

Survey on cooperative medium access control protocols

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Abstract: In the past decade, there has been ever-increasing research attention to user cooperation in the wireless communication networks. The unique challenges of wireless networks such as channel fading and variation can be addressed well by taking advantage of relaying among cooperating mobile terminals. There are many studies on cooperative communications at the physical layer to exploit spatial diversity for improving channel capacity. In recent years, user cooperation from the perspective of the medium access control (MAC) layer becomes a promising new research area. In this study, the authors present a comprehensive survey on the mainstream cooperative MAC protocols in the literature. Focusing on the contention-based solutions, the authors classify the well-known proposals according to how they address two fundamental questions for user cooperation, that is, when to cooperate and whom to cooperate with. In addition to analysing the essential features of classic cooperative MAC protocols, the authors also discuss the major research challenges and project future research directions for MAC-layer cooperation.

1 Introduction

The wireless network offers the benefits of ubiquitous connectivity and mobile access. However, with more randomness and less stability, the wireless network still cannot achieve the same reliability and high data rate as its wired counterpart, because of its unique features such as fading, shadowing and path loss. To address these problems, many techniques have been proposed, among which multiple-input and multiple-output (MIMO) [1, 2] is one of the most promising solutions. Unfortunately, it is not feasible to equip palm-sized and battery-powered mobile terminals with multiple receiving and transmitting antennas [2–5], which limits the application of MIMO technique.

Given the broadcast nature of the wireless medium, data transmission from a source terminal can be overheard by other terminals. As a result, it is possible for the source to cooperate with these overhearing terminals (also known as helpers) to form a virtual MIMO system. This user cooperation can provide many benefits, including system throughput improvement, interference mitigation and seamless service provision [6]. During the past decade, there are many studies on the cooperation at the physical layer [3, 7–10]. Many physical-layer cooperation protocols are proposed, such as amplify-and-forward [8], decode-and-forward [8], compress-and-forward [9] and coded cooperation [10]. The design and analysis of these physical-layer relaying techniques are usually based on the following assumptions:

- A1: Data is always transmitted in a cooperative manner.
- A2: The source always knows who the helpers are to cooperate with.

- A3: Only one dedicated helper is generally involved.
- A4: Helpers are always ready and willing to help.

Apparently, these assumptions may not be always true in real network scenarios. Regarding A1, if the relay channel is of low quality, cooperation may not be beneficial or necessary. Moreover, the source may prefer not to transmit cooperatively because of energy or security concerns. Indeed, from a physical-layer standpoint, the source simply broadcasts its signal and does not need to know about the helpers. However, from a higher-layer's point of view, a link between the source node and the destination node should be established for non-broadcast services. The source must incorporate the address(es) of the selected helper(s) as the destination of a frame so that it will not be dropped but forwarded by the helper(s). Nonetheless, A2 might be invalid when helpers are moving. The source cannot have up-to-date knowledge of the helpers to cooperate with. Furthermore, A3 is a strong assumption since it is challenging to select a best helper among multiple candidates that overhear the transmission from the source. It is also likely that a helper is not dedicated to relay data but has its own data to send. Last but not least, the assumption A4 is unrealistic. Therefore it is essential to design a cooperation protocol that benefits both the source and the helpers.

To enable cooperation at the medium access control (MAC) layer, these assumptions should be relaxed to have a more practical design. For backward compatibility, the cooperative MAC protocol can extend the coordination function of a regular MAC protocol, which is to coordinate multiple nodes sharing the wireless medium and alleviate

the effect of hidden and exposed terminals. In addition, the cooperative MAC protocol should address two fundamental problems [6, 11]:

- *When to cooperate?* (Q1). The nature of this question is to find the conditions when cooperation can be enabled, or the regions where cooperation is beneficial.
- *Whom to cooperate with?* (Q2). To answer this question, the cooperative MAC protocol should determine who are the available helpers and who is the optimal helper(s) that the source is going to cooperate with.

A traditional MAC protocol usually focuses on a single-hop link to coordinate the sharing of wireless medium by multiple nodes. In a cooperative MAC scenario, the MAC design needs to extend to address multi-hop indirect links and the selection of optimal helper(s). Relay selection has been widely explored, particularly for the physical layer, to identify best relays for relaying the signal from the source and to exploit spatial diversity gain [12]. This can be performed in a centralised manner [13–15] or a distributed manner [12, 16]. Although, relay selection algorithms can address Q2, additional factors from a MAC-layer perspective should be considered, such as collisions and hidden terminals. Moreover, a cooperative MAC design is more than relay selection and needs to address when to activate cooperation (i.e. Q1). An appropriate handshake procedure should also be designed to implement the solution algorithms to Q1 and Q2 whereas minimising signalling overhead.

In this paper, we aim to provide a comprehensive survey on existing contention-based cooperative MAC solutions. We not only comment on the strength and weakness of mainstream designs but also highlight potential research directions for future work. The rest of this paper is organised as follows. In Section 2, we briefly introduce preliminaries on traditional MAC and cooperative MAC. In Section 3, we compare representative cooperative MAC proposals and categorise them according to how they deal with the above two fundamental questions Q1 and Q2. In Section 4, we discuss several important research challenges that require further in-depth investigation. The conclusions are given in Section 5.

2 Cooperation at MAC layer

2.1 Traditional MAC protocols

In traditional wireless networks, the primary task of the MAC layer is to coordinate multiple nodes sharing the wireless medium. Channel allocation is a typical way to share the wireless medium. It partitions the wireless channel resource in a certain dimension, for example time, frequency, or spreading code. Correspondingly, there are time division multiple access (TDMA), frequency division multiple access (FDMA), and code division multiple access (CDMA). Another big family of MAC protocols are contention-based random access, such as ALOHA and carrier sensing multiple access with collision avoidance (CSMA/CA) used in IEEE 802.11. In CSMA/CA, the transmitting node senses the channel before sending a packet to avoid collision. Owing to the hidden terminal and expose terminal problems, even when the channel is sensed idle from the transmitting node side, a collision may still occur. A virtual carrier sensing approach can be used by including a handshake before the actual data transmission. The key idea is to have the sender broadcast a request-to-send (RTS) frame to reserve the channel and have the receiver respond a clear-to-send (CTS) frame to confirm the reservation. The other terminals who overhear the RTS and/or CTS should defer their transmission for a period of time indicated by the network allocation vector (NAV).

2.2 Cooperative MAC protocols

Both the contention-based random access and channel allocation-based MAC can be extended to a cooperative scenario. For example cooperative ALOHA is analysed theoretically in [17–19]. There is also interesting research on cooperative MAC based on TDMA [20, 21] and CDMA [22]. Owing to the complexity concern with channel management, channel allocation-based cooperative MAC is not as popular as contention-based MAC. In this paper, we focus on contention-based MAC, which has attracted most research attention.

A typical cooperation topology is shown in Fig. 1, in which there are multiple nodes within the coverage of an access point (AP). If node n_1 decides to cooperate with the helper

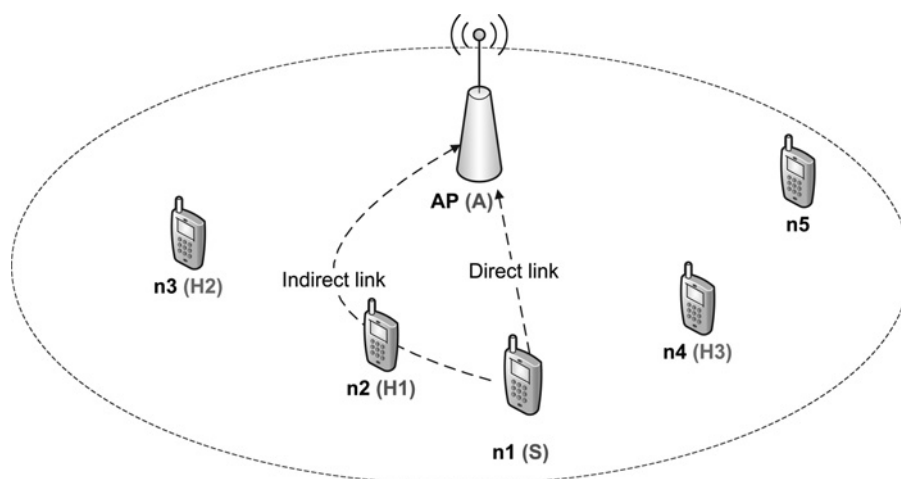


Fig. 1 Cooperation topology

node n_2 for its data transmission, there are three communication entities involved in this cooperation:

- **Source (S).** That is the transmitter of the data, which is n_1 in Fig. 1.
- **Helpers (H).** There can be one or more potential helpers. In Fig. 1, the helpers n_2 , n_3 and n_4 are marked as H_1 , H_2 and H_3 , respectively. At least one of them can be selected as the optimal helper(s), for example, n_2 (H_1) in Fig. 1.
- **Access point (A).** The AP is the receiver or destination of the data from the source.

Accordingly, two types of links can be formed in this topology among the above three entities: (a) the direct link between S and A , which is used for data transmission if no cooperation is activated; and (b) the indirect link involving the helpers. More than one indirect link can participate in cooperative transmission. As shown in Fig. 1, only one helper is selected to form a two-hop indirect link. A multiple-hop indirect link is possible if more than one helper participates. Depending on how the direct link and the indirect link contribute to the data transmission, there are two typical cooperation scenarios shown in Fig. 2:

- **Selective scenario.** In this case, only the better link, either the direct link or the indirect link, is selected to transmit a packet. As seen in Fig. 2a, in the time slot 1, the indirect link is chosen to first send the packet P_1 to H and then H forwards P_1 to D . In the time slot 2, the direct link is selected to transmit the packet P_2 .

- **Diversity scenario.** In this case, both the direct link and the indirect link are involved in each packet transmission. Thus, diversity gain can be achieved with spatial diversity. As shown in Fig. 2b, in the time slot 1, two independently faded replicas of the packet P_1 are received by both H and S in the first subslot. The source S keeps this packet for future processing. In the second subslot, H relays another copy of P_1 to D . At the end of the time slot 1, D can choose a strategy such as maximal ratio combining (MRC) [17, 23] or selective combining [24, 25] to process the two copies of P_1 for the best receiving performance.

3 Contention-based cooperative MAC protocols

Many contention-based cooperative MAC protocols inherit traditional coordination mechanisms from standard MAC to schedule channel access among multiple nodes. Further, as discussed in Section 1, a cooperative MAC protocol must properly address two fundamental questions: 'Q1: When to cooperate?' and 'Q2: Whom to cooperate with?' Specifically, Q1 is to find the conditions when cooperation can be enabled. These conditions to trigger cooperation can be straightforward, for example, less transmission time [4, 26–28], or as complex as the cooperative region [29]. A variety of cooperation conditions are given in the 'cooperation condition' column of Tables 2, 4 and 5.

To answer Q2, there are two aspects to address: (a) 'helper contention', in which available helpers compete to become a

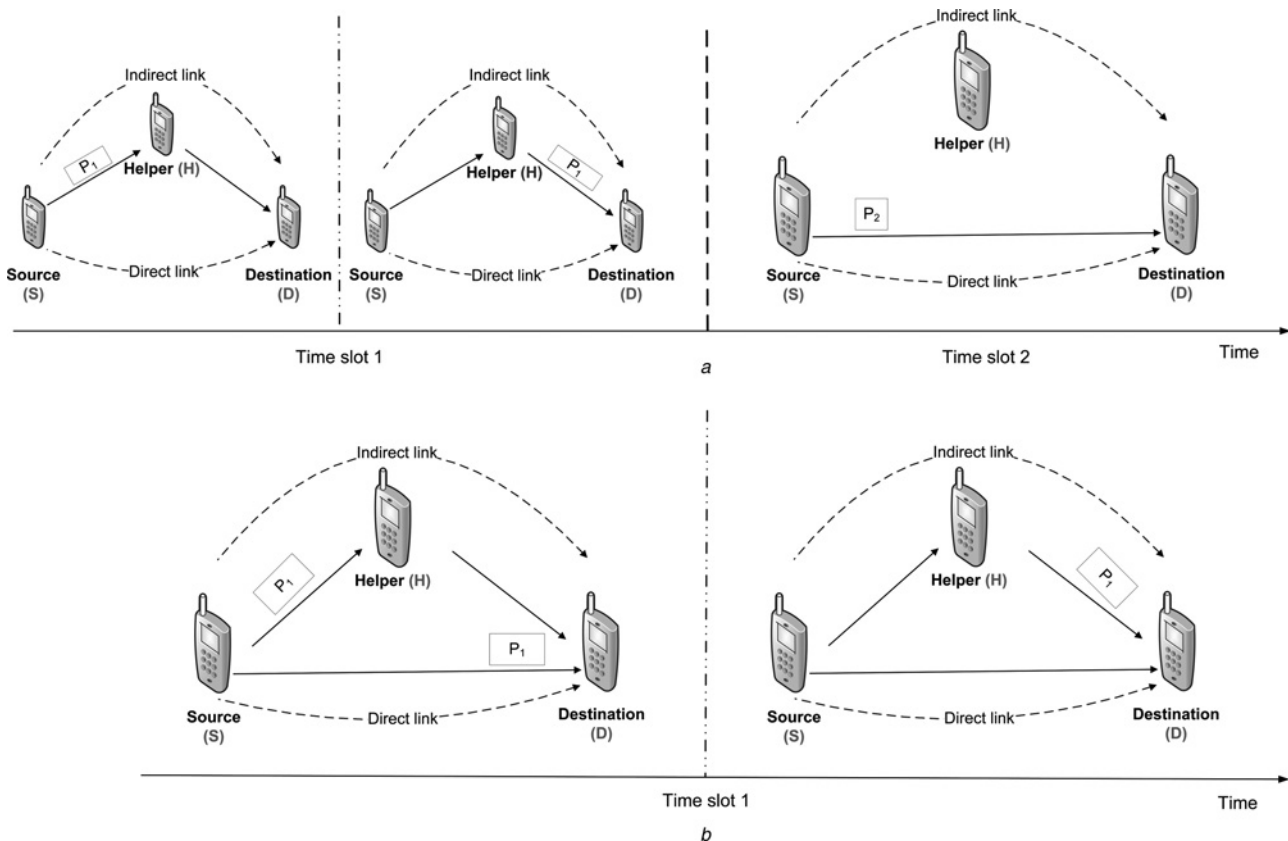


Fig. 2 Typical cooperation scenarios

a Selective scenario
b Diversity scenario

candidate in the potential helper list of the source; and (b) 'helper selection', in which the optimal helper(s) are selected according to certain criteria and decision mechanism. It is worth noting that some cooperative MAC protocols address Q2(a) and Q2(b) in one process, such as CoopMAC [4] and Shan-MAC [29]. Nonetheless, some protocols indeed handle them in different processes by different entities, such as rDCF [30]. Whereas apparently Q2(a) should be addressed before Q2(b), there is no predetermined order of addressing Q1 and Q2. In Shan-MAC [29], Q1 is answered before Q2, whereas rDCF [30] deals with Q2(a) first, followed by Q1 and Q2(b). According to which entity addresses Q1 and/or Q2, we propose the following categorisation of contention-based cooperative MAC protocols in Table 1.

3.1 Category I

For the cooperative MAC protocols of Category I, the source addresses both Q1 and Q2. Typical examples include Ahmed-MAC [14], CoopMAC [4], adaptive distributed cooperative (ADC)-MAC [31]. These protocols generally follow a common procedure as follows:

- The source acquires the knowledge of other nodes such as the transmission rate and transmission time. Such information is usually obtained by overhearing, for example, in CoopMAC [4], or periodical broadcast indicator packets, for example, in ADC-MAC [31]. The collected information is generally maintained in a table, known as CoopTable in CoopMAC and ADC-MAC.
- Based on the information of potential helpers, the source needs to answer the questions Q1 and Q2. For this category of cooperative MAC protocols, some address Q1 first whereas others address Q2 first. The source checks if the cooperation conditions are met and selects a best helper among the candidates. It is worth emphasising that the source makes the selection decision and the best helper is not elected with competition.
- Once the source decides to initiate cooperation with the selected helper, it sends a cooperation request to the helper and starts the cooperative transmission based on the feedback from the helper.

We list in Table 2 some typical Category I MAC protocols and will briefly introduce them in the following. The cooperative proposal in [14] is referred to as Ahmed-MAC in this paper for reference convenience. Ahmed-MAC addresses Q2 firstly and Q1 secondly. Since the source has the knowledge of all available helpers, it chooses an optimal one according to a modified harmonic mean function β . The helper with the maximum β is selected. Whether to initiate cooperative transmission or not depends on the ratio $\beta_{s,d}/\beta_{\max}$, where $\beta_{s,d}$ is the modified harmonic mean function of the channel between the source and the destination, and β_{\max} is that of the optimal helper. If the ratio falls below a threshold, the source only uses direct transmission. Otherwise, cooperative transmission is involved. Nonetheless, Ahmed-MAC does not specify the handshake procedure or how the source obtains the knowledge of the helpers.

CoopMAC proposed in [4, 26] further addresses these problems. The source acquires the overall knowledge of potential helpers by overhearing their transmission. This is feasible for reciprocal channels between the source and the helper. The source maintains the information of the helpers obtained from overheard packets in CoopTable, one example of which is given in Table 3. CoopMAC addresses Q1 first by comparing the transmission time of the direct link and the indirect link, which is calculated by the transmission rate and handshake time. Cooperation is only enabled when the indirect transmission time is shorter. To answer Q2, the source looks up the CoopTable and selects the helper with the highest indirect transmission rate. If multiple helpers have the same highest indirect transmission rate, the source chooses the one with the most recent update and the least number of failures. Compared to Ahmed-MAC, CoopMAC is a more complete solution. It proposes the triangle handshake to reserve an optimal helper and uses the triangle transmission to relay data. However, the reciprocal channel assumption to enable overhearing may not hold when the channel is fast time-varying or different frequencies are used for the uplink and downlink. Also, there must be sufficient packets overheard from the helpers, so that the source can obtain accurate and up-to-date information for the CoopTable. Moreover, the triangle handshake and transmission

Table 1 Categories of cooperative MAC protocols

Category	Q1 is addressed by	Q2		A typical example
		(a) is addressed by	(b) is addressed by	
I	source	source	source	CoopMAC [4]
II	source	helper(s)	source	rDCF [30]
III	source	helper(s)	helper(s)	Shan-MAC [29]

Table 2 Category I cooperative MAC protocols

Protocol	Knowledge collection	Solving order	Cooperation condition	Helper selection	Scenario
Ahmed-MAC [14]	—	Q2, Q1	$\frac{\beta_{s,d}}{\beta_{\max}} > \text{threshold}$	highest β function value	selective
CoopMAC [4, 26]	overhearing	Q1, Q2	less transmission time	highest transmission rate	selective
ADC-MAC [31]	broadcasting	Q2, Q1	SNR meets requirement	highest transmission rate	selective
C-MAC [32]	broadcasting	Q2, Q1	lower transmit power	lowest transmitting power	diversity
CD-MAC [33]	overhearing	Q2, Q1	once a transmission fails	highest SINR	diversity

Table 3 CoopTable structure

Helper	Time, s	Direct transmission rate, Mbit/s	Indirect transmission rate, Mbit/s	Failures
H_1 address	0.1	5	1.69	5
H_2 address	0.2	5	5.5	0
...

procedures are still dependent on the direct link. As a result, CoopMAC cannot deal with the circumstances where the direct link is unavailable.

The ADC-MAC protocol in [31] collects the information of the helpers in a manner different from that of CoopMAC. In CoopMAC, the source overhears the packet transmission of the helper and infers the helper's information accordingly. In ADC-MAC, the helper periodically broadcasts a heartbeat frame, which contains not only the received signal strength indication but also the information about the helper's neighbours. As such, the source maintains a global knowledge of the network in a CoopTable. Based on the CoopTable, ADC-MAC addresses Q2 first by applying a shortest path routing algorithm (e.g. the Dijkstra's algorithm) to determine the most appropriate indirect path. The optimal helper is then selected. The MAC address of this selected helper is included in the RTS frame to reserve the channel. If this helper is available, it acknowledges with an acceptance packet indicating its availability. After the source confirms the eligibility of the helper, cooperative transmission is initiated. Different from CoopMAC, ADC-MAC designs a pure two-hop transmission to avoid using the direct path. This mode is more feasible than CoopMAC when the direct path is not available.

Because the source has complete knowledge of all other nodes in the network, it is possible for it to (a) decide whether cooperation is necessary and then select a helper (Q1–Q2); or (b) predetermine a potential helper and then decide whether to initiate cooperation or not based on the feedback of this helper (Q2–Q1). Which addressing sequence performs better depends on the networking scenario to apply the cooperation protocol. For example a Category I protocol in a Q2–Q1 sequence can perform better in a mobile network, in that the cooperation decision can be further confirmed by the helper feedback to ensure an up-to-date decision, such as ADC-MAC in [31]. On the other hand, the Category I solutions in a Q1–Q2 sequence may have an easier implementation by means of extending current 802.11-based protocols and better fit a more static network topology. Such solutions do not require complicated decision algorithms or handshake control packets to guarantee a timely cooperation decision.

3.2 Category II

In this category of cooperative MAC protocols, the source addresses Q1 and Q2(b), which means the source proposes

to cooperate and selects an optimal helper from a candidate list. The candidate list is first obtained via helper contention in a distributed manner when Q2(a) is being addressed. The number of potential helpers to consider can be reduced when Q2(a) is answered. The addressing sequence of Q1 and Q2(b) can be the same as the Q1–Q2 sequence and the Q2–Q1 sequence discussed in Section 3.1. The Category II of cooperative MAC protocols share the following common features:

- First, the available helpers compete with each other and the winners are qualified for the candidate list of the source. In one way, the helpers are aware of each other before competing through certain mechanism. For all the existing work surveyed in this paper, broadcast is used to accomplish this task. Another is a pure distributed approach, which allows helpers not to be aware of each other. The distributed timer algorithm in [34] is a good option.
- Although cooperative transmission is still initiated by the source, the source only has partial knowledge of the helper nodes, which is different from Category I. The helper candidate list obtained by the source is only the result of helper contention.

In the following, we present and compare a few typical Category II protocols in Table 4, such as rDCF in [30], ErDCF in [5, 35], RAMA in [27] and efficient multi-rate relaying (EMR) in [36]. rDCF [30] is one of the earliest classic cooperative MAC protocols. It creates innovative concepts such as CoopTable and broadcast information frame. The fundamental cooperation questions are addressed in the order of Q2(a), Q1 and Q2(b). A helper decides whether it can help a pair of source and destination nodes by checking the overheard RTS and CTS between them. If the helper is able to improve their transmission by cooperating, it adds this pair into its willing list and broadcasts its willing list periodically. To content with other potential helpers and answer Q2(a), each helper keeps listening to others' willing lists and checking the source and destination pairs contained in their willing lists. If more than M willing lists that contain the same pair are overheard, the helper stops advertising itself. Through this help contention, the source maintains its CoopTable. If the transmission time via cooperation is shorter, the source sends a cooperation request to the helper who provides the shortest cooperative transmission time.

The relay-aided medium access (RAMA) control protocol [27] has a similar idea. The difference is that RAMA broadcasts the information frame in a random manner rather than periodically. If a helper succeeds in accessing the channel first, it starts to broadcast its frame whereas other helpers stop broadcasting and keep silent. Although RAMA [27] and rDCF [30] can be easily extended from an 802.11-based protocol, the competition among the nodes cannot guarantee that the most capable nodes appear in the short-list of helper candidates of the source. In RAMA, helper nodes compete via random backoff so that the nodes

Table 4 Category II MAC protocols

Protocol	Solving order	Helper contention	Cooperation condition	Helper selection	Scenario
rDCF [30]	Q2(a), Q1, Q2(b)	broadcast to overhear M peers	non-empty CoopTable	random by source	selective
ErDCF [5, 35]	Q2(a), Q1, Q2(b)	broadcast to overhear M peers	non-empty CoopTable	random by source	selective
RAMA [27]	Q2(a), Q1, Q2(b)	random backoff contention	less transmission time	highest rate	selective
EMR [36]	Q2(a), Q1, Q2(b)	priority-based contention	higher effective throughput	highest throughput	selective

whose backoff timers run out earlier become winners and qualified potential helpers. Similarly, in rDCF, a helper node stops broadcasting its willing list if the same source and destination pair has appeared in more than M willing lists overheard from other helpers. As a consequence, it is likely that a more capable node may not be even considered as a helper candidate, if it broadcasts its willing list less frequently than other less capable nodes.

The EMR MAC protocol [36] addresses this problem with a simple but reasonable solution. It defines the effective throughput as the criterion to evaluate a helper. A 'priority number' is assigned to each helper according to the effective throughput and broadcast in the helper's indicator frame. Any other helper who overhears this frame compares the priority number with its own and stops broadcasting if the overheard priority number is greater. Although the broadcast frame is a simple solution to helper contention, excessive overhead traffic is brought into the network.

3.3 Category III

In Category III, Q2, including both Q2(a) and Q(b), is addressed by the same entity as in Category I. The difference is that Q2 is addressed by the helpers in a distributed manner rather than by the source in a centralised manner in Category I. In this category, the source only handles the question Q1 and does not know who are the potential helper candidates to select. Once the source determines that cooperative transmission is beneficial, the source can propose cooperation to its overheard neighbours. Then, it is up to the neighbours to make the ultimate cooperation decision. Different from Categories I and II, we believe that Q2 cannot be addressed ahead of Q1 in Category III. For one thing, the helper entity must have received a cooperation proposal signal to start the helper contention and selection procedure. On the other hand, if Q2 were addressed before Q1, it would be unnecessary to reevaluate the cooperation timing since the distributed contention and selection procedure could provide an up-to-date helper.

Although there are few protocols that fall into this category, Table 5 shows three examples, that is, the Feeney-MAC [28], OR [16, 34] and Shan-MAC [29]. Feeney-MAC is a very simple and naive MAC. If there is a possibility that the transmission time over an indirect path is shorter, the source initiates cooperative transmission assuming that certain node may help. If there indeed exist some nodes that are able to help, the one that captures the channel first after random access contention will relay packets for the source. The other nodes will cancel their competition. However, in the absence of proper handshake, Feeney-MAC simply assumes the existence of a helper node and cannot guarantee successful cooperation. The channel access can neither ensure that the optimal helper is selected.

In [16, 34], an opportunistic relaying (OR) protocol is proposed. All the helpers estimate the 'instantaneous channel conditions' based on RTS and CTS frames and set

a corresponding timer based on the channel condition. Two policies to set the timer are evaluated in [16]. Basically, the better the channel condition is, the shorter the timer is. As a result, the optimal helper will time out first and transmit a flag packet to claim itself. After receiving the packet from both the source and the helper, the destination uses MRC to decode the message. Strictly speaking, OR is not a complete Category III solution, since it assumes implicitly that cooperation starts once a helper is selected. That is the question Q1 is not explicitly addressed. Important factors such as energy and security also need to be considered to evaluate if cooperation is really beneficial. If Q1 and the handshake procedure are further appropriately considered, OR can be extended to a good solution in Category III or VIII (see Section 4.1).

The distributed MAC proposed in [29] is a mature solution, which is referred to as 'Shan-MAC' in this paper for easy reference. To answer Q1, a new metric called cooperation region (CR) is defined in Shan-MAC and the acquisition of CR is formulated as an optimisation problem. By solving the optimisation problem, the source starts cooperation if CR exists and uses direct transmission otherwise. To answer Q2, a distributed timer-based selection scheme is specified in Shan-MAC. The key idea is similar to the timer algorithm in [34], in which a better helper is indicated by less channel access time. Thus, the first responding helper is expected to be the optimal one. Hence, no information broadcast is required for the helpers to be aware of other competitors, which alleviates the network from broadcast traffic. To enable the timer-based selection scheme, appropriate synchronisation is necessary among the helpers.

4 Challenges with MAC layer cooperation

4.1 Cooperative MAC protocols of new categories

Most existing contention-based cooperative MAC protocols fall into three categories in Table 1. In particular, Category I has received most research attention. This is mainly because the idea is straightforward and close to the popular cooperative physical-layer protocols. Also, this category of MAC protocols can be easily implemented by extending the mainstream 802.11 MAC. However, there can be a large overhead for the source as the decision entity to maintain the overall knowledge of other nodes (e.g. in CoopTable) when there are a great number of helpers around the source. Overhearing of packet transmissions from helpers is required under the reciprocal channel assumption although overhearing is power consuming. Meanwhile, the broadcast of information frames involves additional traffic. On the other hand, it may be challenging to keep up-to-date accurate information in CoopTable in a highly varying environment, such as with node mobility. Efficient search algorithm is also essential to identify an optimal helper in a large-sized CoopTable.

The solutions of Categories II and III balance the decision intelligence of the source with the helper entities. Category II

Table 5 Category III MAC examples

Protocol	Solving order	Helper contention	Cooperation condition	Helper selection	Scenario
Feeney-MAC [28]	Q1, Q2	random backoff	less transmission time	highest rate	selective
OR [16, 34]	–	timer-based	–	highest SNR	diversity
Shan-MAC [29]	Q1, Q2	distributed grouping, timer-based	CR exists	highest rate	selective

Table 6 Other possible categories of cooperative MAC protocols

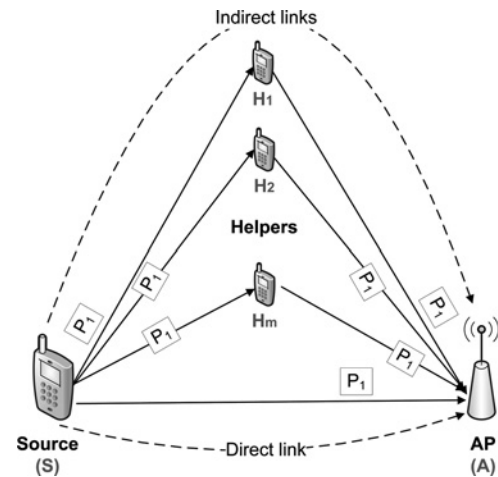
Category	Q1 is addressed by	Q2	
		(a) is addressed by	(b) is addressed by
IV	source	source	helper(s)
V	helper(s)	source	source
VI	helper(s)	source	helper(s)
VII	helper(s)	helper(s)	source
VIII	helper(s)	helper(s)	helper(s)

includes helper contention to reduce the size of CoopTable so that the source makes a cooperation decision among less helper candidates. In Category III, helper selection is taken over by the helpers. Thus, a major challenge for Categories II and III is to design a reliable and efficient helper contention and/or selection algorithm for the helpers. Also, a handshake procedure can be designed for the helpers to exchange information with each other, or between the source and the helper to inform the source of the selected optimal helper.

If we follow the categorisation logic in Table 1, we see that, there exist other potential categories as shown in Table 6. Although, not all of them are reasonable such as Category V, some are quite promising, such as Category VIII. Category VIII is a pure distributed cooperative MAC approach, in which the source is not aware of how Q1 and Q2 are resolved. In this case, each cooperation decision is made by the helpers. As long as a good contention algorithm is designed, the decision is up-to-date to ensure a high success rate of cooperation. The source is informed of the selected thereafter if cooperative transmission is found beneficial. Since a cooperation decision should be made for each packet transmission, the contention overhead needs to be effectively balanced. In addition, Category IV may include some promising solutions as well. For example the source can overhear its neighbours and list some potential helpers based on gathered information to address Q2(a). As a result, when cooperation is triggered to answer Q1, a control packet can be sent to potential helpers instead of all nodes as in Category III. If helper selection is initiated afterwards only among potential helpers in a distributed manner to answer Q2(b), the complexity of distributed selection can be decreased with a smaller number of participating helpers.

4.2 Cooperative diversity and multiple helpers

As mentioned in Section 2.1, a cooperative relay link and the direct link can be used to transmit the same packet in the diversity scenario, or different packets in the selective scenario. From the discussion in Section 3, we can see that most existing cooperative MAC designs focus on the selective scenario [4, 5, 14, 27–31, 35–37], and only a few protocols [16, 32, 33] consider the diversity gain with cooperation. There are the ‘single-helper diversity scenario’, as shown in Fig. 2b, and the ‘multiple-helper diversity scenario’, as shown in Fig. 3. In the latter case, orthogonal distributed space-time coding can be applied to enable that multiple helpers transmit over the same channel [38, 39]. In the diversity scenario, the source and the helpers form a virtual antenna array (VAA) system. The helpers become the virtual external antennas of the source. The study of the physical-layer capacity of VAA system can be found in [40].

**Fig. 3** Multiple helper diversity scenario

From the MAC-layer perspective, many issues remain unsolved. As considered in [33], one possible cooperation criterion may be the minimisation of transmission failures. Cross-layer techniques can be employed to dynamically estimate the channel condition, so that cooperative diversity transmission is initiated to satisfy certain quality-of-service requirements [41] if a transmission failure is very likely to happen with a poor channel condition. Whether the source should always enable diversity transmission or only activate it on demand, depends on factors such as the energy consumption and availability of helpers.

In the selective scenario in Fig. 2a, adaptive modulation and coding (AMC) can be enabled at the physical layer to adapt transmission rates with varying channel conditions. As such, the capacity of the selected optimal link can be fully exploited. Conversely, in a diversity scenario in Fig. 2b, multiple possible links can be utilised at the same time to make a good use of spatial diversity, which is different from choosing an optimal link at the MAC layer in the selective scenario. As a consequence, it is challenging to enable AMC simultaneously for multiple links experiencing different channel conditions.

Another essential question to exploit diversity gain is the selection of a single optimal helper or multiple uncorrelated helpers with limited interference and power consumption. From the physical-layer standpoint, multiple helpers can improve diversity to achieve a higher signal-to-noise ratio (SNR) and better performance. However, for the link layer, multiple relays may not perform better than a single best relay, because of the overhead to coordinate multiple relays and manage transmissions. Intuitively, the more helpers there are, the more complex the coordination is. Besides, multiple helpers may increase possibilities of energy consumption and collisions (e.g. because of the hidden terminal and exposed terminal problems). On the other hand, a single best relay requires less complex coordination and can achieve the full diversity order (selection diversity) [42]. Nonetheless, it is challenging to identify a single best relay in real time since the information available to the source may be out-of-date quickly when nodes are moving fast. As a result, it is necessary to balance a tradeoff between the performance gain and coordination overhead when we decide to choose multiple helpers or a single best helper [6, 11]. This is slightly different view from that of the physical layer, where more relays can provide better performance.

4.3 Mobility challenge for cooperative MAC protocols

Although mobility support is an attractive feature of wireless networks, node mobility may lead to high channel variation. In such a dynamic environment, it is challenging to guarantee an accurate and up-to-date decision on initiating cooperation and/or selecting the optimal helper(s). In a selective scenario, the out-of-date information is a most pronounced problem brought by mobility. Beyond that, the mobility of nodes can increase the correlation (mainly spatial correlation) between the channel coefficients of the cooperating entities, which reduces diversity gain [6] and is particularly detrimental to the diversity scenario.

To ensure a high success rate of cooperation, one possible solution is to apply advanced cooperation criteria which can involve the history profile of helpers [43]. For example, unstable helpers can be excluded from cooperation candidates by using analysis of history data. In addition, the cooperative MAC protocols in Table 6, such as Category VIII that enables cooperation in a pure decentralised manner, can also be a promising approach to address node mobility. Furthermore, the impact of node mobility on the performance of cooperative MAC protocols may vary with the specific mobility patterns. Good surveys on mobility models can be found in [44, 45]. The widely used mobility models include the random way point model [46], Chiang's model [47] and Gauss-Markov model [48]. The impact of different mobility patterns on cooperation performance needs further study.

4.4 Energy concern on MAC-layer cooperation

Mobile nodes are usually portable devices powered with batteries. The energy consumption is an important factor to consider for a cooperative network, since the helpers invest power resources to assist the source in forwarding packets rather than remain idle otherwise. Most existing work on cooperative MAC protocols focuses on performance improvement in terms of system throughput. There are few studies that well address the energy concern in cooperative transmission.

As demonstrated in the study of CoopMAC in [4, 37], energy consumption of cooperative transmission in terms of Joule per bit is even lower than that with only direct transmission. If a helper can provide a sufficiently high transmission rate to forward a large packet, the helper may wait for less time for other nodes to finish their transmission. Eventually, it is likely that the helper has a less idling time by helping others. Consequently, the decrease of the energy spent in idling can compensate for the additional energy spent in forwarding for others. As a result, the total energy consumption of the network is saved under the saturated assumption [37]. However, this analysis actually does not consider the energy cost of the overhearing scheme to maintain the knowledge of helper nodes. The energy consumption analysis in [5, 35] for rDCF [30] and enhanced rDCF (ErDCF) also concludes that there is a significant energy saving with the two cooperative MAC protocols. Similar observation is also found in [27] for RAMA. To come up with a more realistic cooperation solution, it is necessary to include the energy consumption as a critical factor in decision making [32] rather than a bonus feature in addition to throughput improvement as most previous work did.

4.5 Incentive: a perspective from helpers

As mentioned in Section 1, one fundamental assumption for cooperative transmission at the physical layer is that an optimal helper, that is successfully identified is always ready to help. In fact, this is also an assumption of all the cooperative MAC protocols introduced in Section 3. This may not be true in reality. Any successful cooperation needs an agreement on both the source side and the helper side. Even when a cooperation request is proposed to an optimal helper, the helper may deny the request to save power and bandwidth resources. The helper may only care about its own short-term benefit and deny cooperation requests which may benefit it in the long run. Thus, how to stimulate cooperation is still an open issue to really implement cooperative transmission in practice.

Taking stimulation into consideration, a cooperative MAC protocol should not just make a cooperation proposal and select the helper(s) in a pure resource-based fashion as the protocols in Section 3 did. Incentive design should be included as an essential component. According to [49], the incentive schemes are classified into reputation-based [50], resource exchange-based [51] and pricing-based [52]. Although, there has been much theoretical analysis, few MAC protocols are proposed to involve an incentive mechanism. For example nodes that help others can be granted some kind of payment, such as reputation, priority to access resource, or virtual currency to trade with resources. Such reward can be kept for future use. Moreover, advanced features can be added to price different resources and prevent cheaters. When the helper incentive is taken into account, the two fundamental questions of when to cooperate and whom to cooperate with should be addressed in a different manner. Apart from optimisation methods, the game theory, especially dynamic game theory, is another powerful tool to analyse the cooperative MAC protocols with incentive.

4.6 Security issues for cooperative MAC protocols

As cooperative transmission involves not only the source node and the destination node but also helper nodes. Despite the promising performance enhancement, security is an important aspect that may restrict the application of cooperative transmission in the real world. The security issue has been extensively studied in the multi-hop *ad-hoc* network, which has a topology similar to that of a cooperative network [53, 54]. However, the existing security solutions need to be extended when applied to a general cooperative network [2, 55]. From the MAC-layer perspective, there are typical misbehaviours that may lead to security threats.

- *Selfish*: In this case, an 'isolated' node does not respond to any cooperation request even if the system performance can be improved. This case is not strictly a security issue, and a well-designed stimulation strategy as discussed in Section 4.5 may properly address that. In the other case, there is a potential security risk since a 'free-riding' node tends to request cooperation from others to transmit its packets but usually declines to help others [56]. A secure cooperative MAC protocol should be able to detect such behaviour and alleviate its impact via some kind of punishment, for example.
- *Obstructing*: There are three common misbehaviours of an obstructing node. The first one is a 'lying' node that gives false feedback. For example a helper node may pretend to

be an optimal choice but not cooperate at all. A credit list of reliable helpers, or a blacklist of notorious helpers can be maintained to prevent liars. It is worth noting that incorrect feedback may also be caused by mobility or fading. As a result, a node that feeds back incorrect information is not necessarily a lying node. A secure cooperative MAC protocol should distinguish between them.

The second case is a 'cheating' helper that tampers the content of a relaying packet for its own benefit. To prevent this type of cheating, the destination entity can provide direct feedback to the source, so that the source and the destination can identify a cheating node by checking with each other. However, this is not feasible for a pure relay solution such as in ADC-MAC, in which the feedback from the destination is also relayed by the cheating helper who may modify the content of the feedback as well. To prevent cheating in a pure relay case, the destination can randomly choose another neutral helper to relay the feedback and check the credibility of the previous helper.

The third type of misbehaviour is called 'jamming', which exists in the diversity scenario with multiple helpers. A jamming helper may intentionally transmit wrong signals to interfere with the receiving of the destination. Jamming can be even more complicated than the first two cases, since multiple helpers are involved. Both the source and the destination need to cooperate so as to detect a jamming helper. For example a blacklist could be provided by the source. By checking each one in the blacklist, a jamming helper may be investigated.

- *Spying*: 'Spying' nodes are not the destinations but attempt to probe the content of a packet. Although, it is a common security issue in both wired and wireless networks, it cannot be easily solved for cooperative wireless networks. This is because the helpers need to be authorised to examine some information in the packet to properly forward it. Meanwhile, the confidential information in the packet can be encrypted and made only available to the source and the destination to protect user privacy.

5 Conclusions

Cooperative wireless transmission is a promising technique to exploit the benefits of MIMO with affordable terminal complexity. The existing cooperative solutions at the physical layer usually consider some strong assumptions, which may limit their wide deployment in real networks. To deal with user cooperation at the MAC layer, such assumptions should be relaxed to properly address two fundamental questions, that is, 'when to cooperate' and 'whom to cooperate with'. The cooperative MAC protocol may focus on either a selective scenario or a diversity scenario. In this paper, we have reviewed the mainstream cooperative MAC protocols proposed in the literature, which fall into three classes according to the entities (the source or the helper nodes) that handle the above two questions. It is found that Category I has received most research attention, which is usually based on straightforward ideas that are close to the physical-layer solutions. Nonetheless, some other categories such as Categories III and VIII also have a promising prospect with attractive features such as a pure decentralised cooperation approach.

Although, there have been a considerable amount of excellent research on cooperative MAC, there are still many open issues that remain not fully explored. New categories

of cooperative MAC solutions are worthy of further investigation from unique angles. Cooperative diversity exploiting multiple helpers can well offer the MIMO benefits by means of user cooperation, but this area is not sufficiently addressed yet in the literature. Node mobility and energy consumption are challenging research problems and should be handled more intelligently in a cooperative scenario. Incentive design to stimulate user cooperation is another featured direction for cooperative MAC. Last but not least, the security concerns have to be properly resolved, so that a high-performance cooperative MAC solution can be implemented and deployed in practice.

6 Acknowledgment

This research was supported by a research grant from Natural Sciences and Engineering Research Council (NSERC) of Canada.

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