols, the cooperation is initiated with a Negative ACK (NACK) due to collision or error [16]. Reactive protocols are appropriate for applications that are delay tolerant and incur lower overhead.

In what concerns the 802.11 MAC, Fig. 7 shows a basic 802.11b system where nodes have different transmission rates at different distance from AP. Cooperation at MAC enables source node to find a relay node and transmit via that relay. The relay node must be within the cooperation area to rectify the impact of low rate nodes. In Fig. 7, $R_{11}$ is the distance from AP to transmit at 11 Mbps, while $r_{11}$ is the distance from a source node to transmit at 11 Mbps and d is the distance from source to AP. The cooperation area is the intersection of two circles ($R_{11}$ and $r_{11}$), defined as follows [31]:

$$CooperationArea = r^2 cos^{-1}(\frac{d^2 + r^2 + R^2}{2dR}) + R^2 cos^{-1}(\frac{d^2 + R^2 + r^2}{2dR}) - \frac{1}{2}\sqrt{(-d + r + R)(d + r - R)(d - r + R)(d + r + R)} \quad (1)$$

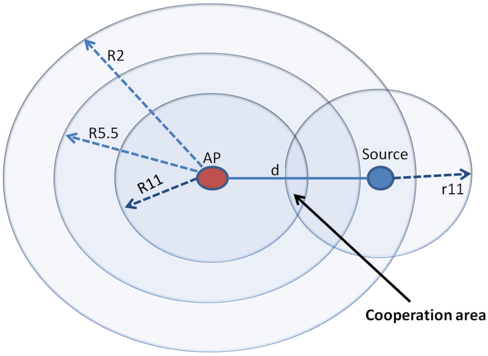


**Fig. 7.** Sample 802.11b network.

Such cooperation may also bring some extra overhead, mainly due to the high interference levels. In this case, the interference caused by relay transmissions will be, in the best case, directly proportional to the relay degree (i.e., number of neighbors). The situation may get worse in the presence of multi-hop networks, where the usage of hop-by-hop cooperation will increase the network cost (e.g., number of transmissions).

### 3.1 Taxonomy

As discussed, cooperative MAC can be classified as proactive and reactive. Proactive protocols work if the direct link between source and destination exists. Whereas, reactive protocols are initiated when the direct link fails. Hence, proactive relaying aims to increase the throughput of wireless networks while reactive relaying aims to decrease degradation by avoiding retransmissions. Proactive relaying can be further split into broadcast-based protocols, and opportunistic protocols, as illustrated in Fig. 8.

Broadcast-based protocols represent a relatively simple strategy by utilizing the broadcasting nature of the wireless medium. While broadcast-based protocols offer more control due to its centralized nature, opportunistic relaying is the one where nodes can independently make cooperation within certain time constraint under some conditions. Such relaying does not require extra control messages. The reactive protocols can be further classified as broadcast-based protocols, opportunistic protocols, and multi-hop protocols.

From the classification of cooperative MAC protocols shown in Fig. 8, it is apparent that most of the literature focuses on the broadcast-based protocols due to their easy implementation and backward compatibility. Multiple relay broadcast protocols, though not very well researched, require better coordination among the multiple relays, thus increasing the complexity. In the next section, we provide details of some existing protocols.

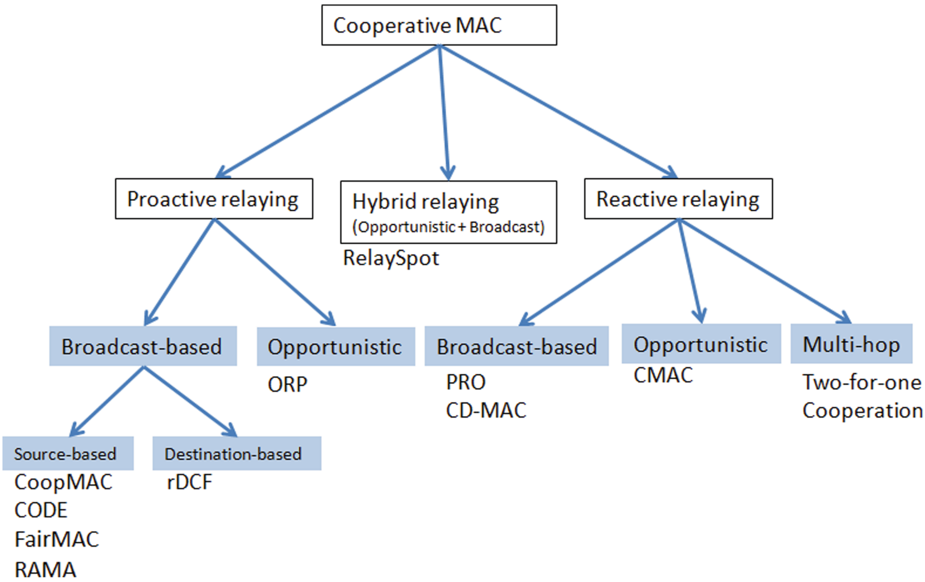


**Fig. 8.** Cooperative MAC classifications.

### 3.2 Cooperative Relaying Protocols

In general, both proactive and reactive approaches have their pros and cons, which greatly depends on individual mechanisms. Therefore, it is important to study individual protocols irrespective of their class. Following we describe cooperative MAC protocols grouped into families as mentioned in Fig. 8.

#### 3.2.1 Broadcast-Based Protocols

In this type of protocols normally sources or destination or potential relays maintain a table which is updated periodically based on broadcasting. The limitations of this sub-class are periodic broadcasts, maintenance of table and extra control overhead which effect the performance. These protocols can be proactive as well as reactive.

Relay-enabled DCF (rDCF) protocol was developed by Zhu and Cao [32] based on Distributed coordination function (DCF), where a high data-rate dual-hop path is used instead of a low data-rate direct path between the source and destination. For a given flow between a pair of sender and receiver, with the measured channel quality, if a relay finds that the data can be transmitted faster, it adds the identity (e.g., MAC address) of the sender and the receiver into its willing list. Periodically, each relay node advertises its willing list to its one-hop neighbors, from where the source picks a relay. rDCF proposed a triangular handshake mechanism for source-relay-destination transmission. First source node send Relay Request To Send (RRTS). After reception of RRTS, the relay and destination can measure the quality of the channel. The relay then sends another RRTS to destination with a piggybacked measurement information of source-relay channel. The destination measures the quality of relay-destination channel and sends Relay Clear To Send (RCTS) to the source including rate information of source-relay and relay-destination channels.

However, rDCF is only suitable if the frame size is larger than 400 bytes. Otherwise, rDCF gives worse performance when compared to DCF because of its relatively higher overhead. Another drawback of rDCF is that when the relay is forwarding the data frame, it does not include the duration field, which increases the probability of collisions.

In Cooperative MAC (CoopMAC) [19], the source uses an intermediate node (relay) that experiences relatively good channel with the source and the destination. Instead of sending frames directly to the destination at a low transmission rate, the source makes use of a dual-hop high data-rate path to the destination via a relay. Based on the CSI broadcasted by potential helpers, sources update a local table (cooptable) used to select the best relay for each transmission. CoopMAC performs 3-way handshakes, which require the selected relay to send a control message Helper ready To Select (HTS) between RTS and CTS messages. First, source sends a Cooperative RTS (CoopRTS) message with the selected relay ID. If the selected relay is willing to cooperate, it then sends an HTS message back to source. If destination overhears an HTS message, it transmits a CTS. After receiving CTS, the source sends the data frame to destination via selected relay.

The solution CODE [30] uses two relays to form the virtual antenna array and additionally makes use of the physical layer network coding technique to achieve the gain. For bidirectional traffic between the source and destination, network coding is applied at the relay node to increase system throughput. In CODE all nodes overhear RTS/CTS frames, and if they find that they can transmit data faster than the source, they add the identity of source and destination to their willingness list. Once the source finds its address in the willing list of relay(s), it adds those relay(s) into its cooperation table.

FairMAC, presented in [3], concerns about the energy cost of cooperation, since there is a trade-off between energy per transmitted bit and achieved throughput. FairMAC, allows the selection of the desired cooperation factor, which represents the limit of frames to be relayed for each own frame transmitted.

Relay-Aided Medium Access (RAMA) [33] protocol proposed the relay-based transmission to improve the performance and reduce the transmission time. RAMA consists of two parts: first is the invitation part which is used to configure the relay and second is the transmission part. RAMA allows only one relay in a transmission and in case of collision of the invitation, the relay node does not need to transmit and wait for the next transmission.

In Opportunistic Retransmission Protocol (PRO) [20] a potential relay may retransmit on behalf of a source when it detects a failed transmission. In PRO the potential relays broadcast their channel information allowing other relays to set their priority level. Based on priority level relays then select their contention window in order to increase chances of retransmission. Thus, each node maintains a table to keep the channel information (priority levels) of neighbors. Such maintenance operation consumes power, resources and affects the network capacity. Another problem is the occurrence of unnecessary retransmissions, if eligible relays do not overhear an ACK frame of successful transmission.

In Cooperative Diversity MAC (CD-MAC) [21], when the direct link fails, retransmission takes place via a relay. First the source and its preselected relay send a Cooperative RTS (CRTS) to the destination. Destination and its preselected relay respond with Cooperative CTS (CCTS). After receiving a CCTS, the source and its relay cooperatively transmit the data frame to destination and its relay. After receiving data frame, destination and its relay cooperatively transmit Cooperative ACK (CACK). There is high overhead of control frames as source, destination and relay repeat the whole control and data frames in different codes.

### 3.2.2 Opportunistic Protocols

These protocols do not maintain tables, therefore, a relay can forward data opportunistically without prior coordination.

Opportunistic Relaying Protocol (ORP) [7] is a relaying solution where nodes are able to increase their effective transmission rate by using dual-hop high datarate links. ORP does not rely on the RSSI for relay selection. It opportunistically makes a frame available for relaying and all nodes try to forward that frame within the time constraint. However, the relays back-off every time they forward. Another drawback of this approach is that the source does not know about the availability of a relay, so it does not know rates of source-relay and relay-destination channels.

Cooperative Communication MAC (CMAC) [28] introduces spatial diversity via user cooperation. In case of CMAC each node stores the source node data frame. If no ACK is overheard the relay forwards the stored data frame on behalf of source. Due to usage of additional queues and channel estimations, CMAC faces the challenges of overhead.

### 3.2.3 Multi-hop Protocols

In the two-for-one cooperation approach [18], cross layering is used to provide routing information to the MAC layer in order to allow simultaneous relaying over two hops. The two-for-one cooperation is particularly suited to achieve high diversity with little bandwidth expansion. At a given Packet-Error-Rate

(PER), the gain of the two-for-one approach can be used to reduce transmit power, improving network capacity. However, it presents the problem of unnecessary transmissions. Another multi-hop relaying approach is proposed by H. Adam el al. [1]. It exploits synergy between single-hop relays (helping only one transmission) and multi-hop relays (helping two transmissions simultaneously) taking into account information provided by a link-state routing protocol. The used scenario excludes a potential (even if weak) direct link between source and destination. Still, as occurred with the proposal presented by H. Lichte et al. [18], the presented solution depends on a global topological view of the network provided by the routing protocol. Moreover, it is not justified why is the usage of a single-hop relay over the destination link, and not the source link, the best choice: considering that a bad channel from source to relay will jeopardize the effort applied from the relay to the destination, it could make sense to have the single-hop relay helping the source transmission.

### 3.2.4 Hybrid Relaying

Hybrid relaying improves the performance of wireless networks by an efficient combination of proactive (broadcast-based and opportunistic) and reactive relaying [10,16]. With hybrid approaches such as RelaySpot [11,12] a relay is chosen for a cooperative transmission opportunistically, without any broadcast overhead. The relay is selected cooperatively without maintaining any table. The cooperative transmission takes place without any further contention or handshake messages. Poor relay selection and relay failures are adjusted dynamically without expecting the relay selection procedure. Therefore, we conclude that such hybrid behavior has potential to rectify drawbacks that occur in prior art, in what concern broadcast-based and opportunistic relaying.

RelaySpot comprises four building blocks: Opportunistic relay selection, cooperative relay scheduling, chain relaying and cooperative relay switching, as explained below:

- Opportunistic relay selection: Intermediate nodes may take the opportunity to relay in the presence of local favorable conditions (e.g., no concurrent traffic) after detecting one of two situations: (i) a broken communication; (ii) a poor direct transmission, by analyzing the wireless data-rate;
- Cooperative relay scheduling: The destination node will be able to cooperate in the relay selection procedure by electing one over several potential relays, based on the quality of the relays. In RelaySpot, the cooperative scheduling mechanism can create diversity higher than two, by selecting more than one relay.
- Relay switching: This functionality aims to compensate unsuccessful relay transmissions. Relay selection faces several optimization problems that are difficult to solve, which means that the best relay may be difficult to find by the destination based on the set of potential relays. Hence, aiming to be suitable for dynamic scenarios, RelaySpot allows the destination to select the best possible relaying opportunity even if not the optimal one (e.g., in terms

of CSI). In order to keep a good quality level in case of a bad decision from the destination, RelaySpot allows potential relays to take over the control of the relay operation, by asking the source to switch the relay for the subsequent data frames.

RelaySpot can also be extended to multi-hop [14] by using chain relaying. With the usage of chain relaying, the relaying will be triggered over relay-destination link. This leading to serial relaying, i.e., multi-hop relaying. Such relaying can be beneficial only if the relay is aware of next hop. Hence, the relay can forward the frame to next hop. This way complexity of hop-by-hop relaying can be mitigated. In chain relaying, the destination node may receive more than two independent signals of the same frame (e.g., directly via the source, via the intermediary node identified by the routing protocol and via the selected relay node). This extra spatial diversity increases robustness and performance. However, the price to pay is the extra network overhead to transmit redundant information, and the cross layering needed to collect routing information, which may not be updated with the frequency required to react in environments with mobile devices.

### 3.3 Cooperative Relaying Functionalities

All proposed solutions have their benefits and drawbacks, and none of them is completely superior to the others. In this section, we identify the common functionalities that the protocols follow. In [4] the cooperation process is proposed into four phase process, which are (i) discovery and request, (ii) negotiation, (iii) transaction, and (iv) evaluation and feedback. The first phase is cooperation initiation, negotiation refers to conditions, transaction refers to rewards while last phase refers to quality of experience.

From the analysis of cooperative MAC protocols, it is clear that cooperation brings benefits to the operation of wireless networks but its usage over large networks may introduce undesirable levels of overhead and complexity. The complexity is mainly due to the number of channel estimations, while the overhead is mainly due to the multiple copies of data messages and feedback signals. The complexity may increase due to the number of times relay transmission fail. Moreover, waiting for optimal relay to assist one transmission degrades the overall performance of the network and decreases its capacity.

Before investigating suitable solutions, we need to answer the following questions: (i) when do we really need to use cooperative relaying? (ii) how to coordinate? and (iii) whom to cooperate with? For cooperation to be triggered, we need to compare the transmission throughput achieved by proposals that take advantage of spatial diversity (cooperative relaying) over the direct link. The coordination between cooperative nodes can be done implicitly or with minimum feedback. To devise a cooperative relay solution able to achieve a good balance between interference and transmission throughput it is important to start by investigating the choice of relay selection parameters, as well as consideration of evaluation scenarios. The performance of cooperative relaying greatly depends upon the used scenario, on the other hand it gives opportunity to analyze various aspects, such as concurrent transmissions.

As mentioned before, cooperative relaying comprises of relay selection and cooperative transmission as explained below.

### 3.3.1 Relay Selection

With cooperative relaying, the relay selection process requires special attention, since it has a strong impact on network and transmission performance. Independently of operating only at the link layer or in combination with cooperative diversity schemes at the physical layer, the performance of cooperative relaying strongly depends upon the efficiency of the process used to select one or more relays.

It is clear that the major challenge in cooperative relaying is to select a node, or set of nodes, which can effectively improve data transmission. Although most of the current schemes envision operation under a single AP, relay selection mechanisms should be carefully defined thinking about large networks. A reason is the impact that one relay may have on concurrent transmissions.

The first aspect that needs to be considered when analyzing relay selection mechanisms is related to the selection criteria. The most common in the literature are: CSI, SNR and Bit-Error-Rate (BER). Since such parameters need to be measured in both sender-relay and relay-receiver links, relay selection may require the exchange of meta-data, usually transported within RTS and CTS frames.

The second aspect is the impact on the overall network. Normally, relays are selected to improve the performance of a source-destination communication [19], but no consideration is taken about the impact over the overall network capacity. Such selfish behavior may lead to higher probability of transmission blocking and interference.

In what concerns the level of interaction, relay selection mechanisms has two categories: *Distributed or Opportunistic Relay Selection* (ORS) and *Centralized or Cooperative Relay Selection* (CRS) [9].

With ORS each potential relay decides about forwarding frames, based on the information that it has about the network. This may lead to a high probability of selecting more than one relay whose transmissions end up competing for the wireless medium. Such mechanisms present a high probability of collisions.

While CRS process encompasses two phases: In the first phase relays broadcast willingness to relay and local information that will be useful for relay selection. Such information is overheard by other nodes, which can then participate in the selection of one or more relays in a second phase. One drawback of cooperative relay selection is the potential lack of synchronization between the two operational phases. As a consequence, relaying may not occur if a node that was selected as relay is not available when transmission occurs, due to mobility or lack of energy. Another problem with this class are the periodic broadcast and extra handshaking signals which can limit the efficiency.

### 3.3.2 Cooperative Transmission

Since the wireless channel condition varies from time to time, a source node may not always need help from relay nodes. Therefore, the first issue is when cooperative transmissions should be enabled. To initiate cooperation, implicit or explicit notifications are required, such signaling overhead should be considered in making a decision on whether or not to use cooperation. It is necessary to compare the non-cooperative scenario with the cooperative options in terms of proficiency and cost.

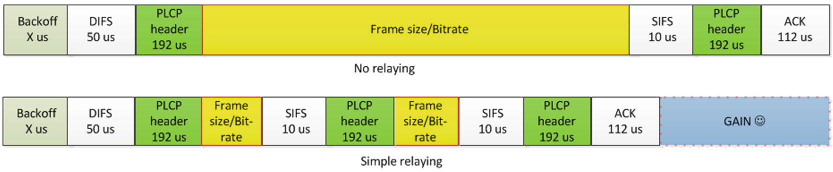


**Fig. 9.** Simple relaying gain.

Relaying involves transmission of two data frames separated in time and space; therefore, it introduces overhead, which increases due to additional control messages. However, significant gain can be achieved by a careful selection of reservation duration and back-off timings. Figure 9 shows the gain of cooperative relaying in 802.11 (when there is no extra control message). As seen in Fig. 9 a regular data transmission with acknowledgment takes longer to send data when compared to the data transmission based on a relay protocol. With a relay protocol the relatively slow nodes would reserve the channel for a duration of *frame_size/(fast_data_rate=11Mbps)* instead of *frame_size/(slow_data_rate=1Mbps)* and the other nodes will benefit from this with higher probability of accessing the channel.

Irrespective of relay selection mechanism, one of the important issue is relay management. Most cooperative MAC protocols require an image of their surroundings, typically implemented through a neighbor table, possibly featuring estimates of link qualities and cooperation possibilities. The neighbors discovery mechanism, either passive (overhearing) or active (polling), leads to creation of willing list. Unfortunately, even if a relay is being able to cooperate, it might refuse to do so due to changes in network conditions etc. Therefore, the relaying protocol needs to track the network changes and relying over stable parameters.

## 4 Open Research Issues

From the realized analysis we make two strong observations: (i) all approaches assume static devices, small networks with high probability or a direct source-destination link usage, and the need to use always one relay; (ii) there is no single approach that presents good behavior in terms of both transmission and network capacity. These observations lead to the identification of two important research issues: (i) achieve a good balance between interference and transmission throughput; (ii) improve the capacity of large mobile networks.

To limit communication overhead, especially in large networks, it is important to investigate the intelligent usage of thresholds over local variables, since they can filter out poor relays as well as unwanted transmissions.

In what concern the parameters themselves, majority of previous work uses local variables such as SNR, BER, CSI (with the exception of RelaySpot). Since these are very unstable parameters, we propose the usage of less volatile parameters, namely interference level, and stability. Interference level provides an indication about the probability of resource blockage. Node degree and queuing delay are examples of measures that can be used to estimate the interference level, without using physical layer measurements [13,15]. Another parameter is stability, which has not been considered by most of the prior work. Stability is the measure of mobility, and can be obtained by estimating pause time or link duration. The more stable (less mobile) nodes are, the more suitable are they to operate as relays. So, this investigation leads to the conclusion that the most suitable parameters for large scale networks are devised by using local parameters characterized by being less volatile than the usual SNR, BER and CSI parameters.

Apart from stability and interference, there are other issues we identified, such as usage of multiple relays, protocol overhead, energy efficiency and multi-hop relaying.

With the exception of CODE and RelaySpot, all analyzed proposals rely upon the usage of one relay to help one transmission. However, the advantage of selecting more than one relay to help the same transmission (even if in different time frames), should be further investigated. The presence of multiple relays over the same link requires the analysis of the gains that physical layer coding offers in comparison to a full link layer approach.

While relaying in wireless communication networks can improve network performance, such protocols can incur a considerable overhead. This overhead includes signaling and network control overhead for cooperative transmission, relay selection and coordination, additional required resources such as radio bandwidth for relay transmission. Another form of cooperation overhead is the incurred delay of the whole communication process which includes the time consumed in selecting the relays and establishing the cooperative paths. Finally, this cooperation overhead also includes the overall added complexity to the networking process. The cooperation overhead affects the decision of whether or not cooperation should proceed. In literature, only signaling overhead for relay selection and coordination is considered in the decision process [26]. Other forms of cooperation overhead should be appropriately modeled and taken into account in the cooperation decision.

Introduction of power control and rate adaptation in relay based MAC protocols to increase spatial reuse, reduce interference and improve energy efficiency. Most of the relay selection is based on the available rates only and may result in reuse of the same relay again and again. This would drain the energy of this relay thus lose a potential cooperative partner. This requires the design of efficient and fair relay selection algorithms that can select the potential relays based on energy consumption and network throughput together. This would result in network lifetime maximization and fairness.

Although significant efforts have been made on the study of cooperative systems, there has been very little work on cooperative routing. Some of the relevant studies focus on the theoretical analysis on routing and cooperative diversity [8]. With regard to the implementation of a cooperative routing protocol, the theoretical optimal route is too complicated and therefore unsuitable for the current status of ad-hoc and sensor networks.

An alternative way to extend cooperative relaying to the routing layer (multiple-hops between source and destination), it would be beneficial to further exploit the selection of relays that can help over multiple hops simultaneously (multi-hop relay selection), namely trying to identify the most suitable relay/hops ratio. However, current multi-hop relay selection approaches rely on link-state routing information, which means that they are not suitable for scenarios with intermittent connectivity. Hence the investigation of the usage of multi-hop relay selection in the presence of more opportunistic routing is an important research topic.

## 5 Summary

Cooperative Networking is a very active research area with promising developments. The MAC layer is the most important for a cooperative networking (relaying), as this relies on identifying alternative ways of transmission within a networked context. Therefore, for cooperation to be implemented at the link layer, link layer needs to be changed in order to allow indirect transmission between source and destination.

The development of cooperative relaying raises several research issues, including the performance impact on the relay itself, and on the overall network, leading to a potential decrease in network capacity and transmission fairness. Such research issues can be influenced not only by fading, but also by other performance constrains in wireless networks, such as the distance at which wireless nodes are from APs, as well as the mobility of such nodes.

This chapter discussed the topic of cooperative networking with emphasis on cooperative relaying. We proposed a taxonomy for cooperative systems comprising of PHY approaches and relaying stages. We further provided a taxonomy for cooperative relaying (MAC). This chapter has addressed a number of significant issues such as analysis and performance of relay based MAC protocols.

The advantage of cooperative relaying is possible if MAC layer is cleverly designed. Most relaying protocols rely on handshake messages, modifying the DCF of 802.11 MAC, either in cooperative or opportunistic way. Relaying protocols are expected to minimize signaling exchange, remove estimation of channel conditions, and improve the utilization of spatial diversity, minimizing outage and increasing reliability even in mobile environments.

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