A Survey of Cooperative MAC Protocols for Mobile Communication Networks

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Abstract

Cooperative communication is a promising and practical technique for realizing spatial diversity through a virtual antenna array formed by multiple antennas of different nodes. There has been a growing interest in designing and evaluating efficient cooperative medium access control (MAC) protocols in recent years. With the objective of translating a cooperative diversity gain at the physical layer to cooperative advantages at the MAC layer, an efficient cooperative MAC protocol should be able to accurately identify a beneficial cooperation opportunity, efficiently select the best relay(s), and coordinate the cooperative transmission with reasonable cost and complexity. However, due to the randomness of channel dynamics, node mobility, and link interference, the design of an efficient cooperative MAC protocol is of great challenge, especially in a wireless multi-hop mobile network. In this article, we aim to provide a comprehensive overview of the existing cooperative MAC protocols according to their specific network scenarios and associated research problems. Three critical issues (i.e., when to cooperate, whom to cooperate with, and how to cooperate) are discussed in details, which should be addressed in designing an efficient cooperative MAC protocol. Open research issues are identified for further research.

Index Terms

Cooperative medium access control (MAC), beneficial cooperation, fully-connected networks, multi-hop mobile networks, spatial reuse, relay selection.

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I. Introduction

Research in wireless ad hoc networks has been attracting more and more interests in the past decade [1], [2]. A wireless ad hoc network is formed by a group of wireless nodes that can dynamically self-organize and self-configure the network into an arbitrary topology, and can also establish and maintain the connectivity among themselves. Generally, each node can serve as a data source or destination, or a relay that can help forwarding data on behalf of its neighboring nodes. Therefore, when a destination node is out of the transmission range of its source node, multi-hop forwarding can be carried out as an effective technique to enhance the network connectivity and extend the network coverage. Specifically, a fully-connected network can be seen as a single-hop network, in which all nodes can communicate directly with each other. The infrastructure-less nature of a wireless ad hoc network renders it very suitable for applications that are constrained by economic conditions and/or geographical locations. For example, a typical application scenario of wireless ad hoc networks includes fast establishment of communication networks in battlefield, natural disaster area where network infrastructures are out-of-work, and emergency rescue area without adequate network coverage [2].

Channel fading and signal interference are two main causes of performance degradation in wireless transmissions. Through exploiting spatial diversity and multiplexing gains, multiple-input multiple-output (MIMO) systems [3], [4] combined with space-time signal processing techniques [5], [6] can effectively mitigate detrimental effects of wireless channel impairments to improve the channel capacity and reliability. The deployment of multiple antennas on a single node, however, may not be feasible due to the limited physical size and cost constraints. Fortunately, cooperative communication [7]–[9] as an alternative technology has been proposed, in which cooperative diversity can be achieved by coordinating multiple nodes that are geographically close to work together and form virtual antenna arrays.

The main idea of cooperative communications can be simply summarized as follows. Thanks to the wireless broadcast advantage (WBA) and wireless cooperative advantage (WCA), the neighboring nodes, which overhear data packets that are transmitted from a source node, can help forwarding the data packets to the specific destination node when necessary. By combining two or more copies of data packets that are transmitted through independent links, a diversity gain can be achieved at the destination node to enhance the reception quality. In general, the process of cooperative communications can be separated into two phases, namely information sharing phase and cooperative transmission phase, which are carried out by fully utilizing the WBA and WCA respectively. In addition, according to forwarding operations by the relays, the cooperative relaying schemes can be classified into three categories, namely amplify-and-forward (AF), decode-and-forward (DF), and compress-and-forward (CF) [10]. In an AF relaying scheme, the relays simply amplify and forward a received noisy signal to the destination node, in which the noise level in a signal is also enlarged. In a DF relaying scheme, the relays decode the received signal and then forward the re-encoded signal to the destination node, while the relays in a CF relaying scheme map the received signal and only forward the compressed signal to the destination node. Because of simplicity, AF and DF relaying schemes are widely used in designing distributed cooperative medium access control (MAC) protocols.

Cooperative communication at the physical layer has been widely studied [11], [12], and the cooperative advantages have been demonstrated by analyzing different relaying strategies from the viewpoint of information theory. It is deemed that the fundamental advantage of cooperative communication is the diversity gain achieved by spatial diversity. For different application scenarios, the diversity gain achieved at the physical layer can be mapped to specific advantages at the MAC layer as needed, such as increasing transmission rate and throughput, reducing transmission power and improving spatial reuse, enhancing transmission reliability, and enlarging transmission range and network coverage [13].

Most works on cooperative communication at the physical layer mainly focus on the improvement of diversity order, but ignore the detrimental effects from cooperation, e.g., extra protocol overhead and enlarged interference area. However, these effects are critical to the overall network performance as the cooperation gain may decrease or even disappear if the high-layer protocols are not appropriately designed. Therefore, more attention has recently been paid to the design of cooperative MAC protocols, which is a relatively new research area [14].

To facilitate the design of cooperative MAC protocols, three critical issues should be carefully studied, i.e., when to cooperate, whom to cooperate with, and how to cooperate. All three issues should be well addressed to activate only beneficial cooperation and to select the best relay(s). Till now, many cooperative MAC protocols have been proposed to address some or all the aforementioned issues. According to different cooperation strategies, existing cooperative MAC protocols can be classified into proactive and reactive schemes. In a proactive scheme, relay selection takes place before the source node transmits the actual data packets, while relay selection in a reactive scheme is performed after a reception failure at the destination node. Intuitively, the relay selected by a proactive scheme should be able to increase transmission rate or reduce energy consumption, while the relay selected by a reactive scheme should enhance transmission reliability.

Regardless of cooperation strategies, it is always desirable to activate only beneficial cooperation. However, developing such an efficient cooperative MAC protocol is technically challenging, due to the scarce radio spectrum resources, sharing nature of wireless medium, and lack of a central controller, as elaborated in the following:

Vulnerable and unpredictable wireless channel - A wireless channel is time-varying with node mobility, and so is the channel capacity. Such an unpredictable channel requires frequent cooperation decisions and fast relay selections, which would incur non-negligible protocol overhead to estimate the instantaneous channel state information (CSI) and to coordinate the relay selection. Or, even worse, unnecessary cooperation may be activated when the instantaneous CSI is not available due to the highly dynamic wireless channel. Therefore, an efficient cooperative MAC protocol should be able to dynamically adapt to channel conditions and accurately identify cooperation opportunities.

Inevitable protocol overhead - To activate cooperative transmissions, more nodes (i.e., relays) in addition to the source node should take part in the data transmission, thereby introducing more protocol overhead for coordination signaling and relay selection. In general, more relays can contribute to a higher cooperation gain, but also lead to more protocol overhead. Hence, the tradeoff between the cooperation gain and protocol overhead should be thoroughly studied for the design of an efficient cooperative MAC protocol.

Node mobility - Node mobility results in high channel dynamics and frequent link breakages, which can significantly complicate the judgement of beneficial cooperations and the selection of the best relay(s). Further, in a highly dynamic scenario, the mobility-insensitive metrics, instead of instantaneous CSI, can be utilized to help making the cooperation decision and selecting the best relay(s); however, such metrics cannot fully exploit the time diversity. Thus, node mobility poses a great challenge in cooperative MAC.

Enlarged interference area - Without power control, cooperative transmission gives rise to an enlarged interference area in a multi-hop network, which can reduce the frequency of spatial reuse and possibly degrade the overall network performance. Therefore, when to activate cooperation that is beneficial to the overall network performance is another challenging issue.

Lack of a central controller - Packet transmission collisions happen when multiple beneficial relays contend to be the best relay in the same time-slot, which can significantly reduce the cooperation opportunities and degrade the network performance. Without a central controller, it is difficult to efficiently select the best relay(s) while keeping a low collision probability, especially when the node density is high.

The rest of the paper is organized as follows. Section II gives a brief introduction to the MAC protocol classification. In Section III, we discuss key issues that should be carefully studied when designing a cooperative MAC protocol, namely when to cooperate, whom to cooperate with, and how to cooperate. Sections IV and V provide an overview of the existing cooperative MAC protocols, classified according to their specific network scenarios and associated research problems, followed by open research issues in Section VI. Finally, Section VII concludes this survey.

II. MAC Protocol Classification

Due to the scarce radio spectrum resources and channel sharing nature, MAC is essential to coordinate the channel access of each individual node in an orderly manner [15]. According to whether the wireless medium access is coordinated in a centralized or distributed manner, MAC can be classified into two categories: reservation-based MAC and contention-based MAC [16].

In this section, we give a brief introduction to the reservation-based MAC and contention-based MAC, as most of the existing cooperative MAC protocols are based on either one of them or a hybrid one. Further, the main operation mechanism of IEEE 802.11 DCF (distributed coordination function) [17], a widely-used contention-based MAC scheme, is also presented.

A. *Reservation-based MAC*

For reservation-based MAC, the global knowledge of traffic load, network topology, and time synchronization is required to establish a collision-free schedule or allocate appropriate radio spectrum resources to each node. Time division multiple access (TDMA) is a widely-used and representative example of the reservation-based MAC scheme. In TDMA, once the schedule is set up, each node will be assigned a unique time-slot for data transmission, which can effectively prevent nodes from packet transmission collisions. In addition, a TDMA scheme can ensure fairness among all nodes, guarantee bounded latency, and make full use of wireless resources when the traffic load is high.

However, the requirements of the global knowledge of network topology and time synchronization can introduce significant signaling overhead, especially when the network topology changes frequently. Besides, the fixed schedule cannot adapt to a bursty traffic load. As a result, reservation-based MAC is mostly suitable for a static scenario with periodic and high-load traffic.

B. Contention-based MAC

In comparison, contention-based MAC is simple and flexible as both the global knowledge of network topology and time synchronization is not required. ALOHA [18] and carrier sensing multiple access (CSMA) schemes are two well-known examples. In an ALOHA scheme, all nodes contend randomly for the shared wireless channel. Hence, frequent packet collisions can greatly degrade the throughput performance when the node density is high [19]. In order to reduce packet transmission collisions, a CSMA scheme is introduced. Each node that has a data packet to transmit should first sense the wireless channel before the actual transmission. If the channel is sensed to be busy, the node should keep silent and defer its transmission to avoid interrupting the ongoing transmissions.

The flexibility of contention-based MAC makes it robust to node mobility and suitable for bursty traffic load; however, its performance may degrade when the network is congested and/or the collisions occur frequently.

C. IEEE 802.11 DCF

The IEEE 802.11 DCF [17] is a standardized MAC scheme for wireless local area networks (WLANs), which employs CSMA and collision avoidance (CSMA/CA) with a binary exponential back-off algorithm. In DCF, each node should first sense the channel before the actual transmission. If the channel is sensed to be idle for a time duration that equals to DCF inter-frame space (DIFS), then it can transmit. Otherwise, if the channel is busy, it should keep sensing until the channel is idle again for a duration of DIFS. To alleviate collisions, the node is required to wait for a random back-off time instead of transmitting directly, where the back-off time is determined by the binary exponential back-off algorithm. If a transmitter expires its back-off timer first, it transmits a request-to-send (RTS) frame to its receiver, which responds with a clear-to-send (CTS) frame after a period of short inter-frame space (SIFS). After overhearing the exchanging of RTS/CTS frames, the neighboring nodes in the transmission range of the transmitter and/or receiver should set up their network allocation vectors (NAVs) and freeze their back-off timers. Following by the successful exchanging of RTS/CTS frames, the transmitter and receiver will proceed with the transmission of data packets and acknowledge (ACK) frame.

When a node senses the channel to be busy or fails to receive the CTS/ACK frames, it initiates the back-off algorithm. More specifically, the back-off time is randomly selected between zero and current contention window (CW). Initially, the CW is set to CW_{min} and the CW doubles after every unsuccessful transmission until the CW reaches a preset maximum value, CW_{max}. The CW will be reset to CW_{min} after every successful transmission.

III. Fundamental Issues in Cooperative MAC

The main objective of a cooperative MAC protocol is to fully map the cooperative diversity gain at the physical layer to cooperative advantages at the MAC layer, for instance, increasing transmission rate, reducing transmission power, and/or extending transmission range. More specifically, by taking into account the protocol overhead, node mobility, and link interference, an efficient cooperative MAC protocol should be able to accurately identify the cooperation opportunity, efficiently select the best relay(s), and coordinate the cooperative transmission with reasonable cost and complexity. In this section, we will discuss in detail the fundamental issues in cooperative MAC, i.e., when to cooperate, whom to cooperate with, and how to cooperate.

A. When to Cooperate?

Intuitively, it is desirable to enable beneficial only cooperation. To achieve this goal, we should first understand when cooperation is beneficial. From a physical layer viewpoint, cooperation is beneficial if a diversity order can be achieved [20], [21]. The evaluation of beneficial cooperation at the MAC layer, however, is much more complex.

The detrimental effects incurred by cooperation (e.g., extra protocol overhead and enlarged interference area) should be considered while evaluating whether or not the cooperation is beneficial, as such effects may reduce or even completely remove the cooperation gain. In

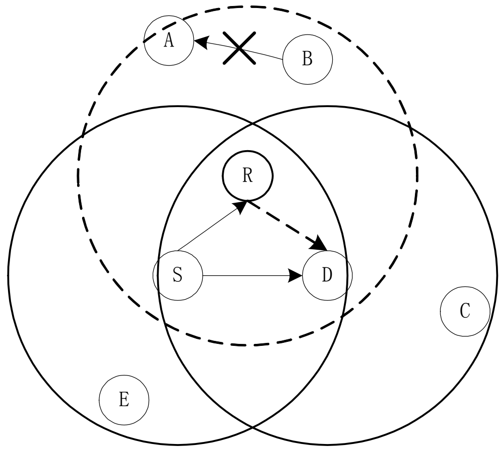

Fig. 1. With cooperation, more nodes suffer from interference. In this case, link $S-D$ can benefit from relay R; however, link $B-A$ would be blocked because of the enlarged interference area. It is not clear whether the cooperation gain achieved by R can compensate for the performance degradation caused by blocking link $B-A$.

addition, the randomness of channel dynamics and node mobility makes the cooperation decision more challenging.

Further, the criterion of beneficial cooperation depends on the networking scenario, which can be classified into fully-connected (small-scale) and multi-hop (large-scale) wireless networks. In a fully-connected network, cooperation is beneficial if the performance of the current transmitter-receiver pair can be improved, while in a multi-hop network cooperation is considered to be beneficial only when the overall network performance can be enhanced, which should take into account the interactions among different transmission pairs. More specifically, as shown in Fig. 1, cooperation benefits the current transmitter-receiver pair, but also enlarges the interference area to block the neighboring transmitter-receiver pairs, which can reduce the frequency of spatial reuse of the radio channel and in turn degrade the throughput performance of the whole network [22].

For different networking scenarios, the main objective of cooperative MAC protocols may be quite different, e.g., maximizing effective transmission rate, overall throughput, or energy efficiency. Based on the objective, we will illustrate what detrimental factors should be emphasized when evaluating whether or not the cooperation is beneficial.

1) Maximizing effective transmission rate: While cooperative transmission can increase transmission rate, it can also incur non-negligible protocol overhead in coordination signaling and relay selection, which will inevitably decrease the cooperation gain. For the sake of error control, the payload length is always limited in practical applications, which amplifies the detrimental effect of the protocol overhead. On the other hand, a higher transmission rate is likely to result in lower reception reliability under the same channel condition. Hence, more packet transmission failures reduce the effective transmission rate.

With the objective of maximizing the effective transmission rate, an efficient cooperative MAC protocol should jointly take account of extra protocol overhead, finite payload length, and transmission reliability, and stop unnecessary cooperation. For example, the effective payload transmission rate is used as a metric in [23] to determine whether or not cooperation is beneficial in a fully-connected network.

2) Maximizing overall throughput: Throughput is an important performance metric for a wireless ad hoc network. In the context of cooperative communications, the relays not only receive data packets from the transmitter, but also forward data packets to the intended receiver. As more nodes take part in the transmission of one data packet, the interference area for one cooperative link is enlarged if power control is not considered. In a wireless multi-hop multi-flow network, an enlarged interference area implies a reduction in the average number of concurrent transmissions.

To enhance the overall throughput performance, the tradeoff between the spatial reuse and transmission reliability should be carefully studied to prevent inappropriate cooperation that only benefits the concerned link at the cost of harming the overall network performance. More specifically, in a multi-hop network, the decision of beneficial cooperation should take account of node distribution, traffic load, and multi-user interference. For instance, the node degree of a relay and its relative distance to its transmitter-receiver pair can be used as metrics to select the spatially efficient relay(s) to enhance the overall throughput performance [24].

3) Maximizing energy efficiency: Energy efficiency is a critical performance metric that requires much attention, especially when the nodes are powered by batteries and the replacement or recharging is very difficult. In order to activate cooperation, the neighboring nodes are required to receive data packets that are not destinated to them, so as to identify cooperation opportunities and help forwarding data packets to the destination when necessary. As a result, the neighboring nodes should always keep listening. Besides, to alleviate packet transmission collisions, non-negligible coordination signaling is required for channel access and relay selection.

Energy efficiency can be reduced in overhearing packet transmissions and in extra coordination signaling. Therefore, the extra energy consumption should not be neglected in evaluating whether or not the cooperation is beneficial [25]. Otherwise, improper cooperation can consume more energy than direct transmission. Power control [26] and low power listening integrated with cooperation can help to improve the energy efficiency.

Further, if the information of instantaneous CSI, node mobility, and traffic load is available, a more accurate decision on beneficial cooperation can be made, which can lead to better performance. The implementation complexity incurred by cooperation is also an important factor that should be considered when deciding whether or not to cooperate.

B. Whom to Cooperate with?

With the criterion for beneficial cooperation, the next issue to address is whom to cooperate with if multiple potential relays are available. In order to answer this question, we should first understand the impact of cooperation strategy, and then investigate the relationship between the cooperation gain and the number of relays. Impacts of cooperation strategy and relay number are in general correlated.

1) Impact of cooperation strategy: Cooperative communication consists of two phases, namely information sharing phase and cooperative transmission phase. In the information sharing phase, the transmitter broadcasts its information to the relays and receiver. Then in the cooperative transmission phase, the relays forward the same copy of information packets to the intended receiver through independent links. Two different cooperation strategies can be adopted in the cooperative transmission phase, which are repetition-based cooperative transmission [27] and space-time coded cooperative transmission [28].

In repetition-based cooperative transmissions, each relay is assigned an orthogonal time-slot to forward packets to the receiver sequentially. As a result, the transmissions via different relays experience independent channel fading. A total of n time-slots are required by n relays to finish the cooperative forwarding. Therefore, there is a tradeoff between the diversity order and bandwidth efficiency. More relays achieve a higher diversity gain, but also consume more time-slots.

On the other hand, the independence in space-time coded cooperative transmissions is obtained by assigning each relay an orthogonal code, through which all relays can forward packets to the receiver in the same time-slot. In this way, both diversity gain and bandwidth efficiency can be achieved, which comes at the cost of complex signaling and information processing at the receiver and precise synchronization among cooperating relays. For example, the instantaneous CSI between every relay and the receiver is required for successful decoding.

2) Impact of relay number: Intuitively, employing more relays will lead to a higher diversity gain. However, from the MAC layer point of view, more relays incur more protocol overhead and larger interference area, which may degrade the cooperation gain in a multi-hop network. Without a central controller, more coordination overhead is required to select and coordinate more relays in an orderly fashion. Because of the protocol overhead, the energy efficiency of cooperative transmissions can decrease with an increase in the number of relays. If the number of relays is not sufficient, the multi-relay cooperation cannot be established and the radio spectrum resources used for cooperative information exchange are wasted [29]. It is pointed out in [30] that the interference area caused by cooperation is enlarged proportionally to the number of relays, which reduces the frequency of spatial reuse and in turn possibly degrades the overall throughput performance. Compared with a multi-relay cooperative scheme, a single-relay cooperative scheme requires neither cooperative beamforming nor distributed space-time coding [5].

Overall, single-relay cooperation is easier to implement and incurs less protocol overhead and smaller interference area. It is proved in [31] that selecting the best relay can achieve the same diversity-multiplexing tradeoff (DMT) as that of multi-relay cooperation. Therefore, many existing works focus on the repetition-based scheme by selecting the best single relay because of its simplicity and efficiency.

3) Cooperate with the best relay: The best relay is one of the potential relays that can improve the target performance to the maximum extent. The definition of the best relay depends on the application scenario. For instance, to maximize the effective transmission rate, the relay with the best channel condition should be selected [32]; to maximize the network lifetime, the relay with the most residual energy is preferred [33]; to improve the spatial reuse, the relay with the least neighboring nodes is favored [24]; to maximize the overall throughput, the relay that can achieve the highest cooperation gain and incur the smallest interference area should have the highest priority.

C. How to Cooperate?

After determining the cooperation strategy and the maximum number of relays, selecting the best relay(s) efficiently and effectively in a distributed manner plays a pivotal role in determining the overall performance of cooperation. An efficient relay selection scheme should have the following characteristics:

- The relay selection should be fast (time efficient);
- The relay selection should keep the collision probability at a low level or even be collision-free;
- The best relay should be guaranteed to be selected;
- The relay selection should be able to adapt to time-varying channel conditions and node mobility;
- The hidden relay problem should be avoided.

In the following, we discuss several representative relay selection schemes that have been proposed. A table-based relay selection scheme is proposed in [34], in which the best relay is preselected by the transmitter according to the observation of historical transmissions. Although this table-based relay selection scheme is fast and collision-free, it cannot adapt to time-varying channel conditions and the best relay is not guaranteed to be selected. To alleviate the drawback of the non-adaptivity while maintaining the merit of being fast and collision-free, more potential relays can be preselected by the transmitter [35]; however, it is still not guaranteed to select the best relay.

In order to select the best relay, many contention-based relay selection schemes have been proposed. For instance, a busy-tone based relay selection scheme is effective to select the best relay without collisions [36]. As the best relay is required to transmit the longest busy-tone to win the contention, this relay selection approach is not efficient in terms of spectrum and energy usages. A back-off scheme as an effective approach is proposed to select the best relay as fast as possible [31]. Each relay maps its current utility or cooperation metric to a back-off time, and the best relay will get the shortest back-off time and broadcast the cooperation intention first. In general, there is a tradeoff between the efficiency of relay selection and collision probability. A longer relay selection period results in a lower collision probability, and vice versa. Thus, it is challenging to efficiently select the best relay while keeping a low collision probability. In addition, a fast and scalable splitting-based algorithm is proposed for relay selection, through which the best relay is guaranteed to be selected [37]. However, this scheme requires the transmitter to feed back the outcome of relay selection after every contention time-slot.

Table I summarizes the main advantages and disadvantages of the existing relay selection schemes. As we can see, it is challenging to design an efficient relay selection scheme that can satisfy all requirements. Table II summarizes the main differences of several representative cooperative MAC protocols, according to the aforementioned various classification criterions.

TABLE I
COMPARISON OF EXISTING RELAY SELECTION SCHEMES

Schemes	Representatives	Advantages	Disadvantages
Preselect, Historical information	CoopMAC [34] rDCF [38]	Fast relay selection, collision-free, no hidden relay problem	Best relay not guaranteed, not able to adapt to node mobility and channel dynamics
Contention, Statistical information	Spatial MAC [24] Relayspot [39]	Suitable for highly dynamic scenarios	Best relay not guaranteed, possible collisions and hidden relay problem
Contention, Busy-tone	CTBTMA [36]	Guarantee best relay, collision-free, alleviate hidden terminal problem, adapt to channel dynamics	Long relay selection period, requiring extra spectrum resources
Contention, Back-off	Bene CMAC [23] CRBAR [40] LCMAC [32]	Guarantee best relay, efficient relay selection, adapt to channel dynamics	Tradeoff between protocol overhead and collision probability, hidden relay problem
Contention, Splitting	Split-Tradeoff [37] Split-DMT [41]	Guarantee best relay, fast relay selection, adapt to channel dynamics	Very sensitive to errors of synchronization and channel feedback

IV. COOPERATIVE MAC PROTOCOLS FOR WLANS AND FULLY-CONNECTED NETWORKS

In this section, we present an overview of the existing cooperative MAC protocols for WLANs and fully-connected networks, in which the protocols are further classified according to the associated research problems. Specifically, we summarize the main causes of performance degradation in terms of throughput and energy efficiency, discuss the corresponding cooperative solutions, and present several representative cooperative MAC protocols. A broad classification of the existing cooperative MAC protocols is shown in Fig. 2.

A. Combating Deep Channel Fading

Packet transmission through a wireless link suffers from deterministic path loss, time-varying large-scale and small-scale fading, and interference [51]. In the case of a transmission failure

TABLE II

COMPARISON OF EXISTING COOPERATIVE MAC PROTOCOLS

Cooperative MAC Protocols	Network Scenario	Research Objective	Cooperation Strategy	Cooperation Decision	Relay Number	Relay Selection Scheme
2rcMAC [42]	Small-size	Throughput	Repetition-based, Proactive	Relay	Two	Contention, Mapping
AR-CMAC [43]	WLAN	Throughput	Repetition-based, Proactive	Transmitter	One	Contention, Backoff
Bene CMAC [23]	Fully-Connected	Throughput	Repetition-based, Proactive	Relay	One	Contention, Backoff
CCMAC [44]	WLAN	Spatial Reuse	Repetition-based, Proactive	Transmitter	One	Preselect, Historical Information
CDMAC [45]	Multi-hop	Throughput	Space-time-coded, Proactive	Transmitter	Two	Preselect, Historical Information
Coop MAC [26]	Fully-connected	Energy Efficiency	Repetition-based, Proactive	Relay	One	Contention, Backoff
CoopMAC [34]	WLAN	Throughput	Repetition-based, Proactive	Transmitter	One	Preselect, Historical Information
CRBAR [40]	Multi-hop	Throughput	Repetition-based, Proactive	Relay	One	Contention, Backoff
CTBTMA [36]	Multi-hop	Throughput	Repetition-based, Proactive	Relay	One	Contention, Busy-tone
DQCOOP [46]	WLAN	Delay	Repetition-based, Reactive	Receiver	One	Contention, Backoff
Hybrid ARQ [47]	Multi-hop	Throughput	Network Coding, Reactive	Receiver	One	Contention, Backoff
LCMAC [32]	Multi-hop	Throughput	Space-time-coded, Proactive	Relay	One	Contention, Backoff
Opt-MAC [48]	Fully-connected	Energy Efficiency	Repetition-based, Reactive	Receiver	One	Contention, Backoff
PRCSMA [25]	Fully-connected	Energy Efficiency	Repetition-based, Reactive	Receiver	One	Contention, Backoff
RCF-MAC [35]	WLAN	Throughput	Repetition-based, Proactive	Transmitter	One	Preselect, Priority
rDCF [38]	Multi-hop	Throughput	Repetition-based, Proactive	Receiver	One	Preselect, Historical Information
Retr CMAC [49]	WLAN	Throughput	Repetition-based, Proactive	Transmitter	One	Preselect, Statistical Information
Spatial MAC [24]	Multi-hop	Spatial Reuse	Repetition-based, Proactive	Relay	One	Contention, Backoff
STiC MAC [50]	WLAN	Throughput	Space-time-coded, Proactive	Relay	Random	Qualification
WcoopMAC [33]	Sensor Network	Lifetime	Repetition-based, Proactive	Relay	One	Contention, Backoff

(e.g., timeout of the ACK frame), a transmitter tries to retransmit the data packet to its intended receiver until the receiver decodes the data packet successfully or the number of retransmission attempts reaches a maximum limit. However, if the transmission failure is due to deep channel fading rather than packet collisions, it is likely that a retransmission from the transmitter does not help, especially when the channel coherence time is long. Hence, much radio spectrum and

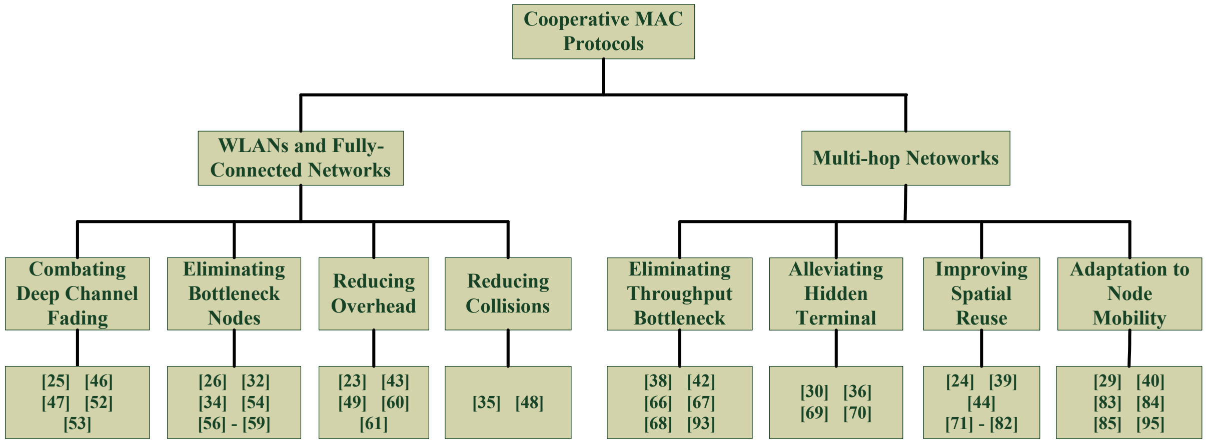

Fig. 2. Classification of cooperative MAC protocols according to specific network scenarios and associated research problems.

energy resources will be wasted if a transmitter keeps retransmitting over a deep fading channel.

Cooperative automatic repeat request (ARQ) is an effective method to combat deep channel fading [52]. Through exploiting the wireless broadcast nature, cooperative ARQ can efficiently recover the corrupted data packets. The main idea of the cooperative ARQ scheme is as follows. Whenever a receiver fails to receive a data packet, it requests packet retransmission from its neighboring nodes that overhear the original transmission rather than from the original transmitter. In this way, a spatial diversity gain is achieved as the receiver obtains multiple copies of the same packet over channels that experience independent fading. Consequently, the reliability and throughput performance can be improved [52].

With a cooperative ARQ scheme, the maximum performance improvement can be obtained by selecting the best relay that has the best link quality with respect to the receiver; however, selecting the best relay incurs extra protocol overhead and possible packet collisions. The effects caused by both protocol overhead and packet collisions are contrary to the goal of improving the throughput performance. The issue of packet collisions is addressed in [46] where a DQCOOP protocol is proposed to coordinate relay selection by using a clustering method. On the other hand, uncoordinated cooperative ARQ is effective to eliminate the protocol overhead at the cost of a higher collision probability, as each potential relay contends to retransmit according to the local information and spatial distribution of potential relays [53]. Obviously, there is a tradeoff between the coordination overhead and collision probability. Besides, a network coding technique can be integrated with cooperative ARQ to further improve the throughput performance and motivate the neighboring nodes to cooperate. Specifically, the selected relay can transmit a linear combination of the corrupted packet and its own packet that is destinated to the same receiver [47]. In this way, the receiver can decode both data packets simultaneously.

Cooperative ARQ is a reactive cooperative scheme as it is activated only when the direct transmission fails. In order to identify the cooperation opportunity, the neighboring nodes are required to receive data packets that are not destinated to themselves. Hence, extra energy consumption at the neighboring nodes is unavoidable. Even so, cooperative ARQ may still achieve better performance in terms of energy efficiency [25]. As cooperative ARQ may not always be beneficial, it is necessary to address the tradeoff between the cooperation gain and corresponding cost (e.g., extra protocol overhead and energy consumption, and transmission collisions).

B. Eliminating Bottleneck Links

Due to the channel sharing nature in WLANs and fully-connected networks, one active transmitter exclusively occupies the medium for a period of packet transmission time once it wins the channel contention, while all other nodes should keep silent until the channel is free again. Thus, performance anomaly can be witnessed by high-quality links as more time and energy resources are consumed by low-quality links (i.e., bottleneck links). Specifically, with the same payload length, a low-quality link takes a longer time to transmit a packet than a high-quality link, which reduces the efficiency of channel utilization [54], [55]. On the other hand, in order to support the same transmission rate, a low-quality link should employ a higher transmission power than a high-quality link, which degrades the energy efficiency [26] and increases the interference level.

It is pointed out in [55] that the root of the performance anomaly is the CSMA/CA scheme, which guarantees a fair channel access opportunity for all nodes in the long term. Cooperative communication combined with adaptive modulation and coding (AMC) techniques is effective to eliminate the performance anomaly without revising the CSMA/CA scheme. The main idea is to identify a poor-quality direct link and proactively find an alternative faster two-hop link to eliminate the performance anomaly. The exchanging of control frames, activated before the actual data transmission, is effective to identify the performance anomaly, as control frames are relatively short and transmitted with the maximum power at the basic rate [32], [34]. On the other hand, an efficient relay selection scheme is required to select the best relay that can maximize the two-hop data rate [23].

Each transmitter in CoopMAC [34] maintains a CoopTable by passive listening, which contains the historical transmission rates of its neighboring nodes. After probing a poor-quality direct link, a transmitter proactively selects the best relay based on its CoopTable. Throughput performance can be improved when the direct link quality is poor; however, CoopMAC may not adapt to time-varying channel conditions. A higher transmission rate may be achieved by further using a maximum ratio combining (MRC) technique, as the receiver can combine data packets that are transmitted from the source node and its relay(s). However, the receiver is required to store an analog version of received data packets from the source node, which incurs complex physical layer modifications [56]. In addition, the network performance improvement by combining two copies from the source node and relay may not always be achieved over that of decoding a copy from the relay only [57]. Therefore, MRC should be opportunistically activated at the receiver according to measurements of the instantaneous CSI. Moreover, based on joint power allocation and relay selection, energy efficiency can be improved by mitigating the detrimental impact of bottleneck links. Specifically, the best relay can be selected to minimize the energy consumption or maximize the network lifetime [26].

Another method to deal with the performance anomaly is to fully utilize the time diversity by opportunistically accessing channel and activating cooperation. Specifically, to enhance the overall network performance, a poor-quality link may activate cooperation, or give up the transmission opportunity and let all other transmitters re-contend. In this way, a bottleneck link will not transmit its data packets until a high-quality direct or cooperative link is available. Hence, by avoiding the transmissions of poor-quality links, the throughput performance can be enhanced. By modeling the opportunistic channel access and cooperation activation problem as an optimal stopping problem, an optimal channel access and cooperation strategy can be obtained [58], [59].

C. Reducing Overhead

While cooperation in mobile communication networks can enhance network performance, it can incur non-negligible cooperation overhead. This cooperation overhead includes coordination signaling, which is required to coordinate efficient and effective medium access as more nodes take part in the transmission of one data packet. The time consumed for selecting the best relay is another form of cooperation overhead. There is a tradeoff between the relay selection period and the collision probability. When multiple beneficial relays are available, a shorter relay selection period will result in a higher collision probability, and vice verse. Both cooperation overheads can affect the cooperation decision and decrease the cooperation opportunities as they can reduce or even eliminate the cooperation gain, especially when the payload length is short. Therefore, it is desirable to design a distributed relay selection scheme that takes account of the cooperation overhead incurred by both coordination signaling and relay selection. This issue is addressed in [23] where the concept of cooperation region is introduced to describe the opportunities of beneficial cooperation. An optimal grouping strategy based distributed back-off scheme is effective to select the best relay. The grouping parameters are optimized to shorten the relay selection period, while keeping a low collision probability. Besides, cooperation overhead can also be compensated for by eliminating the channel access time of the selected relay [43], [60]. Specifically, an active relay can transmit its own packet immediately after helping to boost the transmission rate of its neighboring link.

The delay incurred by packet retransmissions should be considered as a form of overhead [49]. An unreliable wireless link suffers from frequent packet retransmissions that is detrimental to the overall network performance. Hence, in order to reduce the retransmission overhead, reliability should be considered when selecting the best relay. Through reducing the retransmission overhead, the beneficial cooperation opportunity can be seized more precisely and the cooperation gain can be exploited. Finally, the extra overhead also includes the energy consumptions for coordination signaling and relay selection. A CSMA/CA based reactive cooperative MAC protocol can be more energy-efficient as the number of control frames is reduced. For example, the exchanging of RTS/CTS frames can be disabled, and the best relay can be selected based on the local information (e.g., residual energy and measured CSI) [61].

As we can see, there is a tradeoff between the achieved cooperation gain and the incurred protocol overhead. The protocol overhead can be reduced by shortening the relay selection period, decreasing the channel access time, reducing packet retransmissions, and disabling the exchanging of control frames. Further reduction in cooperation overhead can be achieved by combining the relay selection and channel access periods. Reducing cooperation overhead can create more beneficial cooperation opportunities.

D. Reducing Collisions

Collisions in a relay selection period happen when multiple beneficial relays contend to be the best relay in the same time-slot. Frequent collisions can significantly reduce the cooperation opportunities and degrade the network performance. However, due to the wireless broadcast nature and the lack of a central controller, it is challenging to select the best relay(s) efficiently and effectively while keeping a low collision probability. There is a tradeoff between the relay selection period and collision probability. In general, a longer relay selection period can provide a lower collision probability, and vice versa. There are two solutions to alleviate the collision problems in relay selection. One is to preselect one or more potential relays and specify corresponding priorities according to the historical or statistical information. After exchanging control frames, each preselected relay independently decides whether or not to cooperate according to the instantaneous CSI and contends to act as the final relay according to its priority [35]. In this way, the relay selection period is shortened dramatically and the collisions among potential relays is eliminated. However, this method does not guarantee to select the best relay as it does not adapt to time-varying channel conditions and not fully exploit the selection diversity.

Recently, many cooperative MAC protocols adopt a back-off scheme to select the best relay because of its simplicity and effectiveness. However, the effectiveness of a back-off scheme may be reduced when applied to a dense network scenario, due to possible high collision probabilities. Therefore, an intuitive solution is to increase the relay selection period so as to alleviate the contention level among potential relays; however, this method also reduces the efficiency of relay selection. Hence, the tradeoff between the efficiency of relay selection and the collision probability should be carefully addressed. For example, according to the node density, an optimal SNR segmenting method is presented in [48] to establish a mapping relationship between the instantaneous SNR and contention time-slot.

There is no clear winner between both solutions, as both have their own pros and cons for different application scenarios. If more information (e.g., relay distribution and density) is available for relay selection, the collision probability may be reduced without extending the relay selection period.

V. COOPERATIVE MAC PROTOCOLS FOR MULTI-HOP NETWORKS

A multi-hop network suffers from the same causes of performance degradation as a single-hop network. Further, because of dynamic network connectivity and complex interactions among active links, more problems (e.g., hidden and exposed terminal problems, untractable accumulative interference, and frequent node mobility) may arise and reduce cooperation gain.

In this section, we provide an overview of the existing cooperative MAC protocols that are designed for multi-hop networks. We summarize the main causes of performance degradation, discuss the cooperative solutions, and present several representative cooperative MAC protocols.

A. Eliminating Throughput Bottleneck

Due to the broadcast nature of wireless transmissions and network topology dynamics, both inter-flow and intra-flow contentions lead to unfairness in channel access, i.e., some links may be blocked or even starved by their neighboring links [62]. A link with a low channel access probability or low transmission rate becomes the throughput bottleneck of a multi-hop flow, as the end-to-end throughput is limited by the bottleneck link.

Many non-cooperative MAC protocols [63]–[65] have been proposed to eliminate the performance degradation caused by the inter-flow and intra-flow contentions. For example, priority-based and backward-pressure scheduling schemes are proposed to improve the channel access probability of bottleneck links [63]. In the context of cooperative communications, efficient resource utilization can be achieved by relay load balancing [66] and network load balancing [67] to alleviate the inter-flow contention. In addition, the transmission rate [38] and reliability [42], [68] can be enhanced through cooperative relaying to alleviate the intra-flow contention. Here, we focus on the transmission rate and reliability improvement achieved by cooperative relaying.

Two cooperative MAC protocols, CoopMAC [34] and rDCF [38], mitigate the detrimental effects caused by a low-quality link through enabling an alternative faster two-hop link. In rDCF, a receiver makes the final decision on whether or not to employ the preselect relay according to the instantaneous CSI, while such decision is made at a transmitter in CoopMAC. However, throughput performance is not fully guaranteed by transmission rate, but also affected by transmission reliability. A two-hop cooperation link is more susceptible to a transmission failure due to the independent channel fading of both hops. Based on this observation, a two-hop cooperative link is used as a backup link in UTD-MAC [68] and invoked after the direct transmission fails. In this way, higher reliability can be achieved at the cost of a lower transmission rate. Intuitively, better performance can be achieved by jointly considering the transmission rate and reliability. Hence, a two-relay-based cooperative MAC protocol [42] may be more effective to enhance the throughput performance by selecting the best two relays, where the first relay is used to achieve higher transmission rate while the second relay is invoked as a backup node for higher transmission reliability. However, the extra coordination signaling is required, and two qualified relays may not always be available. As a result, increasing channel access probability and enhancing throughput performance of bottleneck links can eliminate the throughput bottleneck problem.

B. Alleviating Hidden Terminal Problem

In a multi-hop network, contention-based MAC protocols suffer from the notorious hidden and exposed terminal problems. All nodes within the interference area of a receiver, except the transmitter, should keep silent to avoid interrupting the ongoing packet reception. The hidden terminal problem happens when two nodes (which are outside each other's interference area) transmit simultaneously to the same node, resulting in a collision. The exposed terminal problem occurs when two nodes (which are within each other's interference area) avoid to transmit at the same time while their transmissions in fact do not interfere with each other at two receivers far apart. The exchanging of RTS/CTS frames is effective to alleviate the hidden terminal problem in non-cooperative scenarios; however, this problem cannot be eliminated as the RTS/CTS frames themselves suffer from collisions. In the context of cooperative communications, cooperating relays enlarge the interference area. As a result, more nodes (i.e., potential relays and their neighbors) suffer from the hidden and exposed terminal problems. Further, both problems become worse with node mobility. Similarly, the hidden terminal problem can be alleviated at the cost of more radio spectrum resources or lower cooperation gains. For example, a cooperative tripe busy-tone multiple access (CTBTMA) scheme is proposed in [36] to alleviate the hidden terminal problem. Both transmit-busy-tone and receive-busy-tone are employed to protect the transmissions of control frames and data packets. In addition, a helper-busy-tone is used to avoid collisions at potential relays and to select an optimal relay. A busy-tone based scheme consumes more energy and requires more radio spectrum resources.

A different approach is to use distributed back-off to select the best relay [30]. After the initialization of relay selection, the helper indication (HI) frames are broadcasted by potential relays to inform their neighboring nodes about their existence. Subsequently, each potential relay inversely maps its utility (e.g., achievable transmission rate) to a back-off time. The best relay expires its back-off timer first and sends out a ready-to-help (RTH) frame to notify the transmitter and receiver as well as other potential relays. After overhearing the RTH frame from the best relay, other relays quit contention and set up their NAVs accordingly. The hidden terminal problem among potential relays can still happen if multiple beneficial relays cannot hear each other. In order to guarantee that only one optimal relay is selected and eliminate the hidden terminal problem among potential relays, the transmitter can broadcasts a control frame to inform all potential relays to stop contention after one optimal relay claiming its existence [69].

Another approach to overcome the hidden terminal problem in the relay selection period is to construct a constrained relay selection area [70]. All potential relays within this area can hear each other, thus the hidden terminal problem is alleviated without incurring extra coordination overhead. In addition, the contention level can be reduced as some potential relays may be excluded by the constrained relay selection area. However, such an approach does not fully exploit the selection diversity.

C. Improving Spatial Reuse

In a multi-hop network, interference is a major detrimental factor that limits the overall network performance. When cooperative transmission is activated, more nodes take part in the transmission of one data packet, which leads to a more complex interference relationship. Specifically, the neighboring nodes of a relay should be blocked to guarantee the successful cooperative transmission. With constant transmission power, the number of concurrent cooperative transmissions can be reduced and so is the frequency of spatial reuse when compared with non-cooperative transmissions. Hence, in a multi-hop network, the misuse of cooperative transmissions may only benefit one transmitter-receiver pair, but do harm to the overall network performance. It is not clear whether or not the cooperation gain can compensate for the reduced spatial reuse. Recently, several methods have been proposed to activate cooperative transmissions while considering the spatial reuse.

1) Relay assignment: The objective of relay assignment is to assign the available relays to different transmitter-receiver pairs so as to maximize the overall network performance. Under the assumption of infinite orthogonal channels, an optimal relay assignment (ORA) algorithm can maximize the minimum data rate among all transmitter-receiver pairs [71]. For a multi-hop multi-flow network, a joint optimization problem of flow routing and relay assignment should be considered [72]. Further, interference-aware relay assignment can be used in a single channel network to maximize the minimum achievable bandwidth among all pairs [73]. Recently, many works are proposed to generalize the relay assignment, for example, maximizing the sum-rate [74], considering the selfish relays [75], selecting multiple relays [76], combining with network coding [77], and guaranteeing QoS requirements [78].

2) Scheduling: Through collecting spatial distribution information, a distributed scheduling scheme is effective to enhance the overall network performance by jointly considering cooperation gain and spatial reuse. For example, in coordinated cooperative MAC (CCMAC) [44], the access point (AP) takes the responsibilities to collect spatial distribution information and schedule multiple concurrent transmissions. Multiple transmitters transmit data packets to their own relays simultaneously without interfering with each other; after that, the relays forward data packets to the AP sequentially. In addition, a joint physical carrier sensing and virtual antenna array tuning scheme can enhance the spatial reuse and avoid the excessive interference [79].

By jointly considering cooperative relaying and spatial reuse, the performance degradation caused by high mobility and intermittent connectivity in a vehicular ad hoc network can be mitigated. One typical example is a vehicular cooperative MAC (VC-MAC) protocol that is proposed to enable concurrent relaying in a gateway downloading scenario [80]. All vehicles try to receive packets broadcasted from the gateway, and share their reception status with each other. Then, an optimal relay set can be selected to forward packets to their failed neighboring nodes concurrently without incurring packet collisions. As one-cycle relaying may not be sufficient to forward packets to all vehicles, two-cycle cooperative MAC (VC2-MAC) can be used to improve the reachability and downloading efficiency [81].

3) Priority mechanism: Through analyzing the tradeoff between the cooperation gain and spatial reuse, the beneficial cooperation criterion in a multi-hop network can be obtained in average sense. Specifically, as cooperative relays enlarge the interference area, the reduced spatial reuse can be characterized in terms of the increased channel resource consumptions. By modeling the channel resource allocation as a conflict-graph-based coloring problem, the minimum number of orthogonal channels required for both direct transmission and cooperative transmission can be derived, respectively [82]. The ratio of these two numbers can be used as a priority reference for selecting the cooperative relay(s) in a distributed manner.

Without exchanging spatial distribution information, a priority mechanism can be used to select the spatially efficient relays with small protocol overhead. By assigning higher contention priorities to the relays that are closer to the transmitter/receiver and have less neighboring nodes, the spatially efficient relays are more likely to win the contention and improve the frequency of spatial reuse [24]. In addition, for a multi-hop mobile network, other factors (e.g., traffic load, node mobility, and historical information) should be further considered in relay selection to improve spatial reuse [39].

In general, a relay assignment scheme achieves the maximum spatial reuse based on the global network topology in the absence of small-scale fading. A scheduling scheme improves the spatial reuse at the cost of collecting spatial distribution information, while a priority-based scheme increases spatial reuse according to local information. Obviously, there is a tradeoff between the frequency of achievable spatial reuse and the amount of available network information.

D. Adaptation to Node Mobility

Node mobility poses a great challenge for the design of cooperative MAC protocols in a multi-hop network. The channel condition between any two mobile nodes fluctuates with time, which requires frequent cooperation decisions and fast relay selections. Further, node mobility leads to frequent link breakages, which can significantly degrade the network performance. Existing cooperative MAC protocols combat the node mobility from two aspects, namely adapting to channel dynamics and link breakages, respectively. In order to adapt to channel dynamics and improve the transmission rate, the relay candidates can adaptively adjust their transmission schemes and rates according to the instantaneous CSI. For example, the transmission scheme in CRBAR [40] can be smoothly switched among direct transmission, simple relaying and cooperative relaying.

Cross-layer design between the MAC and network layers is effective to combat the link breakages. With routing and location information, the neighboring nodes can be classified into equivalent and remedy nodes, which are introduced to adaptively recover the link breakages [83]. Specifically, the equivalent nodes can substitute the current receiver to forward data packets to the next receiver, while the remedy nodes can help retransmitting data packets to the current receiver. The link breakage happens when the direct link and all alternative two-hop links are in outage. Hence, the robustness to link breakages can be significantly enhanced. In addition, the robustness to link breakages can be obtained by extending the transmission range. With a small extension in interference range, the virtual multiple-input single-output (MISO) links can significantly increase the transmission range [29]. ADC-MAC [84] is another example to combat link breakages by increasing the network coverage. ADC-MAC adaptively exploits spatial diversity to extend the network coverage according to channel quality and relay location. Another cross-layer design method is to allow every intermediate node updating routing path from this point on towards the destination node according to its own knowledge [85]. The neighboring nodes are also allowed to retransmit data packets if the direct transmission fails. In this way, the robustness to both link breakages and channel dynamics can be achieved.

VI. Open Research Issues

The MAC layer design is essential for achieving cooperative diversity, as it is responsible for accurately identifying the cooperation opportunity and efficiently selecting the best relay. Although many cooperative MAC protocols have been proposed to enhance the network performance, there are still many open research issues that need further studies.

A. Beneficial Cooperation Metrics

To achieve the maximum performance improvement, it is important to accurately prevent unnecessary cooperation and to efficiently select the best relay. Therefore, defining an accurate beneficial cooperation metric can help for an efficient cooperative MAC protocol. Most of the existing cooperative MAC protocols take the protocol overhead, instantaneous CSI, and residual energy into consideration while evaluating the effectiveness of cooperation from the viewpoint of a single link. However, to activate beneficial cooperation from the viewpoint of the overall network performance, a cooperation metric that captures only the aforementioned factors is no longer sufficient. Specifically, impacts of traffic load, node mobility, interference relationship, and node density should be incorporated into the beneficial cooperation metric. However, to obtain the information may incur considerable protocol overhead, or even worse the information can be difficult to use for quantitative analysis. Thus, an effective cooperation metric that can accurately identify the beneficial cooperation opportunity needs to be defined for a multi-hop mobile network.

B. Cooperation Gain and Corresponding Cost

Cooperative communication can enhance the network performance by exploiting the spatial diversity; however, it can also incur extra cooperation overhead and complicate the interactions among cooperative links. Many existing works have considered the cooperation overhead incurred by coordination signaling and relay selection. However, the impact of complicated interactions among cooperative links has not received much attention. Specifically, for a multi-hop cooperative network, the interference area of one link is enlarged but the interference level may be reduced, which can be seen as a redistribution of interference. The interference redistribution makes the hidden and exposed terminal problems more complex to deal with. For example, in a relay selection period, the potential relays may be blocked by their neighboring transmitters unnecessarily (exposed terminal problem) and collide with their neighboring receivers without intention (hidden terminal problem). Therefore, cooperative MAC should alleviate or eliminate the hidden and exposed terminal problems in a multi-hop networking environment. In summary, the tradeoff between the cooperation gain and corresponding cost should be carefully studied, so as to achieve better cooperation performance and eliminate the obstacles for the practical implementations of cooperative communications.

C. Performance Analysis

In a multi-hop network, spatial reuse becomes possible and multiple transmissions can be carried out concurrently; however, accumulative interference may lead to low reception quality at each receiver. Stochastic geometry [86]–[88] as an effective method has been used to model and analyze the impacts of both spatial reuse and accumulative interference on the overall network performance. Till now, by assuming that nodes are distributed according to a Poisson point process, transmission capacity of the overall network is analyzed for different scenarios, such as slotted ALOHA [89], slotted ALOHA with two-way transmission [90], and CSMA [91]. However, because of complexity, the performance analysis for a CSMA-based cooperative scheme has not been carried out yet. Such analysis will provide better understanding on the impact of interference redistribution on the overall network performance, and help to answer questions such as whether to use a single relay or multiple relays to maximize the overall network performance.

D. Cross-Layer Design

For simplicity and compatibility, traditional layered architecture for wireline networks is based on independent operation at each layer of the protocol stack; however, this layered design does not adapt well to the channel dynamics in wireless communications. In contrast, the flexibility obtained by the cross-layer design can help to deal with channel dynamics and make more efficient use of limited radio spectrum resources [92]. Many existing cooperative MAC protocols [23], [40], [84], [93] use cross-layer design between the physical and MAC layers, as relay selection is related to rate adaptation and power control. Recently, cross-layer design has been extended to between the MAC and network layers [29], [70], [85], [94], [95]. Routing information can help to improve the transmission reliability by making a better cooperation decision [95]. In general, the cross-layer design between the MAC and network layers is used to select an optimal forwarder, while the cross-layer design between the MAC and physical layer aims to select the best relay [70].

Although some works have addressed the cross-layer design among physical, MAC and network layers, they are still far from optimal as cooperation requires close interactions among different layers. The network layer should be able to alleviate contention level at the MAC layer, while the MAC layer should be able to identify more cooperation opportunities for route establishment at the network layer. However, most existing works decouple the packet forwarding operation with relay selection, which may restrict the cooperation opportunity along a non-cooperative path. Therefore, it is desirable to design a contention-aware and cooperation-opportunity-aware cross-layer protocol, which can establish a routing path with better robustness and more cooperation opportunities.

E. Multi-Hop Cooperation

Existing studies on cooperative communications are mainly focused on the performance improvement of a single link, which may not be optimal for a multi-hop network. By further exploiting the wireless broadcast nature, a relay that is beneficial to multi-hop performance should be considered. End-to-end throughput and outage performance can be enhanced by adaptively selecting the single-hop relay(s) and multi-hop relay(s) according to the instantaneous CSI and network topology. However, the coordination and relay selection become more complicated as the channel and traffic conditions over multiple hops should be jointly considered.

To enhance the overall network performance, interference-aware relay assignment is an effective method, especially in a single channel network. However, relay assignment is always centralized and suitable for a static networking scenario. To be more practical, traffic load, link fairness, and implementation complexity should be carefully studied. Hence, it is necessary to design a distributed cooperative MAC protocol that can jointly incorporate flow scheduling and relay assignment to maximize the overall network performance, while taking account of the interference caused by neighboring links.

VII. Conclusions

By utilizing the wireless broadcast nature and allowing multiple nodes to work together as a virtual antenna array, cooperative communication is expected to achieve a cooperative diversity gain. It is an effective technique to enhance the network performance in terms of throughput and energy efficiency. Nevertheless, the cooperative diversity gain may reduce or even disappear if the MAC protocol is not well designed.

In this survey, we first summarize the key challenging issues in developing an efficient cooperative MAC protocol, including vulnerable and unpredictable wireless channel, inevitable protocol overhead, node mobility, enlarged interference area, and lack of a central controller. Then we discuss in detail three fundamental issues that should be carefully studied, that is when to cooperate, whom to cooperate with, and how to cooperate. Subsequently, for different networking scenarios (i.e., WLANs and fully-connected networks, or multi-hop networks), we investigate the main causes of performance degradation, discuss the cooperative solutions, and present several representative cooperative MAC protocols. Finally, open research issues that need further consideration are identified, which include beneficial cooperation metrics, cooperation gain and corresponding cost, performance analysis, cross-layer design, and multi-hop cooperation.

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