Design and Evaluation of CRDMAC: Circular RTR Directional MAC Protocol for WANETs

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Abstract: Using directional antennas in wireless ad hoc networks (WANETs) offers great potential for reducing the radio interference, and improve the communication throughput. Directional antennas, however, introduces new problems in the wireless media access control (MAC), deafness and new hidden terminals, which may cause severe performance degradation. To solve the deafness problem and the new hidden terminal problems, in this paper, we propose an effective Circular RTR Directional MAC (CRDMAC) protocol for WANETs by using a sub-transmission channel and RTR (Ready To Receive) packets, which modifies the IEEE 802.11 distributed coordinated function (DCF). The sub-channel avoids collisions to other ongoing transmission, and the RTR packets notify the neighbor nodes that the mutual transmission has been finished. We evaluate the CRDMAC protocol through simulations. Simulation results show that the proposed protocol outperforms the existing DMAC (Directional MAC) protocol and the CRCM (Circular RTS and CTS MAC) protocol in terms of throughput and packet drop rate.

Key words: WANETs; MAC protocol; directional antenna; deafness; new hidden terminal

I. INTRODUCTION

A wireless ad hoc network (WANET) is a decentralized type of wireless network with a collection of wireless nodes. WANETs can dynamically self-organize into arbitrary or temporary network topologies without using any local infrastructure [1]. The main advantages of WANETs are flexibility, low cost, and robustness. WANETs can be easily set up, and can endure to natural catastrophes and wars. The characteristics of WANETs make it well met for wide applications, such as military activities, emergency operations and disaster recovery [2]. The design of a WANET has to consider several interesting and difficult problems. For example, in the media access control (MAC) layer, the issues consist of the collision detection, the hidden and the exposed terminal problems, which demand new medium access algorithms [3-4].

Traditionally, in WANETs, all nodes are equipped with omni-directional antennas. Such an example is the IEEE 802.11 MAC protocol [5]. However, the MAC protocols with omnidirectional antennas consume a large portion of the network capacity by reserving the wireless medium over the area [6]. The usage of directional antennas has been proposed to alleviate this problem, in which sender and receiver nodes control the transmitting and receiving beams towards each other only. Directional antennas have great potential to improve the network performance of WANETs, such as spatial reuse and range extension. Directional antennas can also provide higher gain and reduce interference by directing the radio beam towards a desired direction [3]. Several MAC protocols using directional antennas for WANETs have been proposed [6-8], which are referred to as Directional MAC (DMAC) protocols. Most of the proposed DMAC protocols are adapting the usage of IEEE 802.11 over directional antennas [9].

The application of IEEE 802.11 to WANETs with directional antennas, however, induces channel access problems of location-dependent carrier sensing, including deafness and three new hidden terminals. The deafness problem arises because of the beamforming in directional antenna operations [10]. The *asymmetry-gain new hidden terminal* problem arises because of the beamforming gain asymmetry in directional antennas, the *unheard-RTS/CTS new hidden terminal* problem arises because of directional operations [11], and the *multi-channel new hidden terminal* problem arises because of operations in multi-channel MAC protocols [12]. These problems may result in severe performance degradation by packet drop and waste of network capacity. We give a comprehensive study of deafness and hidden terminals in section III.

In this paper, we propose a novel Circular RTR Directional MAC (CRDMAC) protocol for WANETs to solve the deafness problem and hidden terminal problems. The proposed CRDMAC protocol utilizes directional transmissions and multi-channel separation techniques to increase the coverage area for wireless communication. It employs the directional RTS (Request To Send) / CTS (Clear To Send) handshake,

DOI: 10.6084/m9.figshare.761310

the data transmission in the main data channel, as well as the broadcast of RTR (Ready To Receive) messages in the control sub-channel. It is based on a sub-channel for circular directional RTR messages, which notices the neighbor nodes around the transmitter for the intended communication.

The rest parts of this paper are organized as follows. Section II provides an overview of related work. Section III describes the deafness problem and the new hidden terminal problems. Section IV provides the system description and the objectives for WANET with directional antennas. Section V presents the proposed CRDMAC protocol for WANETs. Section VI analyzes the proposed CRDMAC protocol with network simulations. In the last section, we conclude the paper.

II. RELATED WORK

The usage of directional antennas has been studied over recent years. In this section, we present the related work including the preliminary knowledge for comprehending the CRDMAC protocol.

2.1 IEEE 802.11 Distributed Coordinated Function

IEEE 802.11 distributed coordinated function (DCF) is a contention based MAC technique of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) by using omni-directional antennas at the physical layer. The RTS and CTS control packets relieve the hidden-terminal problem through the Network Allocation Vector (NAV) [5]. IEEE 802.11 DCF uses binary exponential backoff, which multiplicatively decreases the rate of transmission, in order to gradually find an acceptable rate. IEEE 802.11 is a CSMA/CA protocol which performs physical carrier sensing before initiating transmissions [13]. When the channel is sensed as idle for the DIFS (DCF Inter-frame Spacing) duration, the protocol invokes a backoff mechanism for contention resolution.

2.2 Classification of Directional Antennas

Directional antennas are different from omni-directional antennas. They are constructed to have certain preferential transmission and reception directions. In WANETs, directional antennas, which are also called smart antennas, consist of a number of radiating elements and a network control unit. The control unit is normally implemented by using a digital signal processor, which is the intelligence of smart antennas. Smart antennas are generally categorized as the following two types [14-15].

1) *Switched Beam Antenna:* In switched beam systems, the antenna array is combined with a fixed Beam Forming Network (BFN), which consists of a predetermined set of weight vectors. Based on the direction-of-arrival estimation (DoA), the BFN chooses a weight vector to be applied to the signal transmission/reception by the antenna array. In a word, the antenna adaptively switches to one of the predefined set of beams in a desired direction. Switched beam antennas can provide most of the benefits of smart antennas with small complexity and expense.

2) *Adaptive Array Antenna:* The adaptive array antenna systems, which are also known as the Steered Beam Antenna systems, provide a high degree of flexibility in configuring the radiation patterns. The DoA algorithm is applied for signal transmission/reception and continuous tracking. The antenna array of the main lobe is directed towards the target using phase shifters, which constructs a steerable radiation pattern. In spite of that, the requirements on continuously locating and tracking signals complicate the signal processing task, and result in a significant increase in the power consumption.

In this paper, we utilize the switched beam antennas in the DMAC protocols for WANETs for energy efficiency.

2.3 DMAC Protocols

Directional antennas need to be appropriately controlled by upper layers of the networking protocol stack to realize the potentials of beamforming systems [4]. The MAC layer is the most important layer to be modified, because it lies just above the physical layer. The goal of the Directional MAC (DMAC) protocols is to set the rules in order to enable efficient and fair sharing of the common directional wireless channel. Recently, many DMAC protocols have been proposed, which attempt to mitigate the issues in WANETs with directional antennas. Korakis *et al.* [16] proposed a Circular RTS MAC. It sequentially transmits multiple RTS on all beams for each data frame to scan the area around the transmitter. The protocol offers improvement over that of omni-directional transmissions, however, the excess control packets caused by circular directional RTS degrade performance. Jakllari *et al.* [17] proposed a circular RTS and CTS MAC (CRCM) protocol, in which multiple directional CTS frames are transmitted consecutively in a circular way to handle deafness at the receiver side. Circular transmission, however, increasing the delay and incurs large control overhead. Gossain *et al.* [18] proposed a MAC protocol for directional antennas, in which multiple directional RTS and CTS messages are transmitted simultaneously through the antenna beams, which are in diametrically opposite directions with neighbors. In order to acquire the ongoing transmission information of neighbors, these schemes require circular transmission of RTS and CTS messages for each transmitted data packet, which may incur large

DOI: 10.6084/m9.figshare.761310

control overhead.

2.4 Multi-channel MAC Protocols

The MAC protocol is to set the rules in order to enable efficient and fair sharing of the common wireless channel. The multi-radio multi-channel MAC protocol typically maximizes the channel utilization by having as many communications as possible [13,19]. Recently, the multi-channel MAC protocols have been proposed in many researches, which use control separation techniques generally in multi-channel radio systems [12,20-21]. Multi-channel diversity in MAC provides different purposes and usage: some intend to enable simultaneous data transmission, some reserve future data usage while the current data channel is occupied, some use separate signalling to solve hidden terminal problems. In this paper, we employ the multi-channel MAC protocol following the idea of splitting one radio channel into two sub-channels, a data channel and a control channel.

III. DEAFNESS AND NEW HIDDEN TERMINAL PROBLEMS

In this section, we first introduce the four-way handshake for channel reservation [4] in the MAC protocols. We then describe the channel access problems of DMAC protocols for WANETs with directional antennas, the deafness problem [7,10] and three new hidden terminal problems [7,11-12,16]. For the sake of convenience, the directional RTS and the directional CTS are called DRTS and DCTS for short in the following.

3.1 Four-Way Handshake and Channel Reservation

The four-way handshake is the technique for channel reservation and data transmission in wireless communications. It performs similarly to that of IEEE 802.11 standard [5] in the DMAC protocols, including RTS (Request To Send) transmission, CTS (Clear To Send) transmission, DATA exchange, and ACK (ACKnowledgement) exchange. An idle node listens to the channel in the omni mode. When it receives a signal arriving from a particular direction, it locks on to the signal and receives it. Here, we refer to a sender node as node *S* and the receiver node as node *R* for describing the four-way handshake in the DMAC protocols.

- *RTS Transmission*

To detect whether it is safe to transmit RTS to node *R*, node *S* first performs physical carrier sensing using a beamform B^R. If the channel is sensed idle, the DMAC checks its Directional NAV (Network Allocation Vector) Table, which maintains a virtual carrier sense status for every DoA (Direction of Arrival). Once node *S* finds out that it is safe to transmit using B^R, the DMAC at node *S* requests the physical layer to transmit the RTS to node *R* using beam B^R.

- *RTS reception and CTS transmission*

Having received the RTS from *S*, node *R* determines the direction to send the CTS in response. If the NAV table at *R* permits transmission in this direction, then the DMAC at node *R* requests the physical layer to beamform in this direction with beam B^S for the CTS.

- *CTS Reception and DATA/ACK Exchange*

If node *S* receives the CTS, it initiates the transmission of DATA packets using beam B^R. Node *R*, on receiving the DATA successfully, transmits an ACK using the beam B^S for response. The other neighbor nodes in the transmission range, receive the ACK packet, and update their NAV tables with the respective DoAs.

3.2 Deafness

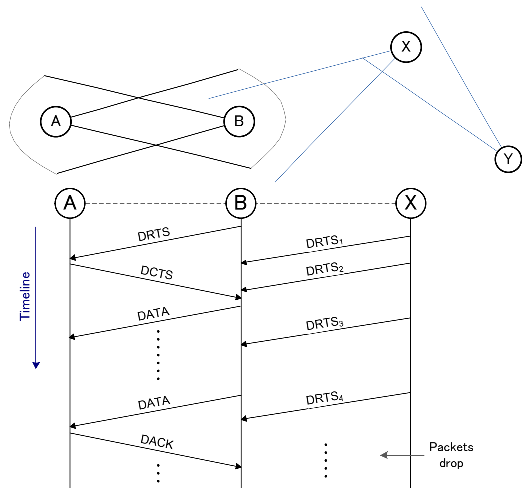

Fig. 1 A scenario of deafness in DMAC protocols

We explain the deafness problem in the DMAC protocols using the scenario in Figure 1. Assume that all nodes are idle and that node B intends to transmit a data packet to node *A*. The DMAC requires node *B* to beamform in the direction of node *A*, and detect if the channel is idle for a DIFS duration. When the channel is found idle, node *B* proceeds to the backoff phase and counts down the backoff counter while still beamformed towards *A*. Observe that while node *B* is counting down its backoff counter, node *X* may intend to communicate with node *B*. If node *X* transmits an RTS to node *B*, node *B* would not receive the RTS in that direction. In the absence of the response from node *B*, node *X* would repeatedly backoff and retransmit the RTS, until the dialog between node *B* and *A* is over. The unproductive retransmissions from node *X* are the outcome of deafness.

Once node *B* has finished transmitting the first data message, it may immediately prepare for transmitting the next message by beamforming in the same direction towards *A*, and then repeating the sequence of DMAC operations with *A*. If node *B* remains backlogged for a long time, node *X* may end up dropping

DOI: 10.6084/m9.figshare.761310

the packets. Meanwhile, repeated failure to communicate to node *B*, causes node *X*'s contention window (CW) to grow exponentially. If node *X* has multiple packets queued for node *B*, it would remain engaged either in backoff or in transmitting a directional RTS. Thus, node *Y* would experience prolonged deafness in the same way, until *X* has dropped all its packets. When the nodes in a chain transmission, where none of the nodes communicates successfully, evokes a new problem, *deadlock* [10]. It is a serious problem on multi-hop transmission, where the intended receiver of a node is a transmitter.

3.3 New Hidden Terminals

The well-known hidden terminal problem [22] in multi-hop wireless networks can be resolved by using RTS/CTS control packets in the CSMA/CA of 802.11 DCF [5], which are transmitted omni-directionally. Directional transmission of RTS/CTS in DMAC protocols introduce two types of new hidden terminals, the *asymmetry-gain new hidden terminal* and the *unheard-RTS/CTS new hidden terminal*. We also describe another new type of hidden terminal problem pertaining to multi-channel MAC protocols, the *multi-channel new hidden terminal*.

3.3.1 New hidden terminal due to asymmetry in gain

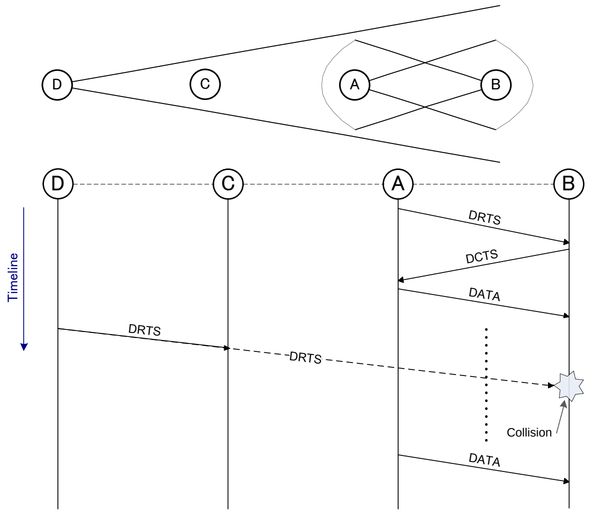

Fig. 2 A scenario of asymmetry-gain new hidden terminal in DMAC protocols

We introduce the first new type of hidden terminal problem pertaining to packet collision in WANETs with directional antennas. We call it the *asymmetry-gain new hidden terminal* in this paper, and explain it using the following scenario.

Now consider the scenario in Figure 2. Assume that all nodes in this scenario are idle, and nodes in the idle state have a gain of G^o (Omni mode). Assume that node A transmits a DRTS to node *B*, and *B* responds with a DCTS. Subsequently, DATA transmission begins from node *A* to *B*, and both nodes are pointing their transmission and reception beams with a gain G^d. Node *D* cannot sense this transmission when this communication is in progress, and assume that node *D* has packets to send to *C*. Node *D* senses the channel with a directional beam pointed towards *C* and concludes that the channel is idle, and thus sends a DRTS to node *C*. However, since node *B* is receiving DATA from *A* in the same direction, it is very much possible that the DRTS from *D* interferes at node *B*. In other words, collisions may occur at the unexpected receiver nodes within the range in the same direction, when they transmit and receive with directional beam of G^d.

3.3.2 New hidden terminal due to unheard RTS/CTS

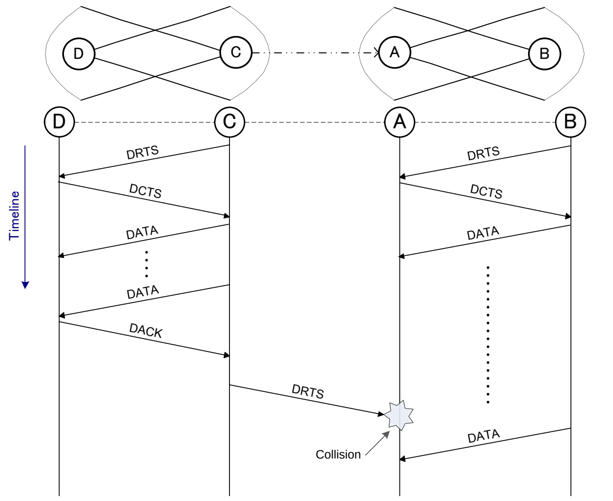

Fig. 3 A scenario of unheard-RTS/CTS new hidden terminal in DMAC protocols

We call the second new hidden terminal, the *unheard-RTS/CTS new hidden terminal* in this paper, and explain it in the following. Consider the scenario in Figure 3. Assume that, node *C* is communicating with *D* with directional beams towards each other. While this transmission is in progress, node *B* is transmitting packets *A* using directional antennas at the same time. While communication between *B* and *A* is in progress, assume that node *C* finishes communication with *D*, and now wants to transmit packets to *A*. Node *C*'s Directional NAV table indicates that it is free to transmit towards *A*, and *C* finds out that the channel is idle on performing physical carrier sense. Thus, node *C* transmits the RTS, and a collision occurs at node *A* (because *A*'s receiving beam is pointing in the direction of *B*).

3.3.3 New hidden terminal due to multi-channel collision

We introduce the third new type of hidden terminal problem pertaining to packet collision in multi-channel environment using omni-antennas, which is called the *multi-channel new hidden terminal* in this paper. In the traditional multi-channel MAC protocol, a node with a single transceiver, which is communicating in one channel, cannot hear packets transmitted

DOI: 10.6084/m9.figshare.761310

in other channels.

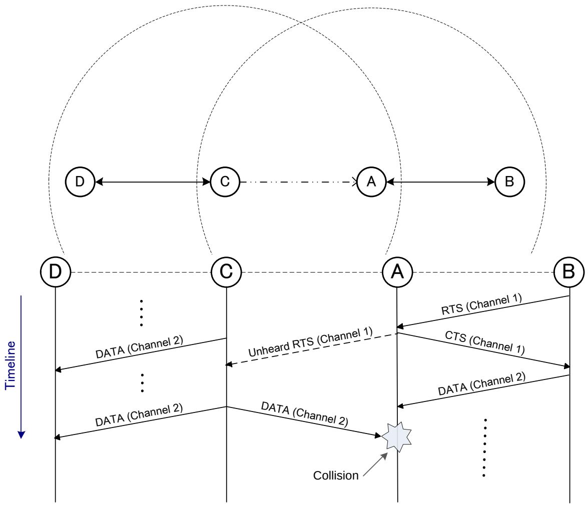

Fig. 4 A scenario of multi-channel new hidden terminal in multi-channel MAC protocols

We explain the multi-channel new hidden terminal problem in multi-channel MAC protocols using the following scenario in Figure 4, which have two radio channels, a control channel for RTS/CTS packets and a data channel for data packets. Node *B* has packets for *A*, so *B* sends an RTS on Channel 1, which is the control channel. Node *A* replies a CTS back to *B*, and selects Channel 2 for data communication. In this scenario, however, when node *A* sent the CTS to *B*, node *C* was busy transmitting DATA on another channel (channel 2) to *D*, so it did not hear the CTS from *A*. Not knowing that *A* is receiving DATA on Channel 2, *C* might be continuously communicating with *D*, and will result in collision at node *A*. The multi-channel new hidden terminal occurs due to the fact that nodes may listen to different channels, which makes it difficult to use virtual carrier sensing to avoid the hidden terminal problem.

IV. SYSTEM DESCRIPTION AND OBJECTIVES

This section first presents the system description with the network structure and the antenna model taken into consideration. Then we investigate the objectives for WANETs with directional antennas.

4.1 Network Structure

We consider a WANET system consisting of a number of wireless nodes equipped with directional antennas, they are mobile and randomly distributed. In addition, we assume that, all the nodes use symmetric radio channel, which are homogenous in functionalities and capabilities.

The illustrations of the network structure are shown in Figure 1, 2 and 3, where the nodes in the network are attempting for communications through MAC protocols. We can see that, nodes communicate or try to communicate with others in directional mode. In the scenarios, some nodes may endure the deafness problem and the new hidden terminal problems during the ongoing data transmission period between node *A* and node *B*.

4.2 Antenna Model

In this paper, we consider that each node is equipped with a switched beam antenna which comprises *M* fixed beam patterns, as shown in Figure 5. The antenna system possesses two separate modes, omni mode and directional mode. In omni mode, a node receives signals from all directions with gain G^o. A node in idle state waits for signals in omni mode. When a signal is sensed in omni mode, the antenna locates the direction on which the signal power is strongest and goes into the directional mode. In the directional mode, a node points its beam toward a specific direction with gain G^d ($G^d > G^o$). Most existing research utilizes the same antenna model [15]. In the CRDMAC protocol, the omni mode is utilized for receiving signals, whereas the directional mode is utilized for data transmission and reception. We assume that the pattern in the directional mode is a circular sector with a constant gain in the sector, such that, there is no antenna gain outside the sector.

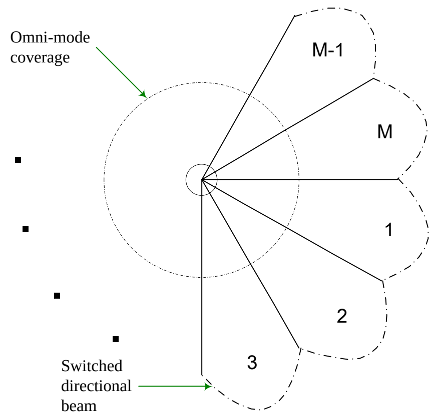

Fig. 5 Antenna model with M beams

In the directional mode, the antenna can transmit a signal in any direction, using an array of elements. Individual omni-directional transmissions from these elements interfere with each other, resulting in the increase of the signal strength in one or more directions, and the elimination in other directions. There are directional antennas with 1, 2, 4, 8, 16 etc. elements [3,23]. They assume that, a smart antenna can provide effective omni transmission with *M* sequential directional transmissions, when it has *M* antenna elements. An important element of the proposed CRDMAC protocol covers the whole area around the transmitter with successive sequential transmission.

4.3 Objectives

The deafness problem and the new hidden terminal

DOI: 10.6084/m9.figshare.761310

problems caused in the basic DMAC and multi-channel MAC protocols waste the network capacity, and result in unfairness as well. When multiple nodes attempt to communicate with the same node, the node that wins channel contention retains the privilege to access the channel for a long time. Although the receiver remains busy almost all the time, the other transmitter nodes experience unfairness. In this paper, we study the deafness problem (including the deadlock problem) and new hidden terminal problems in DMAC protocols. We consider the conditions above in WANETs, and focus on solving these problems with an effective CRDMAC protocol for WANETs.

V. PROPOSED CRDMAC PROTOCOL FOR WANETS

This section presents the details of the proposed CRDMAC protocol, including the antenna gain employed in the protocol, and the operation of the CRDMAC protocol.

5.1 The Gain of Antennas

The antenna radiates the time-averaged power in all directions. The power gain $G(\theta,\phi)$ of an directional antenna is the ratio of radiation intensity to average intensity over all directions [24], which is defined as

$$G(\theta,\phi) = \eta \frac{U(\theta,\phi)}{U_{ave}}, \quad (1)$$

where U(θ,ϕ) is the power density in direction (θ,ϕ), U_{ave} is the average power density over all directions and η is the efficiency of the antenna. If the antenna transmits power equally in all directions, then U(θ,ϕ) will be equal to U_{ave} and the antenna is called *isotropic*. An isotropic antenna has a spherical pattern and is only used for analytical purpose. If no direction is specified, the gain usually means the maximum gain value over all directions. Due to the reciprocity, all the gain and radiation pattern characteristics are known to be the same for both transmission and reception [4].

5.2 Operation of the CRDMAC Protocol

The key contribution of the Circular RTR DMAC (CRDMAC) protocol lies in the use of two sub-channels and circular transmission of RTR (Ready To Receive) to alleviate deafness and new hidden terminals. We observed that, both deafness and new hidden terminals occur primarily because a transmitter is unaware of the activities of its intended receiver. The main idea of the CRDMAC protocol is to inform a node's neighborhood of its activity.

In the CRDMAC protocol, the common channel is split into two sub-channels: a data channel and a narrow control channel. We adopt the control separation concepts from [12] for transmission in multi-channel MAC protocol. In this way, directional RTS, directional CTS, DATA and ACK packets are transmitted on the data channel, and the RTR packets are assigned on the control channel. We assume that an idle transceiver is capable of tuning into both data and control channels.

The RTR packets serve as indicators that nodes *B* and *A* were recently engaged in communication. A neighboring node, *C*, unable to communicate with node *A* or node *B* in the meanwhile, can get the RTR packets in the control channel, as an indication of recent deafness. The information in RTR packets is only the ID of sender so the control narrow can be very narrow. The neighbors who received it can know which neighbor was transmitting just now by the ID of RTR packets.

After exchanging the DATA/ACK, both the sender *A* and the receiver *B* will turn to control channel. Then circularly send RTR packets to notify its neighbors that it has finished its transmission which maybe has caused deafness and new hidden terminals. Because the RTR packets may interfere with the transmission between other neighbors we send RTR in control channel. The time to send a RTR packet is

$$t_{rtr} = \frac{S_{control}}{R_{control}} + \iota + c, \quad (2)$$

where $S_{control}$ is the size of the RTR packet, $S_{control}$ is the data rate of control channel, ι is the channel latency and c is the beam switching time.

We illustrate the operation of the CRDMAC protocol in Figure 6, where node *B* is transmitting data to node *A*, meanwhile, node *C* attempts to communicate with node *A*. However, node *A* is deaf to node *C*, thus node *C* waits for RTR messages in the control channel. We introduce the operation of the proposed CRDMAC protocol in both transmitting sides and waiting sides as follows.

1) *Transmitting sides:*

In this scenario, node *B* and node *A* are the transmitting sides, in this case, node *B* initiates dialogs with node *A* and transmits data to node *A*.

- *Step 1.* Node *B* initiates the RTS message, and broadcast it to node *A*.
- *Step 2.* After received the RTS message, node *A* responds node *B* the CTS in a four-way handshake [5] on data channel.

DOI: 10.6084/m9.figshare.761310

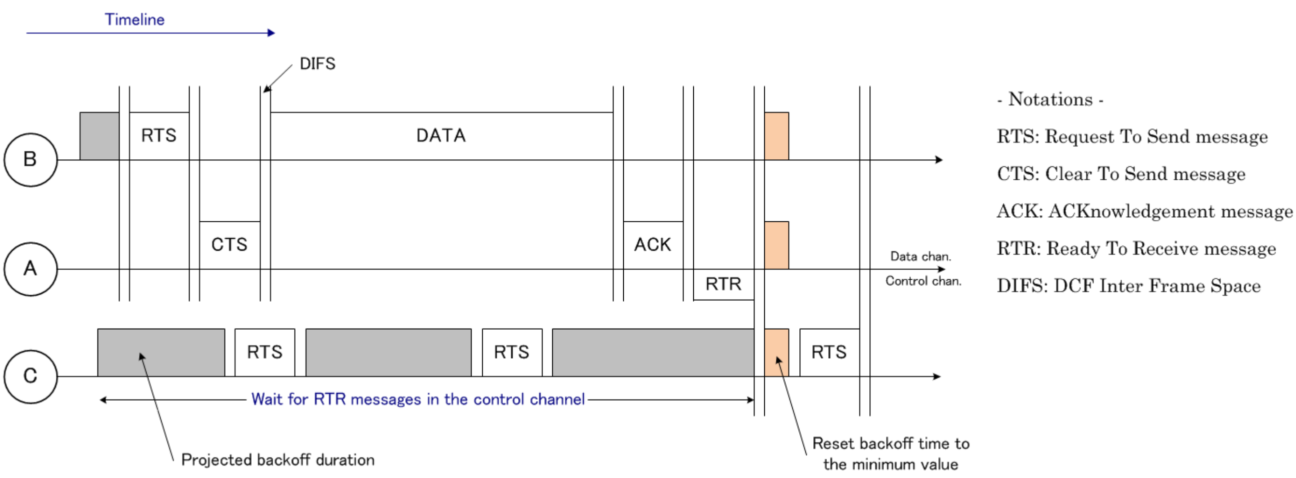

Fig. 6 An illustration of operations of the CRDMAC

- *Step 3.* After received the CTS message, node *B* transmits data to node *A* and get the ACK back if succeeded.
- *Step 4.* When the four-way handshake of data communication is over, node *B* tunes into the control channel for declarations. It initiates RTR messages, then transmits circularly with the directional antenna to their neighbors. As we have mentioned in section III, we adapt antennas with predefined number of beams, *M* in Figure 5, which cover the whole area around the transmitter. Therefore, node *B* starts transmitting its RTR in a predefined direction, assuming with beam 1, then turns its transmission beam sending the same RTR with beam 2. It continues this procedure repeatedly (until beam *M*) until the transmission of RTR covers all the area around the transmitter.
- *Step 5.* After sending the RTR packets circularly, node *B* tunes back to the data channel for other operations, e.g., starting communication with another node.

2) *Waiting sides*:

In this scenario, node *C* is the waiting side, and it has to wait for RTR messages since node *A* is deaf to it.

- *Step 1.* Since node *C* is attempting transmission towards node *A*, it sends RTS packet to node *A*.
- *Step 2.* Node *C* waits for a backoff time and tunes to control channel for RTR messages, because no CTS responding from node *A*. When the backoff counter reaches 0, node *C* tunes to the data channel, transmits the RTS packets again, and waits for a backoff time repeatedly if no CTS received.
- *Step 3.* If node *C* receives a RTR packet, it reset the backoff time to the minimum value CW_{min}, and broadcasts the RTS packet to node *A* for potential communication.

Observing in Figure 6, the projected backoff duration shows the duration over deafness, and node *C* can compete against node *B* fairly in the proposed CRDMAC protocol. Figure 7 shows the flowchart of the proposed CRDMAC protocol at the waiting sides (node *C*).

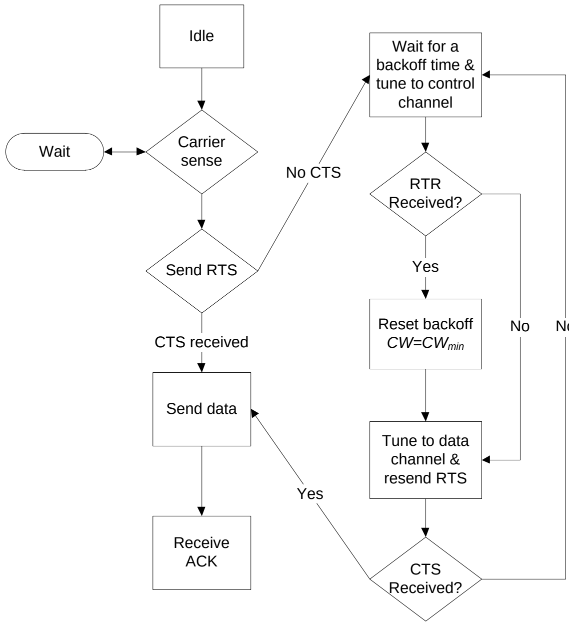

Fig. 7 The flowchart of the waiting node

VI. PERFORMANCE EVALUATION

In this section, we focus on the throughput and the packet drop rate from the network simulation. We use the network simulator QualNet 4.5 [25] with Java Runtime Environment 6 [26] to simulate the proposed CRDMAC protocol.

6.1 System Parameters and Settings

In the network simulation experiments, we study two typical scenarios below to do simulations. Scenario 1 indicates the random deployed topology condition, and Scenario 2 indicates the common grid topology

DOI: 10.6084/m9.figshare.761310

condition, where deafness and new hidden terminals happen in basic DMAC protocols.

We assume that, the physical channel is error free and the propagation delay is zero, which bandwidth is split into two sub-channels as a data channel and a control channel. The transmission packet length is set as constantly equal to 1024 *bytes*. The transmission range of directional antenna is R_d = 300*m*, the number of beam for a circular directional antenna is 4 *beams*, and the switching time of one beam is c = 1.1*ms*. The channel latency is set to $\iota = 3.1\times10^{-3}$*ms*, and the slot time of DIFS is t = 10*μs*. The minimum value of node contention window (CW) is CW_{min} = 15*ms*, as the CW exponentially grows, the maximum value of CW is CW_{max} = 130*ms*. We compare the proposed CRDMAC protocol with the DMAC protocol [11] and the CRCM protocol [17].

We evaluate the protocols with two performance metrics, throughput and packet drop rate. Network throughput refers to the average data rate of successful data or message delivery over a communication link. Packet drop rate is a useful measure for WANETs, which is relative to the data flows. We are trying to determine how much we alleviate deafness and new hidden terminals by decreasing the drop rate and increasing the throughput.

6.2 Scenario 1

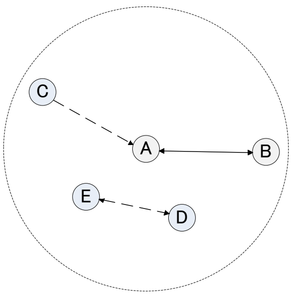

Fig. 8 Scenario 1 for the CRDMAC simulation

We evaluate the performance of the scenario demonstrated in Figure 8. In this experiment, node *C* wants to transmit to node *A* while node *B* is transmitting to node *A*, even when node *B* has finished the transmission, node *B* will transmit to node *A* again and again. Node *A* cannot hear node *C* and will not respond CTS to node *C*. As we have discussed in the previous sessions, the backoff time of node *C* will be set longer after times.

Table I The comparison of drop rate

	CRDMAC	CRCM	DMAC
Packet drop rate of node *C*	0	0	40%

We first consider the packet drop rate. Because the existing DMAC protocol cannot alleviate the deafness problem and new hidden terminal problems, node *C* must wait for its binary exponential backoff time, even when node *A* has finished its transmission with node *B*. In DMAC protocol, the probability of dropping packet of node *C* is very high, because node *C* conflicts with node *B* for many times. But the CRDMAC protocol solves the problems, where node *C* can compete with node *B* fairly. It does not drop its packets as we see in Table I.

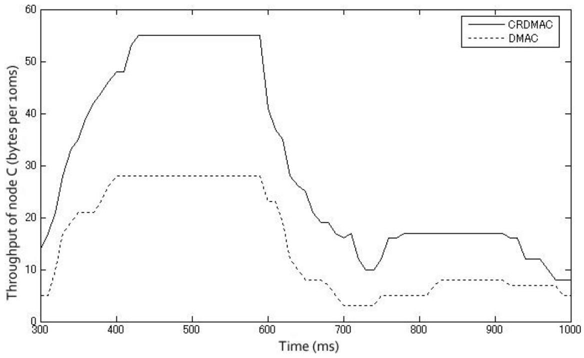

Fig. 9 Throughput of node *C* in scenario 1

Now we compare the proposed CRDMAC protocol with DMAC protocol in term of throughput to verify the effectiveness. Simulation results are the average of 100 runs. The result in Figure 9 shows that, the CRDMAC protocol performs better than DMAC protocol because it solves deafness and new hidden terminals properly. As node *A* informs node *C* for the intended transmissions by the circular RTR, it induces a higher throughput than that of DMAC protocol. As Node *C* receives the RTR packets and set its backoff time to the minimum value, node *C* can compete with node *B* fairly and will not drop its packets for the long time waiting.

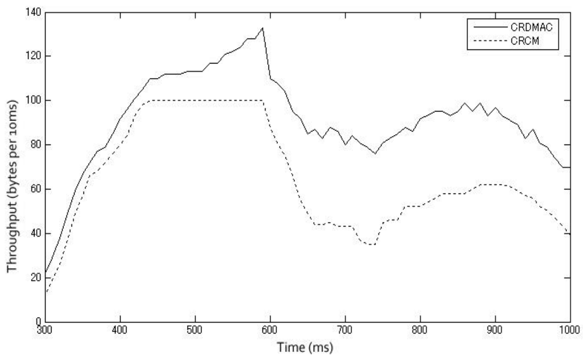

Fig. 10 Network throughput in scenario 1

Figure 10 shows the network throughput of the CRDMAC protocol compared with the CRCM protocol. The result shows that, the network throughput of the CRDMAC protocol is better than that of the CRCM protocol, because we use the control channel to send RTR packets which don not interfere with the transmission of node *D* and node *E*. In the CRCM, the circular RTS and CTS will be sent to its neighbors when taking handshake and the transmission of node *D* and node *E* will be interfered.

DOI: 10.6084/m9.figshare.761310

6.3 Scenario 2

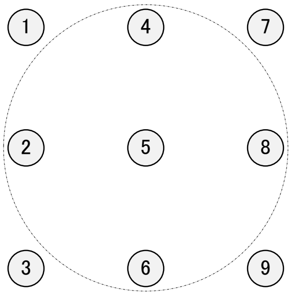

Fig. 11 Scenario 2 for the CRDMAC simulation

The second simulation uses the scenario in figure 11. There are 9 nodes in a grid topology. The neighbors of a node can be concluded by the circular range around node 5, which depicts the coverage range of the 4 beams of this position, thus each node only can communicate nodes in horizontal and vertical directions. During the network simulation, we randomly let two nodes communicate with each other at one time frame, and change the transmission rate of the sender node.

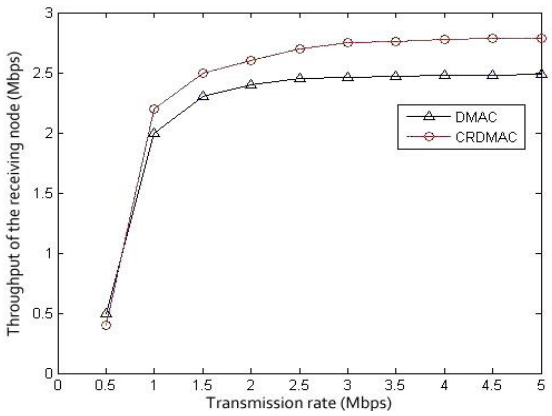

Fig. 12 Throughput of the receiving nodes in scenario 2

The simulation results are shown in Figure 12. In the low transmission rate, the CRDMAC protocol has lower throughput than that of the DMAC protocol. This is due to that, the available data rate for communication has to allocate part of the bandwidth to the control channel. The CRDMAC protocol is inferior to the DMAC protocol because of the overhead of circular transmissions, however, as the sending rate increases, this extra overhead is quickly canceled.

VII. CONCLUSION AND FUTURE WORK

In this paper, we have proposed a Circular RTR DMAC (CRDMAC) protocol, which use a novel receiver-initiated mechanism to handle the deafness problem and new hidden terminal problems in DMAC protocols. We use circular RTR messages and sub-channel in the CRDMAC protocol reactively, and alleviate the deafness problem and new hidden terminal problems in WANETs using circular directional antennas. The transmission time of circular RTR packets will not delay data transmission, since they are sent after the data transmission. Furthermore, the circular packets will not interfere with the neighbors by using a sub-channel which is better than the CRCM protocol.

Acknowledgments

This work has been partially supported by Grant-in-Aid for Scientific Research of Japan Society for Promotion of Science (JSPS) and Collaboration Research Grant of National Institute of Informatics (NII), Japan. Part of this paper was presented at the conference of MSN2011.

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DOI: 10.6084/m9.figshare.761310