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Performance Analysis of Cooperative Multiple Access With Minimum Interference Range for Large Scale Wireless Networks

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ABSTRACT Cooperative communication techniques are widely used in large-scale wireless networks for improving network throughput. This is achieved through the creation of transmission diversity by forming multiple cooperative transmission links which involve several relaying nodes as helpers for an end-to-end data transmission. Consequently, link interference range will inevitably be enlarged, which will adversely hamper the diversity created and offset the network throughput improvement as a result. This problem has not been properly addressed by most cooperative communication protocols reported so far. In this paper, a novel protocol that performs cooperative medium access control as well as minimizes the interference range, namely MIR-CMAC, is proposed to directly address the enlarged link interference range problem introduced by cooperative communication. Specifically, functions like channel reservation, cooperative priority differentiation and contention for relay selection are collectively enabled in MIR-CMAC to reduce channel access collision and select the suitable helper node that can maximize the integrated link data rate and minimize the link interference concerned. In addition, a full interference model is established to evaluate the effect of interference across the whole process from channel access to packet transmission and derive a new network throughput analysis method for MIR-CMAC. Both numerical and simulation results demonstrate the effectiveness of MIR-CMAC and its performance improvements over other protocols.

INDEX TERMS Large scale wireless networks, medium access control (MAC), cooperative MAC protocol, full interference model, effective throughput.

I. INTRODUCTION

Large-scale wireless networks, in terms of their size, coverage and node density, have attracted increasing interest in the past decade and been widely deployed in many applications within key infrastructures [1], such as mobile ad hoc networks, wireless sensor networks, and vehicular ad hoc networks (VANETs). One of the key challenges for

these networks is the increased interference among links as the network scale increases, resulting in reduced network efficiency and reliability due to rises in latency and packet loss probability.

The performance of large scale wireless networks can be improved by applying multi-spectrum or spread spectrum technologies or deploying multiple antennas at nodes to support Multiple-In-and-Multiple-Out (MIMO) functions [2], [3]. However, due to scarce spectrum resources currently available and feasibility limitation on integrating

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several antennas at a node device, the technologies that are designed for enhancing spectral efficiency and increasing channel capacity would be a more significant and practical solution in this scenario. For this reason, the cooperative communications technique is considered as it can build virtual antenna arrays via neighboring nodes, acting as helpers, and transmit data packets at a higher data rate to improve network throughput without requiring additional spectrum resources [4]. But the interference range of a link will inevitably scales up as the network expands and more relay nodes participate in end-to-end data transmission, which will cause the parallel data transmissions created over the network not being properly realized, and thus offset the network throughput improvement intended to achieve.

The research work on cooperative communication has been mainly focused on how to improve the data rate at physical layer. In face the network performance can also be improved through the optimization of network protocols at upper layers when cooperative communication is employed in large-scale wireless networks. For example, the protocol at the medium access control (MAC) layer, one layer above the physical layer, is used to deal with channel sharing problems among neighboring nodes and critical to network performance. It is important to design a proper cooperative MAC (CMAC) protocol with an optimized relay selection strategy in order to increase the data rate of an end-to-end link, while facing the challenge from the enlarged link interference range caused by the increased number of network nodes used as helpers. However, the enlarged link interference range problem has not been properly addressed by most current CMAC protocols. These protocols focus on increasing the link data rate but overlook the effects of enlarged link interference range and the increased number of collisions in channel access as the network expands.

It is also difficult to analyze the network throughput performance in this scenario due to the random location of each link and each helper node in a large-scale wireless network with cooperative communication. To determine whether a link needs the helper node for cooperation and what data rate can be achieved by cooperative transmission is practically challenging as this relies on several factors such as the location relationship among source, destination and the helper nodes around them. Moreover, it is difficult to estimate the reduced number of concurrent cooperative transmission links because of the enlarged link interference range compared with direct transmission, due to random relay locations [5]. Most research work focuses on throughput for the performance analysis of CMAC protocols in a fully-connected or two-hop network. Specifically, the throughput performance is analyzed in connection with the reliability of link transmission [6], but without considering the process of channel access among neighboring links and handshake between source and destination nodes.

This paper addresses the two important issues for large-scale wireless networks with cooperative communication deployed: 1) how to design a proper CMAC protocol to deal

with the enlarged link interference range problem introduced by cooperative communication while increase the data rate of a link; and 2) what network throughput the CMAC can realistically achieve when the impact of the channel access protocol is taken into account. Our main contributions are as follows.

- A cooperative MAC protocol with minimum interference range (MIR-CMAC) is proposed to improve the network throughput performance in a real-world scenario. In this protocol, channel reservation and relay selection optimization are collectively enabled, so that the interference range can be properly controlled and link transmission data rates can be enhanced as much as possible.
- A full interference model is established, considering the whole process of data transmission of a link and the interference relationship between any two links in a large-scale wireless network. Based on the interference model, the expression of effective network throughput is derived.
- The effectiveness of the theoretical performance models established are verified by numerical and simulation results, showing that cooperative communication can effectively improve the throughput of large-scale wireless networks with the approach proposed in this work.

The rest of this paper is organized as follows. In Section II, the related work is introduced. In Section III, the proposed MIR-CMAC protocol is presented, including both direct transmission and cooperative transmission modes. A full interference model and a related expression of effective network throughput are presented in Section IV. In Section V, the numerical and simulation results of the proposed models are given and discussed. Finally, Section VI concludes the paper.

II. RELATED WORK

When cooperative communication is applied in a wireless network one or more helpers are used for an end-to-end link to exploit the spatial diversity at the physical layer to enhance the reliability, increase data rate, and reduce delay of the link. As protocols at the MAC layer are also critical to the network performance improvement, various CMAC protocols have been proposed, which can be classified as proactive CMAC, reactive CMAC or hybrid CMAC, depending on how the helper is chosen [7].

In the proactive CMAC protocols, each node maintains a cooperative table called CoopTable, which contains information about its neighboring nodes and their cooperation quality. Before data transmission, the source will determine whether the helpers chosen can support a higher equivalent data rate based on the information from the CoopTable. If a higher data rate can be achieved, data packets will be sent via cooperative transmission; otherwise data packets will be sent from the source to the destination directly. Typical proactive CMAC protocols are CoopMAC [4], adaptive distributed cooperative relaying MAC (ADC-MAC) [8], and

relay-enabled distributed coordination function (rDCF) [9]. These protocols are used to determine whether cooperative transmission is needed or not and which neighboring node is selected as the helper to relay the transmitted packets based on the historical information held in the system, but this information may be out of date. Therefore, these protocols are inefficient for networks where network topology and link quality are changing dynamically.

In the reactive CMAC protocols, cooperative transmission is initiated only if the direct transmission fails. Typical reactive CMAC protocols are cooperative ad hoc MAC (CAH-MAC) [10], network coding aware cooperative MAC (NCAC-MAC) [11], and cooperative relaying MAC (CoRe-MAC) [12]. In these protocols, all neighboring nodes overhear channels and receive all transmitted packets for possible cooperation actions to take on, and thus consume a substantial amount of energy unnecessarily.

To solve the problems presented in proactive CMAC and reactive CMAC, the hybrid CMAC protocols are proposed to allow the helper H to decide whether cooperative transmission is needed for data transmission between source S and destination D based on the channel state of the S-H (source-to-helper) section and H-D (helper-to-destination) section, obtained from request-to-send (RTS) and clear-to-send (CTS) handshakes, respectively. Typical hybrid CMAC protocols are CoopMAC-aggregation (CoopMACA) [13], two-relay-based cooperative MAC (2rc-MAC) [14], link-utility-based cooperative MAC (LC-MAC) [15], cross-layer cooperative MAC (CL-CMAC) [16], and reliable and efficient cooperative medium access control protocol for VANETs (RECV-MAC) [26].

The CMAC protocols mentioned above consider only one helper for participating in cooperative transmission. In the space-time code MAC (STiMAC) protocol [17], multiple helpers are used to forward data packet simultaneously through distributed space-time coding (DSTC), which can further increase the data rate and enhance transmission reliability. However, the link interference range is enormously enlarged in this case because of the involvement of multiple helpers.

The enlarged link interference range will inevitably reduce the number of effective parallel data transmissions, created by cooperative transmission, thus will limit the network throughput improvement as a result of reduction in diversity gain and frequency reuse efficiency. Therefore, the CMAC protocols mentioned above are not suitable for large-scale wireless networks when the interference problem is not properly tackled.

Throughput is one of the key network performances, which is defined as the volume of data transmitted successfully over the network per second. It is important to understand what network throughput of a CMAC protocol can be achieved and how to achieve it when cooperative communication is applied in a wireless network. In the CoopMACA protocol [13], the normalized saturation throughput is obtained based on a Markov model in a small-scale network where all sources

compete with each other during channel access. In [18], the network is simplified, composed of one source and one destination with multiple relays, and the link outage probability and network throughput are derived using the Poisson process theory, while in [19] the throughput of BT-COMAC is derived through a Markov chain that describes the backoff process. Different from [13], [18], [19] where a single successful link is allowed for data transmission in the network, a wireless self-aware network is studied in [20], which is capable of receiving multiple data packets at the same time.

The network throughput analysis in the above work features small-scale wireless networks with several or tens of nodes which can sense each other. But in large-scale wireless networks, nodes are deployed in a much wider area and each node can only sense a small portion of network nodes nearby. The link interference relationship should be considered in the throughput analysis of large-scale wireless networks.

In [21], link interference is considered in the classification of network nodes, and an upper bound of network throughput (i.e. the data transmission capacity of a network) is derived based on the outage probability. In [22], the outer interference circle and the inscribed circle are established with the relay as the center. A circular link interference model and a more accurate elliptical interference model are established in [23] and [24], respectively, for deriving and evaluating network throughput.

There is still a big gap between the theoretical throughput in the research and the actual one for large-scale wireless networks. To obtain a more realistic evaluation and reveal the true behavior of network throughput in large-scale wireless networks, a thorough performance analysis approach should be adopted to consider the whole data packet transmission process of a given link and the complete interference relationship of all links involved in the network, which is presented in the following sections.

III. COOPERATIVE MAC PROTOCOL WITH MINIMUM INTERFERENCE RANGE

We propose a cooperative MAC protocol with minimum interference range (MIR-CMAC) for large scale wireless networks, including a direct transmission mode and a cooperative transmission mode. The direct transmission mode is similar to the basic MAC protocol under the IEEE 802.11b standard, in which the mechanisms of carrier sense multiple access with collision avoidance (CSMA/CA) and four-way exchange of RTS/CTS/DATA/ACK are employed for channel access and reliable data packet transmission. The cooperative transmission mode is built on it.

Four data rates, i.e. 1 Mbps, 2 Mbps, 5.5 Mbps and 11 Mbps, can be chosen for direct transmission between source and destination. They are denoted as r_1 , r_2 , r_3 and r_4 , and the corresponding transmission ranges are R_1 , R_2 , R_3 and R_4 , respectively, as shown in Fig. 1. The control packet and the header of data packet are all transmitted at the basic data rate r_1 . Therefore, the interference range of transmitting

nodes is R_1 . In Fig. 1, S_1 and S_2 are source nodes, which have data packets to transmit. D_1 is the destination of S_1 . Nodes H_1 to H_8 are helper nodes around link $L_1(S_1-D_1)$. They can be selected as relays for cooperative transmission by MIR-CMAC.

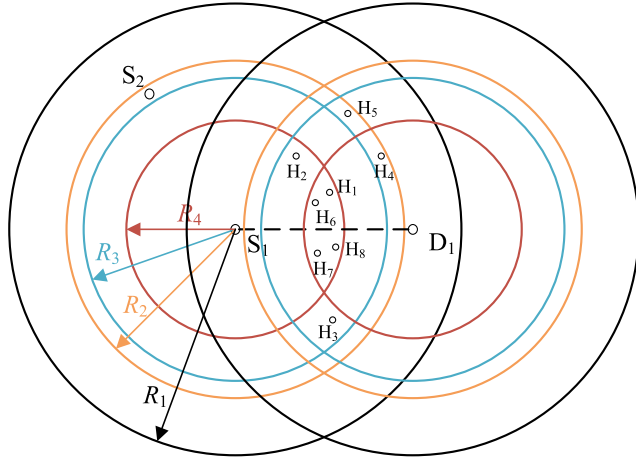


FIGURE 1. Different data rates and corresponding transmission ranges under IEEE 802.11b standard.

A. DIRECT TRANSMISSION MODE

The direct data transmission of MIR-CMAC involves CSMA/CA and four-way exchange for channel access and data packet transmission as shown in Fig. 2.

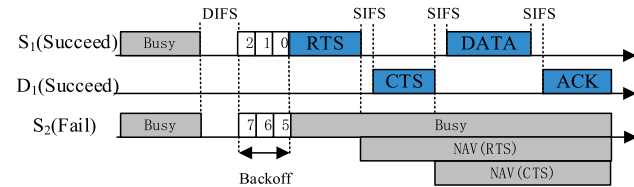


FIGURE 2. Direct transmission mode of MIR-CMAC protocol.

A source with a data packet to transmit senses the channel. If the channel is idle, it waits to see if the channel remains idle for a time equal to DIFS. If so, the source backs off a random slot time and again senses the channel. The duration of one slot for channel access is denoted as τ_1 . If the channel is still idle when the backoff counter reaches zero, the source issues a RTS control packet to the destination. The destination can calculate the maximum data rate of the link between source and destination upon receiving RTS. If the data rate meets the condition of the direct transmission mode (i.e. the maximum data rate is larger than 2Mbps) the destination will respond with a CTS control packet after the SIFS delay. After receiving the CTS, the source transmits the data packet, and the destination responds with an acknowledgment (ACK) packet.

The RTS alerts all the nodes within the interference range of the source that an exchange is under way. The nodes which sensed the RTS will refrain from transmission to avoid collision. Similarly, the CTS alters all nodes within the interference range of the destination. The RTS and CTS

carry the length information of data packets, which is used to update the NAV (Network Allocation Vector) of the nodes within their interference range to keep these nodes “frozen” for the remaining processing time of data transmission. The node in “frozen” state will do nothing.

In Fig. 2, the sources S_1 and S_2 are within each other's interference range. Since S_1 completes the backoff first and will transmit the RTS, and S_2 will enter the “frozen” state when it senses the RTS from S_1 .

B. COOPERATIVE TRANSMISSION MODE

If the maximum data rate calculated by destination upon receiving RTS does not satisfy the condition of the direct transmission mode, the cooperative transmission mode will be enabled in MIR-CMAC. The whole process of cooperative transmission is divided into three phases: channel reservation phase, relay selection phase and data transmission phase as shown in Fig. 3.

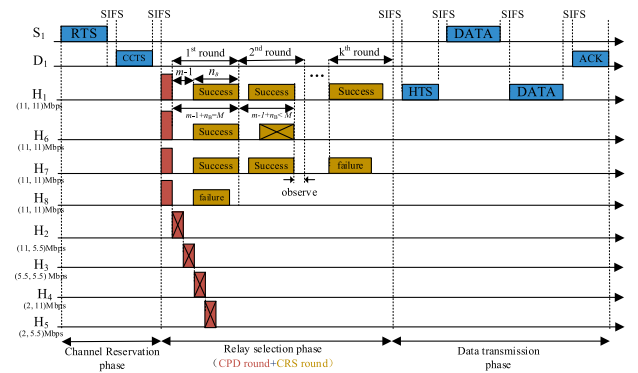


FIGURE 3. Cooperative transmission mode of MIR-CMAC protocol when the maximum data rate of direct transmission is 1 Mbps.

1) CHANNEL RESERVATION PHASE

The destination responds with a cooperative CTS (CCTS), instead of CTS, control packet after receiving RTS from its source to enable the cooperative transmission mode. The helper nodes that overhear only one RTS/CCTS handshake and no busy tone, which is broadcasted in the relay selection phase, will become potential relays for cooperative transmission. The helpers that overhear multiple RTS/CCTS handshakes or any busy tone will go into “frozen.” The remaining helpers that do not overhear the RTS/CCTS handshake or busy tone will keep being “frozen.”

2) RELAY SELECTION PHASE

To minimize the enlarged link interference range introduced by relays, the MIR-CMAC selects only one optimal helper node as the relay to participate in cooperative transmission at the highest equivalent data rate. That means the helper H with the highest data rate combination (i.e. the data rate r_{SH} between H and S , and the data rate r_{HD} between H and D) will be chosen as the relay. Among neighboring helpers the relay with the highest data rate combination must be on or closest to the connecting line between source and destination. Thus

TABLE 1. Relationship among priority level, data rate combination and predefined slot sequence number.

Priority Level	Data Rate Combination (r_{SH} , r_{HD}) (Mbps)	Predefined Slot Sequence Number
1	(11, 11)	1
2	(5.5, 11) or (11, 5.5)	2
3	(5.5, 5.5)	3
4	(2, 11) or (11, 2)	4
5	(2, 5.5) or (5.5, 2)	5

in this way the enlarged link interference region introduced by this relay is minimized. The relay selection phase is further divided into two rounds: the cooperative priority differentiation (CPD) round and the contention for relay selection (CRS) round.

a: COOPERATIVE PRIORITY DIFFERENTIATION ROUND

In CPD, all potential relays try to transmit their busy tones in different predefined slots to distinguish their cooperation priority. The potential relay with the predefined i -th slot will transmit a busy tone if no busy tone is sensed before its transmission. Otherwise, if there are busy tones before the i -th slot, i.e. there are potential relays with a higher cooperation priority, it will cancel the busy tone transmission. The duration of one slot for CPD is denoted as τ_2 .

A potential relay determines its cooperative priority based on the data rate combination (r_{SH} , r_{HD}). The relationship among the priority level, data rate combination, and the predefined slot sequence number can be found in Table 1. The equivalent data rate of cooperative transmission must be higher than the data rate of direct transmission between source and destination. Therefore, the lowest cooperative priority is 5 and the maximum slot number is 5 when $r_{SD} = 1$ Mbps and they both are 3 when $r_{SD} = 2$ Mbps.

If there are potential relays with the same cooperation priority level for a given link. They send busy tones successfully and will enter the next stage for relay selection contention. If there is no busy tone transmission in CPD, meaning that the potential relays do not exist or are not available, source will send data packets to its destination directly in the data transmission phase.

b: CONTENTION FOR RELAY SELECTION ROUND

In CRS, a unique relay is selected from the potential relays winning in the previous stage. There are k rounds of contention with at most M contention slots in each round in this stage, as shown in Fig. 3. The potential relays randomly select the m -th ($1 \leq m \leq M$) slot to send a busy tone with the length of n_B ($n_B \leq M - m + 1$) slots. The duration of one slot for CRS is denoted as τ_3 . Each potential relay senses the channel before sending its busy tone. If there is a busy tone, it will withdraw from contention. Otherwise, it will send the busy tone. Once a potential relay finishes its busy tone transmission, it will observe the channel for one slot of

the remaining slots in the current round. If other busy tones are sensed, it will withdraw from contention. Otherwise, it will enter the next round of contention. In this way the potential relays with the earliest busy tone transmissions and the longest busy tone duration will win the current round of contention and go into the next round. The winners in k rounds of contention will send HTS control packets to announce that they are the finally selected relays.

3) DATA TRANSMISSION PHASE

The HTS packet sent by the selected relays contains the information of r_{SH} and r_{HD} . If there is only one selected relay, S sends its data packet to H at the data rate r_{SH} , and H forwards the received data packet to D at the data rate r_{HD} . When D successfully decodes the data packet forwarded by H, it replies S with an acknowledgment (ACK) packet. If there are more than one selected relays, their HTS packets will collide with each other and S will send its data packet to D directly.

In summary, the process of proposed MIR-CMAC protocol is given in Algorithm 1.

IV. FULL INTERFERENCE MODEL AND PERFORMANCE ANALYSIS

In this section, we establish a full interference model for analyzing the interference relationship of any pair of links in the network, through the whole process of data transmission. The probability that a given link is not interfered is derived for both the direct transmission MAC protocol and the cooperative transmission MAC protocol, i.e. the direct data transmission mode and the cooperative data transmission mode in MIR-CMAC. The expressions of the total successful link number and the total effective network throughput are also obtained along with this establishment.

A. FULL INTERFERENCE MODEL

Assume that there are N links $L_i(S_i-D_i)$ ($i = 1, 2, \dots, N$) with the link distance of d meters, randomly deployed in a circular area with the radius of R_T meters. S_i and D_i are the source and destination of link L_i , respectively. Each S_i in the network always has data packets to send. The helper nodes are randomly scattered in the network with density λ_H . They are always in the idle state and ready to be chosen as relays to help the source within their transmission ranges for cooperative transmission. All the nodes are half-duplex. The proposed MIR-CMAC protocol is employed in the network. $m_i\tau_1$ is the backoff time of S_i for channel access. m_i is the slot number, which is an independent random variable uniformly distributed on $[1, CW]$. τ_1 is the duration of one slot. Link L_i is indexed according to the backoff time of S_i for network performance analysis.

The interference relationship between any two links $L_i(S_i-D_i)$ and $L_j(S_j-D_j)$ in the network is investigated for the whole process of data packet transmission under the condition $i < j$, i.e. S_i tries to send the RTS earlier than S_j . The interference relationship of L_i and L_j when $i < j$ can be classified into four

Algorithm 1 Process of MIR-CMAC Protocol

- 1: **initialization:** Initialize MIR-CMAC parameters $CW/SIFS/k/M/\tau_1/\tau_2/\tau_3$;
- 2: **loop**
- 3: Source S with a data packet for destination D senses the channel. If the channel is idle after DIFS and its backs off time, S issues a RTS control packet to D. Otherwise, it postpones its data packet transmission;
- 4: D determines the maximum data rate of link L(S-D) based on the received RTS packet. If the data rate is equal to or less than 2Mbps, D responds with a CTS packet to activate the direct transmission mode. Otherwise, D responds with a CCTS control packet to activate the cooperative transmission mode and then GoTo 6;
- 5: S transmits its data packet to D, and D responds with an ACK packet. The transmission process of this data packet is ended in the direct transmission mode and GoTo 3;
- 6: The helper nodes that overhear only one RTS/CCTS handshake and no busy tone will become potential relays and then go to the next step, while other helper nodes go into “frozen”;
- 7: CPD: Each potential relay H determines its cooperative priority based on the data rate combination (r_{SH}, r_{HD}) and transmits a busy tone in the predefined i -th slot if no busy tone is sensed before its busy tone transmission. GoTo 5 if there is any busy tone transmission;
- 8: CRS: In each round of CRS every potential relay randomly selects the m -th $(1 \leq m \leq M)$ slot to send a busy tone with the length of n_B ($n_B \leq M - m + 1$) slots if it has not sensed any busy tone, and then senses another remaining slot of this round. The potential relay that has transmitted busy tone and sensed no busy tone transmission will become the winner and enter the next round. The winners in k rounds send their HTS packets, which contain the information of r_{SH} and r_{HD} ;
- 9: If S hears only one HTS packet, it sends its data packet to H at rate r_{SH} , H forwards it to D at rate r_{HD} , and D responds with an ACK packet. The transmission process of this data packet is ended in the cooperative transmission mode and GoTo 3. Otherwise GoTo 5;
- 10: **end loop**

categories: 1) the two links do not interfere with each other, 2) only link L_i is not interfered (i.e. L_j is interfered by L_i and L_i is not interfered by L_j), 3) only link L_j is not interfered, and 4) the two links interfere with each other. The probabilities of these four cases are denoted by $P_{1,1}(i, j)$, $P_{1,0}(i, j)$, $P_{0,1}(i, j)$ and $P_{0,0}(i, j)$, respectively. The subscript ‘1’ of the probability represents the link that is not interfered and can transmit data packet successfully and ‘0’ represents the failing link. The sum of these probabilities is one.

Link L_i can transmit data packet successfully if and only if all the other links in the network do not interfere it during the whole process from channel access to data packet transmission. The state of link L_i , $state(i)$, equals to ‘1’ means that link L_i is not interfered and can transmit data packet successfully and ‘0’ means the opposite.

$$state(i) = \begin{cases} 1 & (\text{if } L_i \text{ is not interfered}) \\ 0 & (\text{if } L_i \text{ is interfered}) \end{cases} \quad (1)$$

The probability that link L_i is not interfered can be calculated as follows

$$P(state(i) = 1) = \prod_{k=1}^{i-1} P_{X,1}(k, i) \prod_{q=i+1}^N P_{1,X}(i, q) \quad (2)$$

where X can be ‘0’ or ‘1.’ The first product term in the right side of equation represents the interfere effects of all the links with smaller backoff time and the second product term is the interfere effects of all the links with larger backoff time. The case that there is one or more links with the same backoff time as link L_i is ignored in our study.

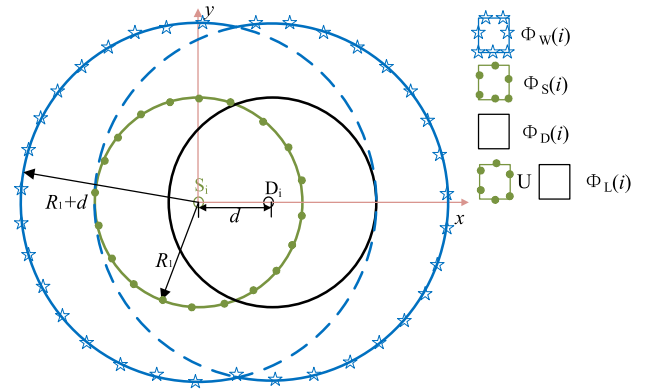


FIGURE 4. Interference region of link L_i for direct transmission.

1) DIRECT TRANSMISSION MAC PROTOCOL

The interference region of link $L_i(S_i-D_i)$ for direct transmission is shown in Fig. 4. $\Phi_S(i)$ is the interference region of S_i with the area $A_S = \pi R_1^2$, and it is also the sensing region of carrier signal and busy tone. $\Phi_D(i)$ is the interference region of D_i with the area A_D of the same size.

$\Phi_L(i)$ is the interference region of link L_i , i.e. the union of $\Phi_S(i)$ and $\Phi_D(i)$, whose area is

$$A_L = 2(\pi - \arccos(\frac{d}{2R_1}))R_1^2 + dR_1 \sin(\arccos(\frac{d}{2R_1})) \quad (3)$$

where d is the link distance.

$\Phi_W(i)$ is the union of two circular regions with S_i and D_i as the center and $R_1 + d$ as the radius respectively, whose area is

$$A_W = 2(\pi - \arccos(\frac{d}{2(R_1 + d)}))(R_1 + d)^2 + d(R_1 + d) \sin(\arccos(\frac{d}{2(R_1 + d)})) \quad (4)$$

The transmission range of RTS/CTS is R_1 , which is equal to or larger than the transmission range of data packets for the direct transmission. If the RTS/CTS transmission of a link is not interfered the subsequent transmission of data packet will be successful. Therefore, the interference relationship of two links for the whole process of data transmission can be simplified as the interference relationship the process of RTS/CTS handshake.

a: THE CASE THAT TWO LINKS DO NOT INTERFERE WITH EACH OTHER

i. When $S_j \notin \Phi_W(i)$, there must be $D_j \notin \Phi_L(i)$ since the distance between S_j and D_j is d . Therefore, link L_i and link L_j are out of the interference range of each other. They do not interfere with each other whatever the backoff slot numbers m_i and m_j are. The corresponding probability is

$$P_{1,1}^{D(1)}(i,j) = P(S_j \notin \Phi_W(i)) = \frac{A_T - A_W}{A_T} \quad (5)$$

where A_T is the area of the network studied, and A_W is the area of region $\Phi_W(i)$.

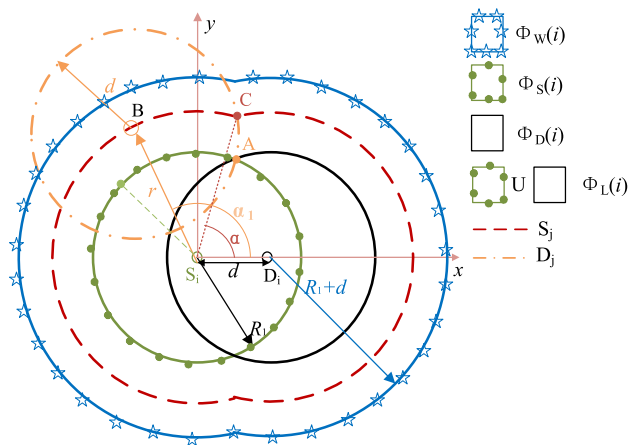


FIGURE 5. Interference relationship when $S_j \in \Phi_W(i) \setminus \Phi_L(i)$ and $D_j \notin \Phi_L(i)$ for direct transmission.

ii. When $S_j \in \Phi_W(i) \setminus \Phi_L(i)$ and $D_j \in \Phi_L(i)$, link L_i and L_j are out of the interference range of each other as shown in Fig. 5. The two links do not interfere with each other. Letting S_i be the origin and the connecting line from S_i to D_i be the reference line, we set up a polar coordinate system. S_j locates at the red curve consisting of two arcs with S_i and D_i as the centers and r as the radius. C is the intersection point of the arcs, and α is its angular coordinate. A is the intersection point of $\Phi_S(i)$ and $\Phi_D(i)$. α_1 is the angular coordinate of S_j when the orange circle represents the possible position of D_j crossing A .

We study only the left side of the midperpendicular of S_i - D_i because of symmetry. The polar coordinate (r, θ) of S_j satisfies $r \in [R_1, R_1 + d]$, $\theta \in [\alpha, 2\pi - \alpha]$. When $\theta \in [\alpha_1, 2\pi - \alpha_1]$ as shown in Fig. 6(a), the possible position of D_j is the dotted purple circle for the given S_j . The probability of D_j falling outside of $\Phi_L(i)$ is $(\pi - \beta)/\pi$, which have

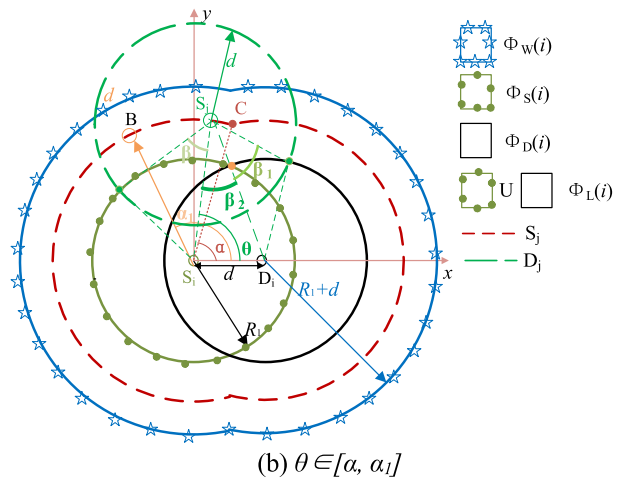
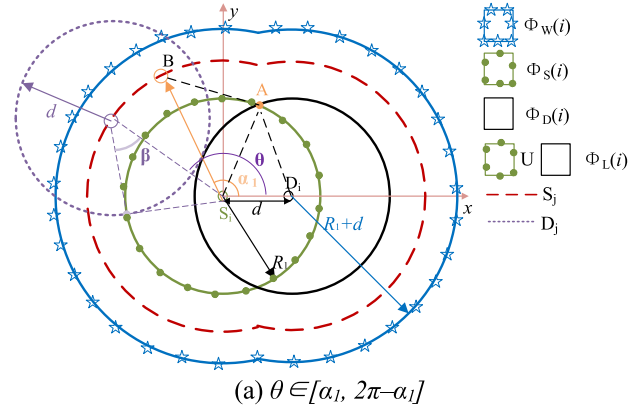


FIGURE 6. Interference relationship of two situations when $S_j \in \Phi_W(i) \setminus \Phi_L(i)$ and $D_j \notin \Phi_L(i)$ for direct transmission.

nothing to do with the location of S_j . When $\theta \in [\alpha, \alpha_1]$ as shown in Fig. 6(b), the probability that D_j falls in $\Phi_L(i)$ can be divided into three arcs corresponding to β , β_1 , and β_2 . The situation when $\theta \in [2\pi - \alpha_1, 2\pi - \alpha]$ is the same as when $\theta \in [\alpha, \alpha_1]$. The corresponding probability is

$$\begin{aligned} P_{1,1}^{D(2)}(i,j) &= P(S_j \in \Phi_W(i) \setminus \Phi_L(i), D_j \notin \Phi_L(i)) \\ &= \frac{2}{A_T} \left[\int_{r=R_1}^{r=R_1+d} \int_{\theta=\alpha_1}^{\theta=2\pi-\alpha_1} \frac{\pi - \beta}{\pi} r d\theta dr \right. \\ &\quad \left. + 2 \int_{r=R_1}^{r=R_1+d} \int_{\theta=\alpha}^{\theta=\alpha_1} \frac{2\pi - \beta - \beta_1 - \beta_2}{2\pi} r d\theta dr \right] \quad (6) \end{aligned}$$

Therefore, the probability that the two links do not interfere with each other is

$$P_{1,1}^D(i,j) = P_{1,1}^{D(1)}(i,j) + P_{1,1}^{D(2)}(i,j) \quad (7)$$

b: THE CASE THAT ONLY LINK L_i IS NOT INTERFERED

i. When $S_j \in \Phi_S(i)$, the earlier RTS transmission from S_i will be sensed by S_j and S_j will suspend the channel access. L_i is not interfered by L_j and L_j is interfered by L_i .

The corresponding probability is

$$P_{1,0}^{D(1)}(i,j) = P(S_j \in \Phi_S(i)) = \frac{\pi R_1^2}{A_T} \quad (8)$$

ii. When $S_j \in \Phi_L(i) \setminus \Phi_S(i)$ and $m_j \tau_1 > m_i \tau_1 + T_{RTS} + SIFS$, S_j tries to send RTS later than D_i sends CTS. S_j will suspend RTS transmission since the CTS transmission from D_i is sensed. Therefore, only link L_i is not interfered. The corresponding probability is

$$P_{1,0}^{D(2)}(i,j) = \frac{A_L - \pi R_1^2}{A_T} \quad (9)$$

iii. When $S_j \in \Phi_W(i) \setminus \Phi_L(i)$ and $D_j \in \Phi_L(i)$, L_j will be interfered by L_i . S_j can transmit RTS successfully after L_i accesses the channel since $S_j \in \Phi_W(i) \setminus \Phi_L(i)$. If $D_j \notin \Phi_L(i)$, D_j can transmit CTS successfully and L_j would not be interfered by L_i . However, since $D_j \in \Phi_L(i)$, L_j will be interfered by L_i . The corresponding probability can be calculated by excluding the probability of $D_j \notin \Phi_L(i)$ from the probability of $S_j \in \Phi_W(i) \setminus \Phi_L(i)$, which is

$$\begin{aligned} P_{1,0}^{D(3)}(i,j) &= P(S_j \in \Phi_W(i) \setminus \Phi_L(i)) - P_{1,1}^{D(2)}(i,j) \\ &= \frac{A_W - A_L}{A_T} - P_{1,1}^{D(2)}(i,j) \end{aligned} \quad (10)$$

Therefore, the probability that only link L_i is not interfered is

$$P_{1,0}^D(i,j) = \begin{cases} P_{1,0}^{D(1)}(i,j) + P_{1,0}^{D(2)}(i,j) + P_{1,0}^{D(3)}(i,j) \\ (m_j \tau_1 > m_i \tau_1 + T_{RTS} + SIFS) \\ P_{1,0}^{D(1)}(i,j) + P_{1,0}^{D(3)}(i,j) \\ (m_j \tau_1 < m_i \tau_1 + T_{RTS} + SIFS) \end{cases} \quad (11)$$

The event of $m_j \tau_1 = m_i \tau_1 + T_{RTS} + SIFS$ is ignored in our study.

c: THE CASE THAT ONLY LINK L_j IS NOT INTERFERED

When $S_j \in \Phi_L(i) \setminus \Phi_S(i)$ and $D_j \notin \Phi_S(i)$, the location relationship of link L_i and L_j is shown in Fig. 7. S_j locates at the purple arc with S_i as the center and r as the radius. D_j is located at one part of red circle, which is outside of $\Phi_S(i)$. S_j is the center of the red circle and d is the radius. The polar coordinate (r, θ) of S_j satisfies $r \in [R_1, R_1 + d]$, $\theta \in [-\beta, \beta]$. β is the angular coordinate of the intersection point of the purple arc and $\Phi_D(i)$.

If $m_j \tau_1 < m_i \tau_1 + T_{RTS} + SIFS$, S_j sends RTS after S_i sends RTS and before D_i tries to send CTS. D_i will suspend the RTS transmission as the RTS transmission from S_j is sensed, thus Link L_i is interfered. However, Link L_j will not be interfered as the RTS/CTS exchange between S_j and D_j can be carried out successfully. The corresponding probability is

$$\begin{aligned} P_{0,1}^{D(1)}(i,j) &= P(S_j \in \Phi_L(i) \setminus \Phi_S(i), D_j \notin \Phi_S(i)) \\ &= \int_{r=R_1}^{r=R_1+d} \int_{\theta=-\beta}^{\theta=\beta} \frac{2\pi - 2\beta}{2\pi} 2\beta r d\theta dr \end{aligned} \quad (12)$$

If $m_j \tau_1 > m_i \tau_1 + T_{RTS} + SIFS$, S_j will suspend RTS transmission since the CTS transmission from D_i is sensed, thus link L_j is interfered.

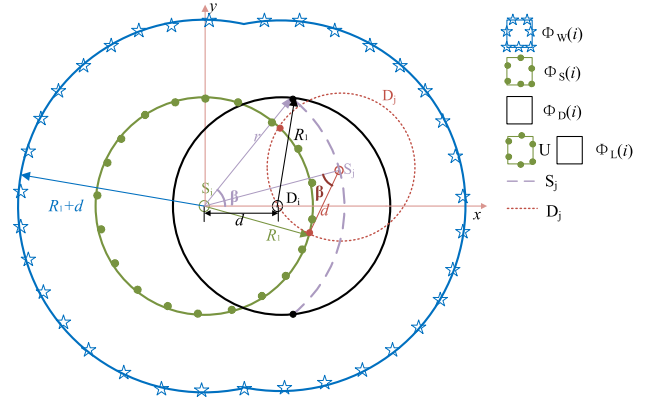


FIGURE 7. Interference relationship when $S_j \in \Phi_L(i) \setminus \Phi_S(i)$ and $D_j \notin \Phi_S(i)$ for direct transmission.

Therefore, the probability that only link L_j is interfered is

$$P_{0,1}^D(i,j) = \begin{cases} 0 & (m_j \tau_1 > m_i \tau_1 + T_{RTS} + SIFS) \\ P_{0,1}^{D(1)}(i,j) & (m_j \tau_1 < m_i \tau_1 + T_{RTS} + SIFS) \end{cases} \quad (13)$$

d: THE CASE THAT TWO LINKS INTERFERE WITH EACH OTHER

When $S_j \in \Phi_L(i) \setminus \Phi_S(i)$ and $D_j \in \Phi_S(i)$, S_i sends RTS successfully and D_i suspends CTS transmission, and S_j sends RTS successfully and D_j suspends CTS transmission if $m_j < m_i + T_{RTS} + SIFS$, thus link L_i and link L_j interfere with each other. When $D_j \notin \Phi_S(i)$ link L_j carries out RTS/CTS exchange successfully and will not be interfered. The corresponding probability can be calculated by excluding the probability of $D_j \notin \Phi_S(i)$ from the probability of $S_j \in \Phi_L(i) \setminus \Phi_S(i)$, which is

$$\begin{aligned} P_{0,0}^{D(1)}(i,j) &= P(S_j \in \Phi_L(i) \setminus \Phi_S(i), D_j \in \Phi_S(i)) \\ &= \frac{A_L - \pi R_1^2}{A_T} - P_{0,1}^{D(1)}(i,j) \end{aligned} \quad (14)$$

If $m_j \tau_1 > m_i \tau_1 + T_{RTS} + SIFS$, link L_i is not interfered since the RTS/CTS exchange between S_i and D_i is carried out successfully before S_j tries to send RTS.

Therefore, the probability that links L_i and link L_j interfere with each other is

$$P_{0,0}^D(i,j) = \begin{cases} 0 & (m_j \tau_1 > m_i \tau_1 + T_{RTS} + SIFS) \\ P_{0,0}^{D(1)}(i,j) & (m_j \tau_1 < m_i \tau_1 + T_{RTS} + SIFS) \end{cases} \quad (15)$$

Finally, the probability that link L_i is not interfered and the probability that link L_j is not interfered can be derived as follows respectively

$$P_{1,X}^D(i,j) = \begin{cases} P_{1,1}^D(i,j) + P_{1,0}^{D(1)}(i,j) + P_{1,0}^{D(2)}(i,j) + P_{1,0}^{D(3)}(i,j) \\ (m_j \tau_1 > m_i \tau_1 + T_{RTS} + SIFS) \\ P_{1,1}^D(i,j) + P_{1,0}^{D(1)}(i,j) + P_{1,0}^{D(3)}(i,j) \\ (m_j \tau_1 < m_i \tau_1 + T_{RTS} + SIFS) \end{cases} \quad (16)$$

$$P_{X,1}^D(i,j) = \begin{cases} P_{1,1}^D(i,j) & (m_j \tau_1 > m_i \tau_1 + T_{RTS} + SIFS) \\ P_{1,1}^D(i,j) + P_{0,1}^{D(1)}(i,j) & (m_j \tau_1 < m_i \tau_1 + T_{RTS} + SIFS) \end{cases} \quad (17)$$

Combing Equations (2), (16) and (17), the probability $P^D(state(i) = 1)$ that a given link L_i in the network is not interfered for the direct transmission MAC protocol can be obtained.

2) COOPERATIVE TRANSMISSION MAC PROTOCOL

In MIR-CMAC, the cooperative transmission mode is built on the direct transmission mode. In the process of cooperative transmission, a link starts relay selection after a successful RTS/CCTS handshake in the channel reservation phase. The RTS/CCTS handshake in the cooperative transmission MAC protocol is similar to the RTS/CTS handshake in the direct transmission MAC protocol and the analysis results of RTS/CTS handshake given above can be used here. For any pair of links $L_i(S_i-D_i)$ and $L_j(S_j-D_j)$ in the network, if they interfere with each other for RTS/CCTS handshake, there will not enter the relay selection phase. Therefore, if the event that two links interfere with each other in the channel reservation phase is true, this event for the whole process of cooperative transmission is also true.

If there is only one link is not interfered for RTS/CCTS handshakes between two links, the other link will not enter relay selection. The winning link will select relay successfully without the interference from the other link. Therefore, if the event that only link L_i is not interfered for the channel reservation phase is true, this event for the whole process of cooperative transmission is also true. It is the same for link L_j .

If link L_i and link L_j do not interfere with each other for RTS/CCTS handshake, both links will enter relay selection. Since $m_i < m_j$, link L_i enters relay selection first and will not be interfered for the rest process, but Link L_j may be interfered by link L_i . Therefore, if the event that two links do not interfere with each other for the channel reservation phase is true, both events for the whole process of cooperative transmission that two links do not interfere with each other and that only link L_i is not interfered can be true.

Therefore, the two probabilities, i.e. 1) for the event that two links interfere with each other and 2) for the event that only link L_j is not interfered for cooperative transmission MAC protocol, are the same as for the direct transmission MAC protocol, which are

$$P_{0,0}^C(i,j) = P_{0,0}^D(i,j) \quad (18)$$

$$P_{0,1}^C(i,j) = P_{0,1}^D(i,j) \quad (19)$$

And the probability that only link L_i is not interfered for the direct transmission MAC protocol is only part of the probability for the cooperative transmission MAC protocol, i.e.

$$P_{1,0}^{C(1)}(i,j) = P_{1,0}^D(i,j) \quad (20)$$

Next let us investigate the interference relationship between link L_i and link L_j for the rest of the data transmission process when the two links do not interfere with each other in the channel reservation phase. The helpers with the highest cooperative priority p are considered as potential relays in the relay selection phase. If there is no helper around link L_i , S_i will send data packet directly to D_i and Link L_j will not be interfered by link L_i for the rest of the data transmission process. If there are helpers around link L_i , they will send busy tones first for relay selection. Their busy tones may interfere link L_j .

When both S_j and D_j are outside the enlarged part $\Phi_H(i, p)$ of link L_i ' interference region introduced by the helpers with priority p , link L_j will not be interfered.

When S_j or D_j is inside the enlarged part of link L_i ' interference region and if $m_j \tau_1 > m_i \tau_1 + T_{RTS} + 2SIFS + T_{CTS} + (p-1)\tau_2$, the helpers of L_i sends busy tones before S_j tries to send RTS, thus S_j or D_j will be interfered by the busy tones. The corresponding probability is denoted as $P_{1,0}^{C(2,p,SD)}(i,j)$.

When D_j is inside the enlarged part of link L_i ' interference region and if $m_i \tau_1 + T_{RTS} + SIFS + (p-1)\tau_2 < m_j \tau_1 < m_i \tau_1 + T_{RTS} + 2SIFS + T_{CTS} + (p-1)\tau_2$, the busy tones of link L_i is sent after S_j sends RTS and before D_j sends CTS, D_j will be interfered by the busy tones. The corresponding probability is denoted as $P_{1,0}^{C(2,p,D)}(i,j)$.

Otherwise, if $m_j \tau_1 < m_i \tau_1 + T_{RTS} + 2SIFS + T_{CTS} + (p-1)\tau_2$, link L_j completes RTS/CTS handshake successfully before the helpers around link L_i try to send busy tones. The helpers sense more than one RTS/CTS handshakes and do not take part in relay selection, thus link L_j will not be interfered.

Therefore, the probability that only link L_j is interfered for the whole process of data packet transmission when the two links L_i and L_j do not interfere with each other for the channel reservation phase can be represented as follows

$$P_{1,0}^{C(2,p)}(i,j) = \begin{cases} 0 & (m_j \tau_1 < m_i \tau_1 + T_{RTS} + T_{CTS} + 2SIFS + (p-1)\tau_2) \\ P_{1,0}^{C(2,p,D)}(i,j) = P(D_j \in \Phi_H(i, p)) & (m_i \tau_1 + T_{RTS} + SIFS + (p-1)\tau_2 < m_j \tau_1 < m_i \tau_1 + T_{RTS} + T_{CTS} + 2SIFS + (p-1)\tau_2) \\ P_{1,0}^{C(2,p,SD)}(i,j) = P((S_j \in \Phi_H(i, p)) \cup (D_j \in \Phi_H(i, p))) & (m_i \tau_1 + T_{RTS} + T_{CTS} + 2SIFS + (p-1)\tau_2 < m_j \tau_1) \end{cases} \quad (21)$$

In the above equation the calculation of $P_{1,0}^{C(2,p,SD)}(i,j)$ is simplified by neglecting the small probability that both S_j and D_j fall in $\Phi_H(i, p)$. $P(S_j \in \Phi_H(i, p))$ and $P(D_j \in \Phi_H(i, p))$ are the probabilities that S_j and D_j fall in $\Phi_H(i, p)$ respectively.

They can be calculated as follows

$$P(S_j \in \Phi_H(i, p)) = \frac{A_{Hp}}{A_T} \quad (22)$$

$$P(D_j \in \Phi_H(i, p)) = \frac{A_{Hp}}{A_T} \quad (23)$$

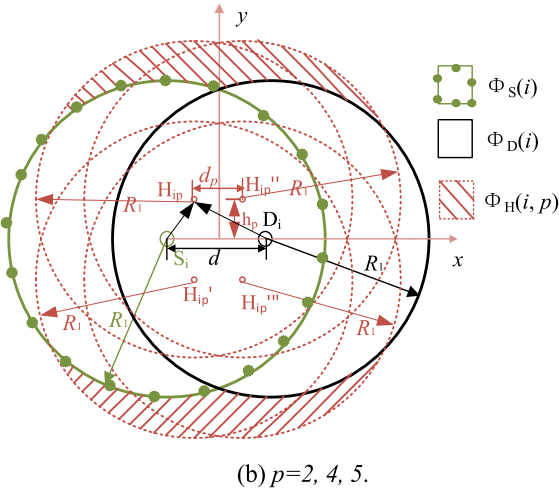
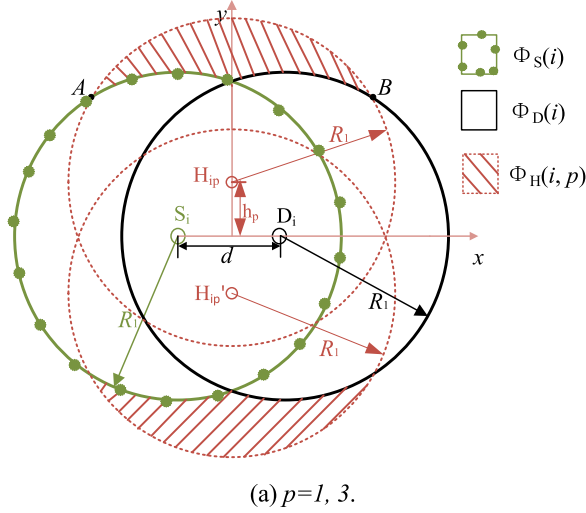


FIGURE 8. Enlarged interference region of L_i introduced by the helpers with priority p for cooperative transmission.

where A_{Hp} is the area of enlarged part $\Phi_H(i, p)$ of link L_i interference region. The enlarged interference region of link L_i introduced by the helpers with cooperative priority p is shown in Fig. 8. The data rate between helper and S_i and that between helper and D_i are the same when $p=1, 3$ in Fig. 8(a). The two data rates are unequal when $p=2, 4, 5$ in Fig. 8(b). H_{ip} , H'_{ip} , H''_{ip} and H'''_{ip} are helpers with cooperative priority p and with coordinates of the largest absolute value. The dotted red circle represents the interference range of helper. The shaded red region represents the enlarged part $\Phi_H(i, p)$ of link L_i interference region introduced by helpers, which is outside of $\Phi_L(i)$. In our study the enlarged link interference region is introduced by helpers with coordinates of the largest absolute value, which will overestimate the interference chance.

The area of enlarged part of link L_i interference region can be calculated as follows

$$A_{Hp} = \begin{cases} 2[\frac{h_p d}{2} + \sqrt{h_p^2 + (\frac{d}{2})^2} \sqrt{R_1^2 - \frac{h_p^2 + (\frac{d}{2})^2}{4}} \\ + R_1^2(\pi - 2 \arctan(\frac{d}{2h_p}) - 2 \arccos \frac{\sqrt{h_p^2 + (\frac{d}{2})^2}}{2R_1} \\ + \arccos \frac{d}{2R_1}) - \frac{d}{2} \sqrt{R_1^2 - (\frac{d}{2})^2}] \\ (p=1, 3) \\ 2[\frac{d+d_p}{2} h_p + \sqrt{h_p^2 + (\frac{d-d_p}{2})^2} \\ \times \sqrt{R_1^2 - \frac{h_p^2 + (\frac{d-d_p}{2})^2}{4}} \\ + \frac{d_p}{2} \sqrt{R_1^2 - (\frac{d_p}{2})^2} + R_1^2(\frac{3}{2}\pi - \arctan(\frac{d-d_p}{2h_p}) \\ - 2 \arccos \frac{\sqrt{h_p^2 + (\frac{d-d_p}{2})^2}}{2R_1} - \arccos \frac{d_p}{2R_1} \\ - \arccos \frac{d}{2R_1} \\ - \arctan(\frac{2h_p}{d-d_p}) - \frac{d}{2} \sqrt{R_1^2 - (\frac{d}{2})^2}] \\ (p=2, 4, 5) \end{cases} \quad (24)$$

where h_p is the distance from the helper with cooperative priority p to link L_i . d_p is the distance between H_{ip} and H''_{ip} . The calculation of these two variables is given in [6].

Therefore we have the probabilities of two cases that only link L_j is interfered and that two links do not interfere with each other as follows

$$P_{1,0}^{C(p)}(i, j) = P_{1,0}^D(i, j) + P_{1,0}^{C(2,p)}(i, j) \quad (25)$$

$$P_{1,1}^{C(p)}(i, j) = P_{1,1}^D(i, j) - P_{1,0}^{C(2,p)}(i, j) \quad (26)$$

Finally, the probability that link L_i is not interfered and the probability that link L_j is not interfered can be derived as follows respectively

$$P_{1,X}^C(i, j) = P_{1,X}^D(i, j) \quad (27)$$

$$P_{X,1}^{C(p)}(i, j) = P_{0,1}^C(i, j) + P_{1,1}^{C(p)}(i, j) \quad (28)$$

Combing Equations (2), (27) and (28), the probability that a given link L_i in the network, which has helpers with the highest cooperative priority p , is not interfered can be obtained as follows

$$P_p^C(\text{state}(i) = 1) = \prod_{k=1}^{i-1} P_{X,1}^C(k, i) \prod_{q=i+1}^N P_{1,X}^{C(p)}(i, q) \quad (29)$$

B. PERFORMANCE ANALYSIS

The total number of successful links in the network is

$$N_s = \sum_{i=1}^N P(\text{state}(i) = 1) \quad (30)$$

The total effective network throughput can be calculated as follows

$$S = N_s L_{DATA} / T \quad (31)$$

where L_{DATA} is the length of data part of data datapacket and T is the whole process time of data packet transmission for a successful link.

For direct transmission MAC protocol, the total number of successful links N_s^D can be obtained by combing Equations (2), (16), (17), and (30). If the backoff time is omitted the whole process time of data packet transmission is

$$T_D = T_{HEADER} + T_{RTS} + T_{CTS} + T_{ACK} + 3SIFS + \frac{L_{DATA}}{r_D} \quad (32)$$

where T_{HEADER} , T_{RTS} , T_{CTS} and T_{ACK} are transmission times of the header part of data packet, RTS, CTS, and ACK at data rate r_1 . The data part is transmitted at data rate r_D , which is related to link distance d

$$r_D = \begin{cases} r_1 & (R_2 < d \leq R_1) \\ r_2 & (R_3 < d \leq R_2) \\ r_3 & (R_4 < d \leq R_3) \\ r_4 & (d \leq R_4) \end{cases} \quad (33)$$

The total effective network throughput S_D can be obtained by combing Equations (30) (31) (32) and (2) for $P^D(state(i) = 1)$.

For cooperative transmission MAC protocol, if there is no helper around link L_i the direct data transmission will be used, and the corresponding probability is denoted as P_{cD} . The probability that the helper with the highest priority p around exists is denoted as P_{cp} . The value taken by p is related to link distance d . $p = 1, 2, 3, 4, 5$ when $d > R_2$, and $p = 1, 2, 3$ when $R_3 < d \leq R_2$. P_{cp} and P_{cD} depend on λ_H and d , which can be calculated according to [6].

The total number of successful links in the network is

$$N_s^C = \sum_{i=1}^N [\sum_{p \in \mathcal{P}} P_{cp} P_p^C(state(i) = 1) + P_{cD} P^D(state(i) = 1)] \quad (34)$$

The whole process time of data transmission for a successful link is

$$T_c = P_{cD} T_{cD} + \prod_{p \in \mathcal{P}} P_{cp} T_c(p) \quad (35)$$

The whole process time of data transmission without helpers around for a successful link is

$$T_{cD} = T_{HEADER} + T_{RTS} + T_{CCTS} + T_{ACK} + 4SIFS + 5\tau_2 + kM\tau_3 + \frac{L_{DATA}}{r_D} \quad (36)$$

When there is helper with the highest priority p around, if the helper is selected as relay successfully with probability $P_s(p)$, then the cooperative data transmission is used for data packet transmission. If the relay selection is failed with probability $1 - P_s(p)$ the direct data transmission is used. The whole

process time of data transmission with helpers around for a successful link is

$$T_c(p) = T_{HEADER} + T_{RTS} + T_{CCTS} + T_{HTS} + T_{ACK} + 5SIFS + p\tau_2 + L_{selection}\tau_3 + P_s(p)T_s(p) + (1 - P_s(p))T_f(p) \quad (37)$$

where $T_{selection}$ is the slot number for relay selection contention, which is related to the protocol parameters M and k . $P_s(p)$ is related to M , k , and p . We can calculate $T_{selection}$ and $P_s(p)$ according to [25]. $T_s(p)$ is the remaining process time including data part transmission when relay selection is successful, which can be calculated as

$$T_s(p) = T_{HEADER} + SIFS + \frac{L_{DATA}}{r_c(p)} \quad (38)$$

The data rate of cooperative data transmission is

$$r_c(p) = \begin{cases} \frac{r_4^2}{r_4 + r_4} & (p = 1) \\ \frac{r_4 r_3}{r_4 + r_3} & (p = 2) \\ \frac{r_3^2}{r_3 + r_3} & (p = 3) \\ \frac{r_3 r_2}{r_3 + r_2} & (p = 4) \\ \frac{r_4 r_2}{r_4 + r_2} & (p = 5) \end{cases} \quad (39)$$

When relay selection is failed the remaining process time is

$$T_f(p) = \frac{L_{DATA}}{r_D} \quad (40)$$

The data rate r_D of direct data transmission is related to link distance d and is given in Equation (33).

The total effective network throughput S_C can be obtained by combing Equations (30), (31), (34) and (35).

V. PERFORMANCE EVALUATION

The simulation program is implemented with the C++ programming language on Visual Studio 2019. The output data of simulations are processed, and performance results are drawn in Matlab. We assume that the network nodes are deployed in a circular region with the radius of 2000m. The pure random backoff mechanism instead of exponential backoff mechanism is applied for the channel access in MIR-CMAC. k and M are set to be the optimal values, which are 3 and 4 respectively. Since the cooperative transmission mode is enabled only when the maximum data rate of direct transmission from source to destination is not higher than 2Mbps, thus the range of link distance is set to be (67.1, 100) meters. The values of RTS, CTS and ACK are set according to the IEEE 802.11b standard. The value of HTS is set as the same as CTS and ACK referred to other CMAC protocols. Some parameters for the network settings are shown in Table 2 as in [6].

TABLE 2. Network parameters.

Parameter	Definition	Value
HEADER	Header length of data packet	464bits
CW	Size of contention window	32
RTS	Length of control packet RTS	160bits
CTS/HTS/ACK	Length of control packets CTS/HTS/ACK	112bits
τ 1/ τ 2/ τ 3/SIFS	Duration of one slot for channel access/CPD/CRS and duration of SIFS	10 μ s
L_{DATA}	Data part length of data packet	8Mbits

A. IMPACT OF RELAY DENSITY

First we investigate how the relay density influence the cooperative transmission mode of MIR-CMAC. The total number of links is set to be 200, and the link distance is 70 meters. The relay density is set to be 0.003/m² and 0.0003/m². The successful link number for direct transmission mode is irrelevant to relay density. There are 132 successful links when direct transmission mode is applied for one experiment.

The successful link number for cooperative transmission mode under different relay density is shown in Table 3. When the helpers are densely distributed in the network, i.e. the relay density is 0.003/m², the total number of successful links is 130, which is almost the same as direct transmission mode. When the helpers are distributed sparsely in the network, i.e. the relay density is 0.0003/m², the total number of successful links decreases to 106. We can also see from the table that there are more chances that the relay adopts a higher data rate combination for the successful link when the relay density is high.

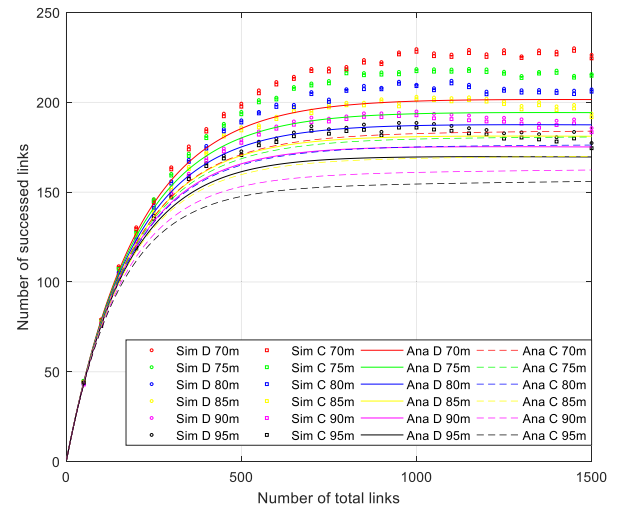
TABLE 3. Successful link number under different relay densities for cooperative transmission mode.

Relay density	Successful link number of different data rate combinations (11,11) (5,5,11)or(11,5,5) (5,5,5,5) (1,1,1)or(11,2) (2,5,5)or(5,5,2)					Total number of successful links
0.003/m ²	125	5	0	0	0	130
0.0003/m ²	42	60	4	0	0	106

When the relay density is high, there are chances that the relays around the link lie on or close to the connection line between source and destination and they can take part in cooperative transmission with higher data rate combination. When we switch direct transmission mode to cooperative transmission mode in MIR-CMAC the link interference range increases by a small amount under high relay density and there are few more collisions among links occurring in the network, therefore the total number of successful links does not change significantly. Since the MIR-CMAC takes the advantage of cooperative transmission for dense relay distribution, the default relay density is set to be 0.003/m² in our study.

B. TOTAL NUMBER OF SUCCESSFUL LINKS

The total number of successful links will be affected by the total link number N in the network and the link distance d between source and destination as shown in Fig. 9. The dot curve and the square curve represent the numerical results of successful link number for direct transmission mode and cooperative transmission mode by simulations respectively. The solid line and the dashed line represent the numerical results by full interference model. The different colors represent different link distance settings.

**FIGURE 9.** The total number of successful links changes with total link number under different link distances.

We can see from Fig. 9 that the number of successful links increases with the number of total links in the network and then reaches a saturation value when the total link number is large for both direct transmission mode and cooperative transmission mode of MIR-CMAC. When the total link number is large there are multiple links in a region with the similar size of link interference region. Only the link which access channel first can transmit data packet successfully in this region. So the number of successful links will no longer increase with the total link number of network.

It can be seen from Fig. 9 that the number of successful links from numerical results is smaller than that from simulation results. In the full interference model, the case that two sources S_i and S_j within the interference range of each other have the same backoff time is ignored. However the two links L_i and L_j will not interfere with each other and can transmit data packets successfully at this case when D_i is out of interference range of S_j , and D_j is out of interference range of S_i . In the interference model, the interference boundary effect of network can also result in the underestimation of successful link number. For a link near the network boundary, the interference from the side of the link close to the boundary is assumed the same as the side far away from the boundary. This does not conform to the fact.

We can see from Fig. 9 that the gap between numerical results and simulation results for cooperative transmission

mode is larger than that for direct transmission mode. In the full interference model the enlarged link interference region is introduced by helpers with coordinates of the largest absolute value, that will overestimate the interference chance and will underestimate the number of successful links for cooperative transmission mode.

We can also see from Fig. 9 that the smaller the link distance is the larger the successful link number is. When the link distance d is small, the area of link interference region A_L is small, thus more links can transmit their data packet successfully without interfering each other. It can be seen from the figure that the difference of successful link numbers for $d = 70m$ and $d = 75m$ is about the same as the difference for $d = 75m$ and $d = 80m$ because A_L is approximately proportional to d when $d \ll R_1$.

C. WHOLE PROCESS TIME OF DATA TRANSMISSION

To study the whole process time difference of data packet transmission for cooperative transmission mode and direct transmission mode in MIR-CMAC we define the transmission time gain as follows

$$G_{Time} = \frac{T_D}{T_C} \quad (41)$$

where T_D and T_C are the whole process time of data transmission for direct transmission mode and for cooperative transmission mode respectively.

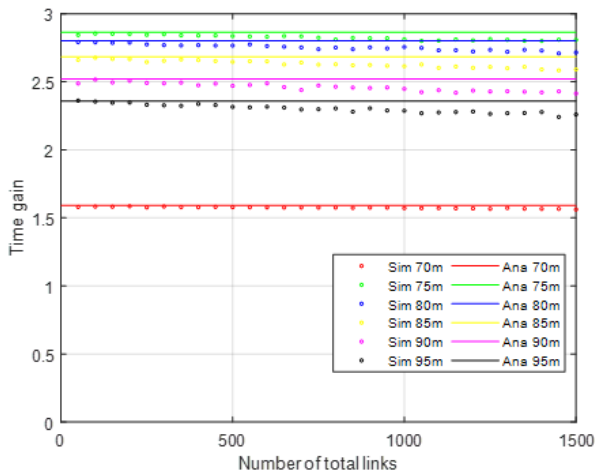


FIGURE 10. The transmission time gain changes with total link number under different link distances.

The transmission time gain changes with the number of total links in the network for different link distances is shown in Fig. 10. We can see from the figure that the time gain remains unchanged in the range of total link number studied for numerical results while it drops slightly when the total link number is large for simulation results. As the total link number increases the number of helpers sensing more than one RTS/CTS handshakes from different links will increase and they will not participate in cooperative transmission. Thus there are more links transmit its data packet by direct transmission instead of cooperative transmission when the

total link number is large and the transmission time gain will decrease. This effect is ignored in the proposed full interference model.

We can see from Fig. 10 that the time gain is significantly lower at the link distance of 70m than that at other link distances. The reason is that the process time for direct data transmission takes different values when the link distance changes through 74.7m. We can also see from the figure that when the link distance is larger than 74.7m the time gain decreases as the link distance increases. As the link distance increases the chance that the helpers with high cooperative priority decreases and meanwhile the chance that there is no helper satisfying the condition of cooperative transmission increases. This results in the increment of T_C and the decrement of transmission time gain.

D. TOTAL EFFECTIVE THROUGHPUT

The network performance of effective throughput is determined by the whole process time of a data packet transmitted over a successful link and the total number of successful links in the network. The two impact factors have been investigated above. The effective network throughput changes with the number of total links in the network for different link distances is shown in Fig. 11.

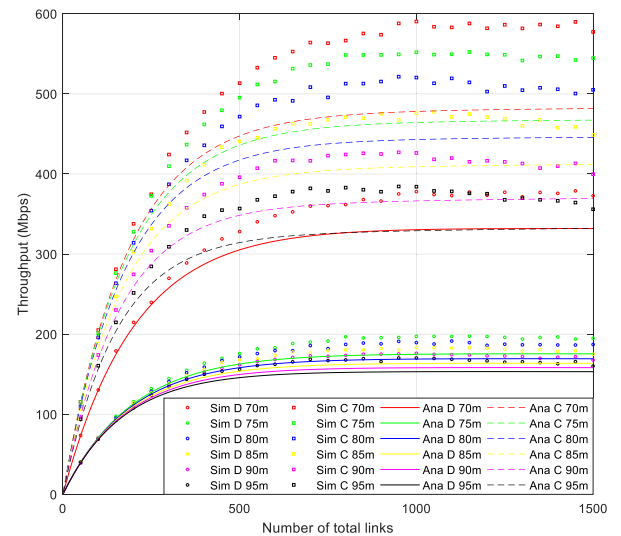


FIGURE 11. The total effective throughput changes with total link number under different link distances.

We can see from the figure that for a given link distance the effective network throughput increases with the total link number and then reaches a saturation value when the total link number is large. It can be explained as follows. The successful link number increases with the total link number and then keep unchanged when the total link number is large. The average equivalent data rate of successful links does not change with the total link number with regard to that the whole process time of a data packet transmitted over a successful link remains unchanged in the range of total link number studied.

Similarly, the numerical results of effective throughput by full interference model is always smaller than its simulation results. This is because that the full interference model always underestimate the successful link number for a given total link number.

The figure shows that the effective network throughput for cooperative transmission mode is much larger than direct transmission mode when other network settings are the same. The successful link number of cooperative transmission mode is close to direct transmission mode but the equivalent data rate for cooperative transmission is much larger than the data rate for direct transmission. This demonstrates that cooperative communication can significantly improve the throughput performance by MIR-CMAC in a large scale wireless network.

To evaluate the effective throughput improvement of cooperative transmission mode over direct transmission mode in MIR-CMAC, we define the effective throughput gain as follows

$$G_S = \frac{S_C}{S_D} \quad (42)$$

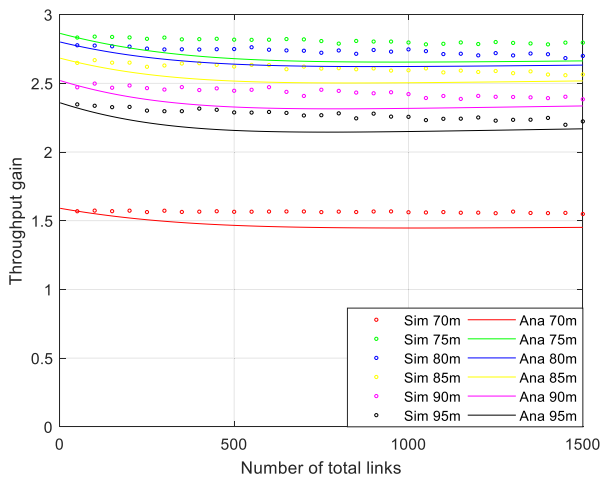


FIGURE 12. The throughput gain changes with total link number under different link distances.

The effective throughput gain changes with the number of total links for different link distances is shown in Fig. 12. We can see that the effective throughput gain is significantly above one for different total link numbers and different link distances. This demonstrates that cooperative transmission mode is superior to direct transmission mode in MIR-CMAC in term of network throughput performance in another way.

It can be seen from Fig. 12 that the effective throughput gain when the link distance is 70m is much lower than that when the link distance takes other values. This means that the cooperative transmission is much more preferred when the link distance is larger than 74.7m and the maximum data rate of direct transmission is 1Mbps than when the link distance is smaller than 74.7m and the maximum data rate of direct transmission is 2Mbps.

It can also be seen from Fig. 12 that the throughput gain drops slightly with the total link number and then keeps unchanged. As we know that the transmission time gain does not change with the total link number, so does the data rate ratio of cooperative transmission mode over direct transmission mode. Thus the throughput gain behavior with total link number is determined by the ratio of successful link number. When the total link number is small, the links are distributed in the network sparsely and there are few interferences between links, thus the successful link numbers for cooperative transmission mode and for direct transmission mode are about the same. As the total link number increases the successful link number of cooperative transmission mode decreases a little faster than direct transmission mode because of the enlarged link interference region for cooperative transmission mode. When the total link number is large the successful link number reaches a saturation value for both direct transmission mode and cooperative transmission mode. Their ratio, which is determined by the area ratio of enlarged link interference region and original link interference region, is a constant. Therefore, the throughput gain no longer changes with the total link number when the total link number is large.

We further compare the performance of MIR-CMAC with RECV-MAC [26], a cooperative MAC protocol for vehicular ad hoc networks (VANETs) published recently. The RECV-MAC protocol is proposed to enhance the reliability of communications in VANETs by mitigating impairments due to user mobility and to improve communication quality with higher throughput and lower delay. The carrier sense multiple access with collision avoidance (CSMA/CA) mechanism is used to access shared wireless channels. The total link number is set to be 1000 and the link distance is set to be 70m. The Performance comparison between MIR-CMAC and RECV-MAC is shown in Fig. 13.

We can see from Fig. 13(a) that the packet loss ratio of RECV-MAC is higher than that of MIR-CMAC for a given network traffic, and the packet loss ratio difference between RECV-MAC and MIR-CMAC increases with the network traffic load. As MIR-CMAC can effectively reduce collisions in channel access through combined mechanisms in channel reservation, cooperative priority differentiation and contention for relay selection, it outperforms RECV-MAC in transmission reliability in term of the packet loss ratio, especially in a network with heavy traffic.

We can see from Fig. 13(b) that the packet transmission delay of MIR-CMAC is larger than that of RECV-MAC. The RECV-MAC protocol is designed for vehicular ad hoc networks, where contention for relay selection has been much simplified, so that safety messages can be transmitted as fast as possible to combat rapid topology changes in VANETs.

It can also be seen from Fig. 13(c) that the network throughputs of both RECV-MAC and MIR-CMAC increase with the network traffic initially. Although slightly higher throughput is achieved by RECV-MAC over MIR-CMAC for light network traffic, when network traffic is larger

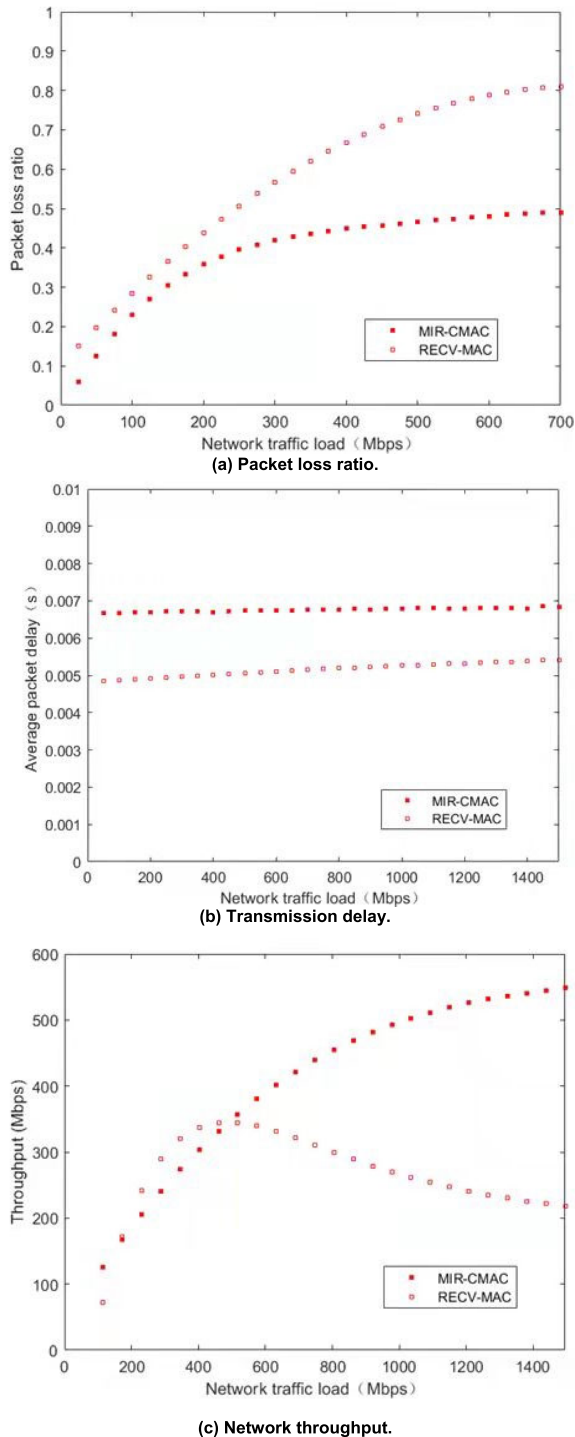


FIGURE 13. Performance comparison between MIR-CMAC and RECV-MAC.

than about 450Mbps the network throughput of RECV-MAC decreases rapidly and considerably with network traffic while the throughput of MIR-CMAC increases continuously. As a result, the network throughput of MIR-CMAC is significantly higher than that of RECV-MAC for heavy network traffic and this gap expands with the increase of network traffic. This is because when network traffic is light there is few channel collisions occurring, so the number

of successful links are about the same for both RECV-MAC and MIR-CMAC. And as RECV-MAC takes less time for packet transmission than MIR-CMAC, as shown in Fig. 13(b), RECV-MAC outperforms MIR-CMAC with moderately higher network throughput in light traffic. But in the heavy traffic scenario rapidly increased collisions will become a dominant problem for packet transmission. This problem can be appropriately handled by MIR-CMAC owing to its deliberated mechanisms described above, which explains why MIR-CMAC can achieve lower packet loss ratio and higher network throughput in large-scale wireless networks than other protocols such as RECV-MAC.

VI. CONCLUSION

In this paper, the MIR-CMAC protocol is proposed based on the basic MAC protocol under the IEEE 802.11b standard to better exploit the potential of cooperative communication in a large-scale wireless network. A full interference model under MIR-CMAC for a given link in the network is built, involving the whole process of data packet transmission of the link and considering the interference effects of all other links. Our work has produced a unique approach to dealing with the problems caused by enlarged interference range in various scenarios such as different transmission modes, diverse interference relationships and impacts from link related parameters. This approach has properly addressed the key challenge when applying cooperative communication in large-scale wireless networks, resulting in substantially improved performance in terms of the effective network throughput and packet loss ratio over other schemes, which are verified by both numerical and simulation results. Our future work may include further investigation on interference models with improved precision and effectiveness by considering equal backoff time among different source nodes and the interference boundary effect in the network.

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