Collision Scattering Through Multichannel in Synchronous Directional Ad Hoc Networks

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Abstract. Unique advantages of directional antennas have attracted much interest of the researchers, such as longer transmission distance, large transmission antenna gains and large spatial reuse gains. However, the feature of directional transmission and reception (DTR) also brings challenges to the media access control (MAC) protocols, which means the nodes can only sense the wireless channel in a given direction and thus the interference or collision between the concurrent transmission links is difficult to be avoided. To address this problem, in this paper a novel collision scattering method is proposed to decrease the collision probabilities of the concurrent transmission links. The basic idea is to distribute the concurrent transmission links to different channels, which are divided in the wireless spectrum, such that multiple transmission links can be ongoing concurrently. A time division multiple access (TDMA) based multichannel MAC protocol is proposed based on the collision scattering method. Extensive simulations are carried out to evaluate the performance of the proposed protocol and the gain of the collision scattering. The simulation results show that the aggregation throughput of the proposed protocol outperforms the existing protocols and the collision scattering gain is achieved.

Keywords: Directional ad hoc networks · Collision scattering
Multi-channel · Medium access control

1 Introduction

Directional ad hoc networks [1,2] are composed of many nodes equipped with directional antennas, which are self-organized and coordinated. Directional antennas have many advantages comparing to omnidirectional antennas, such as large transmission or reception antenna gains, longer transmission distance, less interference and large spatial reuse gains [3,4]. However, directional transmission and reception (DTR) also brings a significant challenge to the media

L. Wang et al. (Eds.): QShine 2017, LNICST 234, pp. 183–193, 2018.
https://doi.org/10.1007/978-3-319-78078-8_19

access control (MAC) protocols, which is that the receiver can only sense the wireless channel in a given direction and thus the interference or collision between the concurrent transmission links is difficult to be avoided. Therefore, the collision between the concurrent transmission links becomes the main concern of the directional MAC (DMAC) protocol designs.

Academic researchers devote extensive works to solve the concurrent transmission collision problems [1,2]. The existing works can be divided into two categories based on the main method to decrease the probability of collisions. The first one is following the carrier sense multiple access with collision avoidance (CSMA/CA) method, the basic idea of which is to use the physical and virtual carrier sensing to avoid the collision. And the second one is the synchronous, i.e., time division multiple access (TDMA), the basic idea of which is to synchronize the network and the time is divided into slots such that the collision only occurs within each slot. These two categories are named as CSMA/CA based one and the TDMA based one in this paper.

The CSMA/CA based multichannel DMACs can be divided into four types, i.e., tone based, control-channel based, no-control-channel based and power-control based.

- *Tone Based*: Ref. [5] proposed a dual-busy-tone DBTMA/DA. The channel is divided into a data channel and a control channel, the data channel is used to transmit ORTS/DCTS/DDATA/DACK frames, while the control channel is used to transmit two busy tones. These two busy tones (transmit busy tone and receive busy tone) which are turned on only when transmitting frames can be heard by all nodes within their directional transmission ranges. The main idea of the protocol is using tones to notify the surrounding nodes and guarantee the current transmission.
- *Control-Channel Based*: Ref. [6] proposed a deafness-aware MAC (DA-MAC) protocol. The channel is divided into two channels: a control channel and a data channel. The sending node sends the DRTS on the control channel and the data channel, and the receiving node makes the corresponding reply according to whether the two channels receive the DRTS. DCTS will be transmitted on both channels if the DRTS is received on both channels. Likewise, data will be transmitted on data channel if the DCTS is received on both channels. The main idea of the protocols is using two channels to ensure the current transmission and to let other nodes quickly occupy the channel.
- *No-Control-Channel Based*: Ref. [7] proposed a multi-channel MAC protocol for directional antennas (MCMDA) protocol. A pair of nodes transmit data in chosen free data channel. When a node receives a DRTS, it replies a DCTS and immediately sends a VCTS in the opposite direction to defer the nodes that can receive the VCTS transmit over this data channel until the current transmission is over in this same free data channel. The main idea of MCMDA is multiple pairs of transmissions can be ongoing in multiple data channels with spatial reuse and multi-channel diversity.
- *Power-Control Based*: Ref. [8] proposed a multi-channel power-controlled DMAC (MPCD-MAC) protocol. The nodes transmit RTS and CTS at full

power on the control channel in each direction, and Data and ACK are transmitted in one of available data channel in the selected direction.
- *Hybrid-Contention Based*: Ref. [9] is a hybrid-contention-based multi-channel MAC protocol with directional antennas (MMAC-DA). A frame is divided into two windows: ATIM window and Data window. Channel access and data transfer reservations are done through random contention in the ATIM window, and the data transfer is done by synchronous mode in the Data window. *The simulation result indicates MMAC-DA has higher aggregate throughput than the Random DMAC in IEEE 802.11.*

Most of the TDMA-based DMACs are based on single channel. Ref. [10] proposed a direction of arrival (DOA) MAC which is based on the slotted ALOHA with each slot broken into three mini-slots. In the first mini-slot, all transmitters transmit a simple tone towards their receivers. The receivers then run a DOA algorithm to identify the direction of the transmitters. Each receiver forms its directed beam towards the direction that has the maximum power. The packet is transmitted in second mini-slots. After receiving the packet correctly, the receiver responds with an ACK in the last mini-slot. The simulation results show that DOA-MAC achieves higher throughput than the Basic Random DMAC. Ref. [11] proposed a Reservation Directional MAC (RDMAC) for multi-hop wireless networks with directional antennas. The RDMAC protocol is divided into a reservation period and a transmission period similar to [9]. Reservations are done in the reservation period and data is transmitted in transmission period. Ref. [12] proposed a Neighbor-Discovery/Reservation/Data-Transmission single-channel MAC protocol (DTRA). Neighbour-Discovery aims to find the neighbour nodes, the purpose of the Reservation is to make data transmission for node pairs and Data-Transmission is for the data transmission.

In summary, the TDMA-based works may outperform the CSMA/CA based works [1,9,10,12]. However, with the using of multichannel the CSMA/CA based multichannel DMACs may outperform the TDMA-based works, since the collision between the concurrent transmission links may be scattered. Furthermore, most of the TDMA-based DMACs are single channel based. Thus, how does it perform if the TDMA-based multichannel DMAC is proposed? Will the collision scattering still gain? To answer these two questions, in this paper a TDMA based multichannel DMAC is proposed and the performance of it and the collision scattering gain is evaluated. The main contributions of this paper are listed as follows.

- A collision scattering method is proposed for the synchronous directional ad hoc networks. The basic idea is to distribute the collisions between concurrent transmission links to different channels such that the collision probability of the concurrent transmission links can be reduced.
- A collision scattering based multichannel TDMA DMAC procol is proposed, and the detailed working procedures are described.
- Extensive simulations are carried out and the performance of the proposed DMAC and the gain of the collision scattering are evaluated.

The rest of the paper is organized as follows. The system model and the frameworks of the proposed protocol are given in Sect. 2. In Sect. 3, the proposed DMAC protocol is vividly illustrated in details. Performance evaluation is presented in Sect. 4. The conclusion and future work are given in Sect. 5.

2 System Models and Frameworks of the Proposed Protocol

2.1 System Models

In directional ad hoc networks, N wireless nodes are randomly deployed, each of which is equipped with directional antennas to communicate with its neighbours. The switched directional antennas are assumed, and at any time instant only one of directional antennas can be activated. Let B denote the number of directional antennas. The angle range of a directional antenna is assumed as ω, $\omega = 2\pi/B$. The switching time from one direction to another direction of the directional antennas is omitted.

Each node is also equipped with a synchronous device, e.g., GPS. Such that the network is synchronized, and the time line is slotted. In each time slot, the node works in a half-duplex mode, i.e., the node can transmit or receive but not both. And in each time slot, only one directional antenna can be activated. The number of the available channels in the network is denoted as E, $E \geq 1$. In each time slot, each node can only work on one assigned channel and the channel switching time is also omitted.

2.2 Frameworks of the Proposed Protocol

Figure 1 shows the framework of the proposed protocol. Firstly the time line is divided into super frames. Each super frame is composed of three phases, i.e., the scanning phase, the reservation phase and the data transmission phase. The main functions of each phase are illustrated as follows.

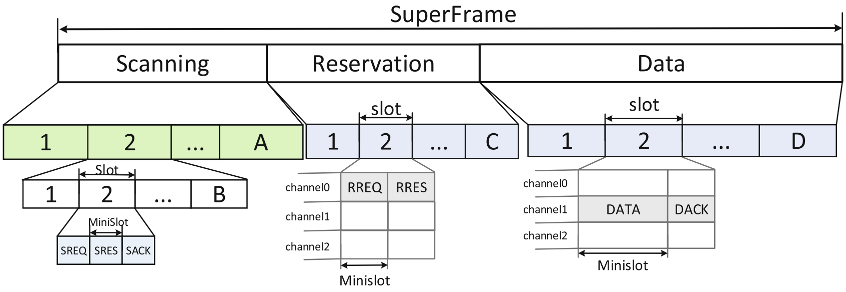

Fig. 1. The framework of the proposed protocol

- In the scanning phase, each node executes the neighbour discovery algorithm to discover its neighbours, and makes reservations with its neighbours that they communicate the data transmission requests in the reservation phase. Particularly, in the scanning phase all nodes work in the same channel, but they can reserve different time slots in different channels in the reservation phase. Suppose that there are $A \times B$ slots in the scanning phase, and each slot can be divided into 3 mini-slots. Note that A is the neighbour discovering number of rounds, and B is the number of directional antennas.
- In the reservation phase, the neighbours which make reservation communicate the transmission requests and then reserve the data slots in the data transmission phase. Same with the scanning phase, the neighbours can reserve different time slots in different channels in the data transmission phase. Suppose that there are C slots in the reservation phase, and each slot can be divided into 2 mini-slots.
- In the data transmission phase, the neighbours transmit their traffic in the reserved data slots and the reserved channels. Suppose that there are D slots in the data transmission phase, and each slot can be divided into 2 mini-slots.

To facilitate the programming the proposed DMAC, we define the data structures of the proposed DMAC as follows. After the scanning phase, each node can obtain the neighbour node table X and the slot reservation table Y, where $X = [x_i]_{1\times B}$ and x_i is the set of neighbours of the ith direction, and $Y = [y_i]_{1\times C}$ and $y_i = (s, r, e)$ is a three tuple meaning that node s will transmit a request packet to node r in the ith slot at channel e. Then in the reservation phase, the nodes communicates with their neighbours according to the slot reservation table Y. And after reservation phase, the data slot reservation table Z in the data transmission phase can be obtained, where $Z = [z_i]_{1\times D}$ and $z_i = (s, r, e)$ is also a three tuple, with the similar meaning of y_i, i.e., node s will transmit a data packet to node r in the ith slot at channel e.

3 Description of the Proposed DMAC Protocol

The whole working procedures are described in this section, particularly the collision scattering method is detailed. We note that the frameworks of the proposed DMAC protocol is based on [12]. Before introducing the proposed DMAC protocol we illustrate the basic idea of collision scattering.

3.1 The Basic Idea of Collision Scattering

We take the scanning phase as an example to illustrate the basic idea of collision scattering. And the disadvantages of [12] is illustrated first and then we illustrate the collision scattering method.

The collision problem between the concurrent transmission links in the reservation phase in [12] may exhibit a phenomenon, where after the scanning phase the node can discover its neighbours and make reservation with its neighbours in the reservation phase, but the communication in the reserved slot fails. The main reasons which cause failure in [12] in the reservation phase, i.e., collisions between the concurrent transmission links, may include the following two terms. The first is that there is only one channel and the second is that there are no coordination between the concurrent transmission links. For example, link $\mathcal{L}_1$ communicates its request in slot i_1 in the reservation phase, while link $\mathcal{L}_2$ communicates its request in slot i_2 in the reservation phase. Although $i_1 \neq i_2$, link $\mathcal{L}_1$ and link $\mathcal{L}_2$ may reserve the same slot i_d in the data transmission phase. Such that a collision may occur between the concurrent transmission links $\mathcal{L}_1$ and $\mathcal{L}_2$ at time slot i_d when these two links transmit data, since there is only one channel.

However, after the collision scattering through multichannel method is employed, although link $\mathcal{L}_1$ and link $\mathcal{L}_2$ may reserve the same slot i_d, they can choose different channels since there are totally E, $E \geq 1$, channels. Such that the collisions between the concurrent transmission links can be scattered.

3.2 Collision Scattering Method in Scanning Phase

In the scanning phase, the scan based neighbour discovering algorithm [12] is employed in this paper. The basic idea is to let the master neighbour discovering nodes switch their directional antennas *clockwise*, while let the slave neighbour discovering nodes switch their directional antennas *counter clockwise*. The directional antennas will be switched at the beginning of the time slot. Note that each slot in the scanning phase is divided into 3 mini-slots, and the SREQ-SRES-SACK (Scanning REQuest packet, Scanning RESult packet, Scanning ACKnowledgement packet) packets exchanging process is defined in [12] with one packet sending in one mini-slot. Therefore, the master neighbour discovering nodes is the nodes who send the SREQ and the SACK packets, while the slaves is the nodes who send SRES packet.

However, we would like to point out the changes when we employ the scan based neighbour discovering algorithm proposed in [12].

- Firstly, we note that in [12] there is only one channel while in the proposed DMAC there are totally E, $E \geq 1$, channels. Thus the main difference of the outcome in the scanning phase is the slot reservation table Y in the reservation phase.
- Secondly, we would like to note that the collision scattering method is employed in this phase with the employment of the multichannel. That is to say when the neighbours make reservation in the reservation phase after they choose a common free slot, they can randomly choose one common available channel, such that the collisions between concurrent transmission links can be scattered.

The detailed working steps are given as follows. Each node is acting as a master node in probability of p_s, while acting as a slave node in probability of $1 - p_s$. The initial direction of the mater node is the 12 o'clock direction while the initial direction of the slave node is 6 o'clock. The switching direction of the master node during scanning is clockwise as the time slot increases. While the switching direction of the slave node during scanning is counter clockwise as the time slot increases. The scanning process is divided into three-way handshake that is similar to [12].

Handshake Step 1-At *Minislot* 0, the master nodes send SREQ packet, meanwhile, the slave nodes are ready to receive SREQ. SREQ contains the source node address, i.e., the mater node's ID, the destination node address, i.e., broadcast ID, and the beam index, i.e., current beam index.

Handshake Step 2-At *Minislot* 1, the nodes received the SREQ will reply a SRES (Scanning Response) packet containing RISI (Reservation Idle Slot Indication) with the probability of p_r, meanwhile, the master nodes are ready to receive SRES. RISI = $[d_i]_{1\times C}$, where $d_i = 0$ denotes the slot i is idle while $d_i = 1$ means the slot i is busy. After receiving the SRES, the master nodes make comparison of RISI that SRES contained with its own and allocates a reservation slot which is randomly selected from the common free slots. Finally, the free slot, a random channel, a random reservation launching state are wrapped to be RRRA (Result of the Reservation Resource Allocation). SRES contains the source node address, i.e., the slave node's ID, the destination node address, i.e., the master node's ID, the reservation idle slot indication, i.e., RISI, and the beam index, i.e., current beam index.

Handshake Step 3-At *Minislot* 2, when the master node received the SRES correctly, it firstly update its X and Y table, and then replies a SACK (Scanning Acknowledgement) packet carrying the RRRA. Likewise, the X and Y table will be updated when the SACK is correctly received at the slave node. SACK contains the source node address, i.e., the request node's ID, the destination node address, i.e., the response node's ID, the result of the reservation resource allocation, i.e., RRRA, and the beam index, i.e., current beam index.

After several rounds of scanning, i.e., A, most of the neighbour nodes are scanned. Each node will generate a X table and a Y table at the end of the scanning phase.

3.3 Collision Scattering Method in Reservation Phase

As described in the previous subsection, during the neighbour discovery process, two nodes detect each other and agree on a common time slot at which the two nodes would see if they can make any reservations. When the time slot arrives, each node only needs to extract its own X table and Y table to prepare for reservation. Next we take the ith slot where $y_i = (s, r, e)$ as an example to illustrate the detailed working steps in the reservation phase.

At *Minislot* 0, the sender s sends RREQ (Reservation Request) to the receiver r in the ith slot (or beam) in channel e. For example, firstly, node 0 extracts $y_0 = (0, 1, 2)$ from its Y table while node 1 extracts $y_0 = (1, 0, 2)$ from its Y table at slot 0. That means node 0 will send a packet to node 1 at slot 0 in channel 2. Secondly, node 0 extracts $x_0 = \{1\}$ from its X table while node 1 extracts $x_3 = \{0, 2\}$ from its X table. That means node 0 will send on beam

0 and node 1 will receive on beam 3. Finally, node 0 sends RREQ on beam 0 while node 1 are receiving on beam 3 at slot 0 in channel 2. RREQ contains the source node address, i.e., the launching node's ID, the destination node address, i.e., the falling node's ID, the traffic demand of the launching node address, i.e., the launching node's demand and the data transmission resource idle indication of launching node, i.e., DRII (Data Resource Idle Indication).

The sender's demand specifically refers to the total packet number to the receiver and each packet will be transmitted in one slot. Let DRII $= [e_i]_{1 \times D}$, where $e_i = 0$ denotes the slot i is idle while $e_i = 1$ means the slot i is busy. The receiver executes the reservation procedure to allocate the data resource block and update its DRII table and Z table after receiving RREQ.

At *Minislot* 1, the receiver node replies RRES (Reservation Response) carrying the reservation result to the launching node, the launching node prepares to receive RRES, respectively. The reservation result table of the launching node is renewed when it receives RRES. RRES contains the source node address, i.e., the falling node's ID, the destination node address, i.e., the launching node's ID and the reservation result, i.e., RDRA (Result of the Data Resource Allocation).

Let RDRA $= [f_i]_{1 \times D}$, where $f_i = 0$ denotes the slot i is not allocated while $f_i = 1$ means the slot i is allocated to the pair nodes. Each node will generate a Z table when the reservation phase ends. A different reservation procedure determines different data allocation result but the overall performance difference is not large. We are more concern about the gain that the multichannel can bring than the single channel, so we proposed a heuristic reservation method that is allocating resources according to traffic demand to illustrate the advantages of our protocol. The heuristic reservation method is divided into two part, the first part is getting the common free data slots by comparing the DRIIs of the two nodes, and the second part is randomly selecting the slots as more as possible according to traffic demand.

3.4 Data Transmission Phase

In the data transmission phase, each node sends packets according to Z table similar to reservation phase. DATA is transmitted at *Minislot* 0 while DACK (Directional ACK) is replied at *Minislot* 1 if the DATA is correctly received. With the density of node increased, even if there will be more than one pairs of node are transmitting DATA in the same mini-slot, the probability of collision will be not increase because the collision will be scattered by multichannel.

4 Performance Evaluation

4.1 Simulation Parameters Setting

To evaluate its performance, our proposed protocol has been implemented in *NS2*. The simulations are conducted with different number of nodes N, i.e., from 10 to 50, which are deployed in a $200m \times 200m$ area. All of the nodes can reach each other in one hop. The number of channels is $E = 4$. Each node discovers the neighbour nodes in scanning phase to form a sender-receiver pair. A node generates and transmits different number of packets, i.e., from 5 to 30, to its receiver. The number of beams is $B = 6$. The scanning round in the scanning phase is $A = 4$. The probability of becoming a master node is $p_s = 0.5$. The probability of reply of SREQ packet is $p_r = 0.5$. The slot number in the reservation phase is $C = 20$. The slot number in the data transmission phase is $D = 100$. Each simulation is conducted in a superframe duration and the simulation results are the average of 100 runs of different topologies.

4.2 Simulation Results

The aggregate transmitted packets with different number of channels, different number of nodes, and different number of packets are simulated, as shown in Fig. 2. There are two result groups. The first one is 10 packets per reservation, and the second one is 30 packets per reservation. That is to say once the reservation between neighbours success, 10 or 30 data slots will be reserved in the data transmission phase.

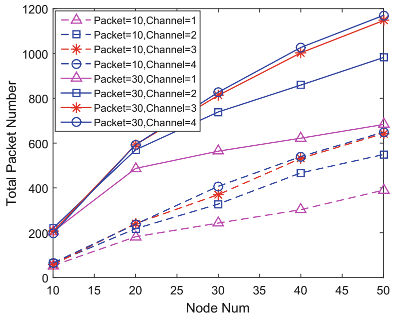

Fig. 2. Performance comparison of different reservation packets with multichannel

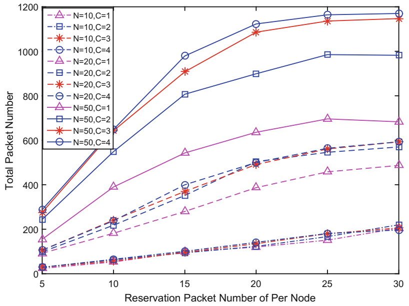

Fig. 3. Performance comparison of different node number with multichannel

From the simulation results shown in Fig. 2, the following conclusion can be drown.

- In general, the performance of the *packet=30* group is better than the *packet=10* one. This is because there are more data slots the *packet=30* group reserves.
- As shown in Fig. 2, the aggregate transmitted packets number increases as the number of nodes increases. This is because the number of concurrent transmission links increase in one data slot.

- In each group, the aggregate transmitted packets increase with different number of channels in the same group, which shows the collision scattering gain with the employing the multichannel. It also can be found that the collision scattering gain decreases as the number of employed multichannel increases. That is to say the gap between the curves *channel=1* and *channel=2* is larger than that between the curves *channel=2* and *channel=3*, and that is larger than the gap between the curves *channel=3* and *channel=4*. This discloses that to scattering the collisions between the concurrent transmission links, not so many channels should be employed.

Similar conclusion can also be drown from the simulation results shown in Fig. 3, where the number of packets is varied from 5 to 30. Figure 3 shows three groups results, i.e., *the nodes number* $N = 10, 20, 50$. In general, the aggregate transmitted packets number increases as the reservation packets number increases. The performance of the first group is almost no difference in the case of different channels, however, the gain of multiple channels is more and more obvious compared to the single channel with the increase in node number as showed in Fig. 3. When adding one channel and two channels, the performance is enhanced of about 30% and 35% as shown in the second group, respectively. Likewise, as the number of channels changes from 1 to 2 and 1 to 3, the resulting gain is 40% and 70% as shown in the third group, respectively. We can find out the gain by increasing channel number has great relevance with node numbers and the gain will become more and more obvious as the number of nodes increases. The reason for this result is that the collision of different node number can be scattered to be a low probability by a fixed channel number.

5 Conclusions and Future Work

In this paper, we propose a collision scattering based TDMA multichannel DMAC protocol for directional ad hoc networks. Our MAC exploit the multichannel reservation and multichannel data transmission to scatter the collisions between the concurrent transmission links. The preliminary simulation results show that our MAC can improve network performance in terms of aggregate packets number. The future work includes theoretical analysis of the collision scattering gain and the comparison with contention based multichannel DMACs.

Acknowledgments. This work was supported in part by the National Natural Science Foundations of CHINA (Grant No. 61771392, No. 61771390, No. 61501373, and No. 61271279), the Science and Technology on Communication Networks Laboratory Open Projects (Grant No. KX162600031, KX172600027), the National Science and Technology Major Project (Grant No. 2016ZX03001018-004), and the Fundamental Research Funds for the Central Universities (Grant No. 3102017ZY018).

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