A Classified Slot Re-allocation Algorithm for Synchronous Directional Ad Hoc Networks

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Abstract. Several typical synchronous directional media access control (DMAC) protocols are proposed for directional ad hoc networks (DAHN), e.g., directional transmission and reception algorithms (DTRA) [4]. One of the slot allocation problems of these DMACs is the unfairness between links, or link starvation, which is caused by the distributed feature of DAHN. That is the earlier discovered link reserve much more slots which results in the later discovered links have few slots to reserve. To address the unfairness problem, in this paper a classified slot re-allocation algorithm (CSRA) is proposed. The basic idea is to classify the data slots into four types according to their status in the data transmission phase, and then when the unfairness problem is found different types of slots are re-allocated. The re-allocation order of these four types of these slots are free slots, sending slots, neighbour transmitting slots, and receiving slot. Extensive simulation are carried out to evaluate the performance of the proposed CSRA. The simulation results show that the Jain's fairness index is improved with little loss of the network throughput.

Keywords: Directional ad hoc networks · Classified slot Re-allocation · Medium access control

1 Introduction

Directional ad hoc network (DAHN) is composed of wireless nodes equipped with directional antennas. Directional antennas have many advantages over the omnidirectional antennas, such as longer transmission distance, larger transmission/reception antenna gains, less interference from the neighbouring transmission links and large spatial reuse gains [1–3]. Several directional media access control (DMAC) protocols are designed to exploit the gains of the directional antennas [5,6]. These works show that the synchronous DMACs may outperform

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the contention based ones, and directional transmission and reception algorithms (DTRA) [4] is one of the classical synchronous protocols for the DAHN. However, one of the typical slot allocation problems of these synchronous DMACs is the unfairness between links, or link starvation.

Extensive synchronous DMACs are proposed in the literature. In [4,7], the author firstly proposes a wireless MAC protocol based on time division multiple access (TDMA) called DTRA. In the transmission and reception process, pure directional antennas are applied. In DTRA, a frame structure is divided into three phases, the neighbour discovery phase, the reservation phase and the data transmission phase. Each phase is divided into a plurality of slots, and each slot is divided into several mini-slots. In the neighbour discovery phase, the node finds its neighbours and selects a time slot for the reservation phase. In the reservation phase, the nodes confirm the neighbours, and choose slots for the data transmission phase. Reference [8] proposes a DMAC named SDVCS (Slotted Directional Virtual Carrier Sensing), which is different from DTRA in the slot allocation phase, i.e., the reservation phase. SDVCS dynamically allocate slots upon demand of each node, and tries to reduce the interference between the concurrent transmitting links when allocating slots for transmission. Reference [9] 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. Reservations are done in the reservation period and data is transmitted in transmission period.

Note that DAHN is a distributed network. Though synchronous DMACs are designed to avoid some shortcomings of omnidirectional protocols successfully, the slot reservation based resource allocations also has some problems. One of them is the unfairness of the slot allocation between links, which is caused by the distributed nature of DAHN. That is the earlier discovered link reserves much more slots which results in the later discovered links have few slots to reserve. Take DTRA as an example, we illustrate the reasons of the unfairness problem.

- Although each node discovers its neighbours in the scanning phase and makes reservations with its neighbours. The data transmission requirements of its neighbours are unaware.
- In one super frame of DTRA, there may exist one scanning phase and several reservation phases and several data transmission phases, and the duration of each super frame may be about one seconds or much more longer. Such that, it is impossible to exchange the data transmission requirements between neighbours in the scanning phase, since some traffic may be delay sensitive and the data traffic of the nodes dynamically varies.
- When the traffic demand of the links increases, or the density of the network is large, if the earlier discovered neighbours reserve enough data slots, the later scanned node pairs could not get enough slots to transmit data, causing these links in starvation and resulting in the unfair problem.

Several related works are proposed to solve the unfairness problem. Reference [10] propose a frame based DMAC. To achieve the collision free data transmission, a graph coloring algorithm is proposed to optimally exploit the spatial reuse gain. The proposed algorithm runs on a central controlled node. To achieve a satisfactory trade-off between the utilization and fairness, Ref. [11] proposes a graph coloring algorithm to allocate data slots under singlebeam situation. However, the node needs to collects traffic information in the neighborhood periodically.

Note that these works either require the whole data transmission requirements or require the interference relationships between the concurrent transmission links, which are difficult to be obtained in DAHN since it is distributed. To address the unfairness problem in the slot allocation period, in this paper a Classified Slot Re-allocation Algorithm (CSRA) is proposed for the synchronous DAHN. The main contributions of this paper are concluded as follows.

- A data slot classified method is proposed to classify the data slots according to their transmission status. And the data slots are classified into four categories, i.e., the free data slots, the sending slots, the neighbour transmitting slots and the receiving slots.
- A Classified Slot Re-allocation Algorithm (CSRA) is proposed to re-allocate the data slots when the unfairness problem occurs. And the re-allocation order is given as the free data slots, the sending slots, the neighbour transmitting slots and the receiving slots.
- Extensive simulations are carried out to evaluate the performance of the proposed CSRA. The simulation results show that the Jain's fairness index is improved with litter loss of the network throughput.

The rest of this paper is organized as follows. In Sect. 2, we illustrate the system model of CSRA. In Sect. 3, the data slot classified method and the CSRA algorithm is presented. Performance evaluations based on CSRA are presented in Sect. 4. The conclusion and future work are given in Sect. 5.

2 System Model

In the directional ad hoc networks, M nodes are randomly deployed. Each node is equipped a switch-able directional antennas and a time synchronous device, e.g., GPS. The time line is slotted and in each time slot only one directional antenna can be activated. The number of directional antenna is denoted as β and the angle range of each directional antenna is set as ω, where $\omega = 2\pi/\beta$.

The DMAC protocol structure is shown in Fig. 1. The time line is divided into super frames, and each super frame is composed of the scanning, reservation and data transmission phases. Each phase consists of several slots. Let $\alpha \times \beta$, γ and δ denotes the number of slots of the scanning, reservation and data transmission phases, where α denotes the scanning round of the scanning phase. In the scanning phase, all of the nodes do the neighbour discovery and the beam aligning process, and the discovered neighbours reserve the slot in the reservation phase. In the reservation phase, the neighbours communicate with their data transmission requirements and reserve data slots for the data transmission phase. Each slot in the reservation phase is divided into 3 minislots, and the REQ-REP-ACK (REQuest, REPly, ACKnowledgement) packets exchanging procedure is

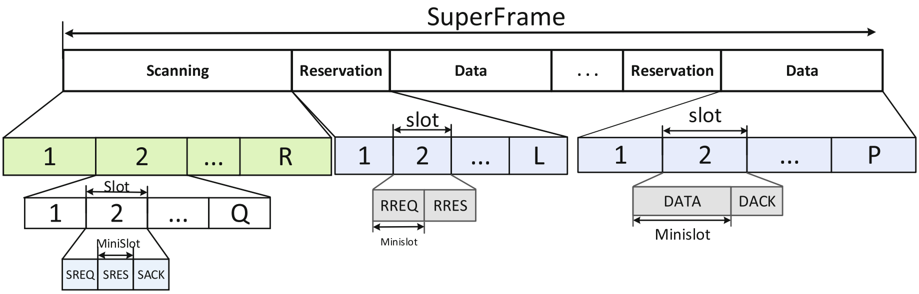

Fig. 1. DMAC protocol structure of CSRA.

carried out to make reservation of the data slots in the data transmission phase. In the data transmission phase, the neighbours transmit the traffic. Each slot in the data transmission phase is divided into 2 minislots, and the DATA-ACK packets exchanging procedure is carried out.

The proposed CSRA works in the reservation phase. To facilitate the illustration of the proposed CSRA, we define the data structures of the protocol as follows. After the scanning phase, each node discovers its neighbours and obtains the slot reservation status table in the reservation phase. Let $X = [x_i]_{1\times\gamma}$ denote the slot reservation status table in the reservation phase, where $x_i = (s, r)$ denotes the sender s will transmit the REQ packet in the first minislot of the ith slot of the reservation phase. Similarly, let $Y = [y_i]_{1\times\delta}$ denote the slot reservation status table in the data transmission phase, where $y_i = (s, r)$ denotes the sender s will transmit the REQ packet in the first minislot of the ith slot of the data transmission phase.

3 The Proposed Classified Slot Re-allocation Algorithm

In this section we illustrate the data slot classified method first, and then propose the classified slot re-allocation algorithm.

3.1 Data Slot Classified Method

We use Fig. 2 as an example to illustrate the basic idea of the proposed data slot classified method. In Fig. 2, suppose that in the reservation phase, node A has reserved the data slots with its neighbours B, C and D, and overhears that its neighbour link $\mathcal{L}_{E,F}$ will also transmit at some time slots. Specifically, we let $\delta = 5$ and let node A's slot reservation status table in the data transmission phase Y is given as

$$Y = [(A, B), (C, A), (D, A), (E, F), (-, -)].$$

Thus, according to the status of each slot in Y the data slots can be classified into four types. That is the free slot is $y_5 = (-, -)$, and the sending slot is

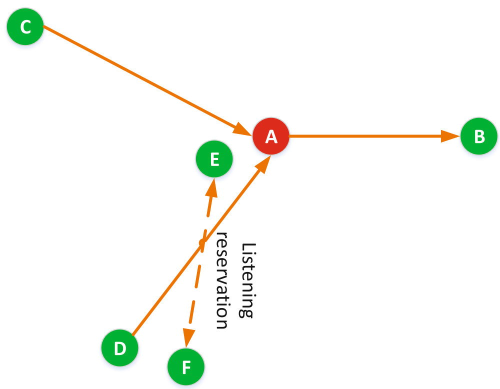

Fig. 2. Different types of data slots at node A.

$y_1 = (A, B)$, and the neighbour link transmitting slot is $y_4 = (E, F)$, and the receiving slots are $y_2 = (C, A)$ and $y_3 = (D, A)$.

To address the unfairness problem, some data slots may be needed to re-allocate to other nodes. Thus, we qualitatively analyse the properties of each type of the data slots in the follows.

- **Free slots:** There is no re-allocation problem for this type of data slots.
- **Sending slots:** If a sending slot is re-allocated to another node, two cases may occur. The first one is that this sending slot is also a sending slot, only with the receiving node of this data slot is changed. If this case happens there will exist no effect to the other nodes, or to the network. The second one is that this sending slot is changed to a receiving slot. If this case happens there will also exist no effect to the other nodes.
- **Neighbour link transmitting slots:** If a neighbour transmitting slot is re-allocated to another node, this may cause collisions between the concurrent transmission links.
- **Receiving slots:** If a receiving slot is re-allocated to another node, then the sending node of this slot may be not aware. And thus if the sending node will transmit data in this slot, and the new allocated node also transmit, these two data packets may collide at node A.

Therefore, if some data slots are needed to re-allocate to other nodes the priority order of the data slot types should be the free slots, the sending slots and the neighbour link transmitting slots. For different types of data slots, we have the following considerations.

- Firstly, when the data slots requirements of each link is very large, i.e., trending to infinity, no matter how to re-allocate the data slots, there may be no effect on the fairness.
- However, when the data slots requirements of each link is large, i.e., to be a large constant, if all of the data slots requirements are meet for the earlier

reserved links in the reservation phase only few of them can be satisfied, even though the data slots are re-allocated. Thus, a threshold for the satisfied data slots requirement is defined as F_r, $0 < F_r < 1$. The physical meaning of it is the average data slots requirement sanctification index. In other words, when the data slots requirements of a given link is obtained, only a fraction of F_r of them can be meet.

- We also note that for the sending slots and the neighbour link transmitting slots, there exists probability of collisions when they are re-allocated, and thus we can define the re-allocation proportion threshold. That is under which a given type data slot can be re-allocated, however if the re-allocated proportion is higher than the threshold that type of data slots should not be re-allocated. Let T_s and T_n denote the re-allocation proportion thresholds of the sending slots and the neighbour link transmitting slots.
- Furthermore, we would like to note that if a data slot is re-allocated it is better to re-allocate it again.

Finally, it can be found that the classification of the data slots do not consider the directions of the transmission links. It should have a higher gain if the direction of the transmission links is considered when classifying the data slots, which will be our future works.

3.2 The Proposed Classified Slot Re-allocation Algorithm

To facilitate the illustration of the proposed CSRA, the following variables are defined. Let $\mathcal{S}_f$, $\mathcal{S}_s$ and $\mathcal{S}_n$ denote the sets of the free slots, the sending slots and the neighbour link transmitting slots. Algorithm 1 presents the pseudo code of CSRA.

Algorithm 1 is called when the protocol runs into the reservation phase no matter for the first time or not. The inputs are the number of slots in the reservation phase γ, the number of slots in the data transmission phase δ, the slot reservation status table in the reservation phase after the completion of the scanning phase X, the average data slots requirement sanctification index F_r, the re-allocation threshold of the sending data slots T_s and the re-allocation threshold of the neighbouring link transmitting slots T_n. Note that only X will be obtained after the scanning phase, and the other parameters are the constant with a given protocol. The outputs is the slot reservation status table in the data transmission phase Y.

From line 1 to line 3, the temp variables are initialized, which includes setting the free slots set to be $\mathcal{S}_f = \{1, 2, \cdots, \delta\}$, setting the sending slots set and the neighbour link transmitting slots to be empty set, i.e., $\mathcal{S}_s = \emptyset$ and $\mathcal{S}_n = \emptyset$. And set the temp variable of the proportion of re-allocation sending slots $t_s = 0$, and the temp variable of the proportion of re-allocation neighbour link transmitting slots $t_n = 0$. Furthermore, the slot reservation status table in the data transmission phase Y is also initialized.

For each slot in the reservation phase, in line 5 after the data slots transmission requirements collection procedure is executed in the ith slot of the reservation phase, the decision is made that whether allocate/re-allocate data slots

Algorithm 1. Classified Slot Re-allocation Algorithm

Input: γ, δ, X, F_r, T_s, T_n.
Output: Y
1: $\mathcal{S}_f = \{1, 2, \cdots, \delta\}$, $\mathcal{S}_s = \emptyset$ and $\mathcal{S}_n = \emptyset$; $t_s = 0$, $t_n = 0$;
2: **for** $i = 0 : \delta$ **do**
3: $y_i = (-, -)$
4: **for** $i = 0 : \gamma$ **do**
5: executes data slots transmission requirements collection in the ith slot of the reservation phase, and let R_s, R_r denote the number of data slots requirements collected from neighbour m;
6: **if** $R_s + R_r > 0$ **then**
7: **if** $|\mathcal{S}_f| \geq F_r \times (R_s + R_r)$ **then**
8: allocate $\mathcal{S}_f$ to neighbour m as $F_r \times (R_s + R_r)$, and update $\mathcal{S}_f$ and $\mathcal{S}_s$;
9: break;
10: **else**
11: allocate $\mathcal{S}_f$ to neighbour m, and update $\mathcal{S}_f$ and $\mathcal{S}_s$; update R_s, R_r;
12: **if** $(T_s - t_s) \times |\mathcal{S}_s| \geq F_r \times (R_s + R_r)$ **then**
13: re-allocate $\mathcal{S}_s$ to neighbour m as $F_r \times (R_s + R_r)$, and update $\mathcal{S}_s$; update t_s;
14: break;
15: **else**
16: re-allocate $\mathcal{S}_s$ to neighbour m, and update $\mathcal{S}_s$; update $t_s = T_s$; update R_s, R_r;
17: **if** $(T_n - t_n) \times |\mathcal{S}_n| \geq F_r \times (R_s + R_r)$ **then**
18: re-allocate $\mathcal{S}_N$ to neighbour m as $F_r \times (R_s + R_r)$, and update $\mathcal{S}_s$ and $\mathcal{S}_n$; update t_n;
19: **else**
20: re-allocate $\mathcal{S}_n$ to neighbour m, and update $\mathcal{S}_s$ and $\mathcal{S}_n$; update $t_n = T_n$; update R_s, R_r;
21: **else**
22: listen and receive the neighbour link transmitting slots, and update $\mathcal{S}_n$;

or update the neighbour link transmitting slots set $\mathcal{S}_n$. Let R_s, R_r denote the number of data slots requirements collected from neighbour m. If $R_s + R_r > 0$ then allocate/re-allocate data slots to neighbour m from line 7, else record the neighbour link transmitting slots and update the neighbour link transmitting slots set $\mathcal{S}_n$ in line 22.

To allocate/re-allocate data slots to neighbour m, the free data slots set is checked firstly in line 7. If the number of free data slots is larger than $F_r \times (R_s + R_r)$, then allocate $\mathcal{S}_f$ to neighbour m, and update $\mathcal{S}_f$ and $\mathcal{S}_s$ accordingly. Otherwise allocate all of the left free data slots in $\mathcal{S}_f$ first, and update $\mathcal{S}_f$ and $\mathcal{S}_s$ accordingly. When there are not enough free data slots, the sending data slots will be re-allocated from line 12.

Similarly, if the number of left sending slots is larger than $F_r \times (R_s + R_r)$, then allocate $\mathcal{S}_s$ to neighbour m, and update $\mathcal{S}_s$ accordingly. Otherwise allocate all of the left sending slots in $\mathcal{S}_s$ first, and update $\mathcal{S}_s$ accordingly. When there are not enough left sending data slots, the neighbour link transmitting slots will be re-allocated from line 17. The operation of re-allocation of the neighbour link transmitting slots is similar with that of sending slots, and is omitted due to space limitation.

4 Performance Evaluation

In this section, we evaluate the performance of the proposed CSRA and DTRA in two parts. In the first part, we keep the number of nodes unchanged, and investigate the performance of the Jain's fairness index and the sum throughput. In the second part, we verify the performance of these two protocols in terms of the Jain's fairness index under the condition that the number of nodes is constant.

The Jain's fairness index defined as follows.

Definition 1 (Jain's fairness index). *The Jain's fairness index indicates the relative fairness of the data transmission between different node pairs [12], and it can be expressed by*

$$FI = \frac{(\sum_{i=1}^{X} r_i)^2}{X * \sum_{i=1}^{X} r_i^2},$$

where r_i denotes the rate of the ith link, and X denotes the number of links for a given node.

4.1 Simulation Parameter Settings

M nodes are randomly deployed in a 200 m × 200 m area. The simulation parameters are listed in Table 1.

Table 1. Simulation parameters

Parameters	Value in simulation
Number of nodes M	4–10
Number of beams β	4
Number of scanning rounds α	50
Reservation and data transmission's rounds	30
Slot number in reservation phase γ	10
Length of a data packet	2500 bytes
Length of per slot	500 µs

4.2 Evaluation on Throughput and the Jain's Fairness Index

Figures 3 and 4 show the total number of packets received and the Jain's fairness index of CSRA and DTRA varying with the number of the demanded traffic slots in the portion of total slots in data transmission phase, and the nodes number $M = 6$. For these two dotted lines, the sending slots' re-allocation threshold T_s are set as 0.3 and 0.6 separately, and the neighbour link transmitting slots' re-allocation threshold T_n is set as 0.9, and the average data slots requirement sanctification index is set as $F_r = 0.3$. From Fig. 3, it can be found that when the traffic demand is increased the proposed CSRA holds a much better performance in terms of Jain's fairness index. At the meantime, from Fig. 4 it can be found that there is a little reduction on throughput for CSRA with the given constant T_s. This implies that a varying T_s should be used with different traffic demand, which can be a future work.

Figures 5 and 6 show the performance of throughput and the Jain's fairness index varying with the node number while keeping the traffic demand as 0.3. For these two dotted lines, the master slots' re-allocation threshold T_s are set as 0.3 and 0.6 separately, and the neighbour link transmitting slots' re-allocation threshold T_n is set as 0.9, and the average data slots requirement sanctification index is set as $F_r = 0.3$. From Fig. 5, it can be found that when the node number M increases, the Jain's fairness index decreases for both these two protocols, but as a result of CSRA's re-allocation among multiple node pairs, the Jain's fairness

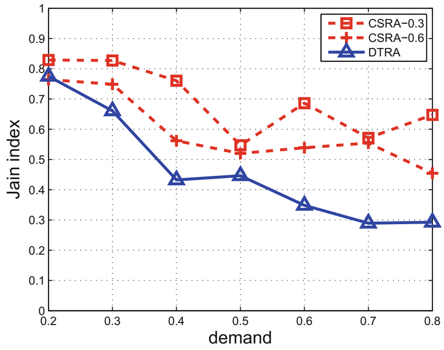

Fig. 3. Comparison of Jain's index varying with demand.

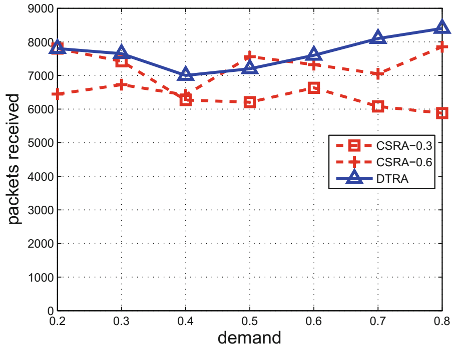

Fig. 4. Comparison of packets received varying with demand.

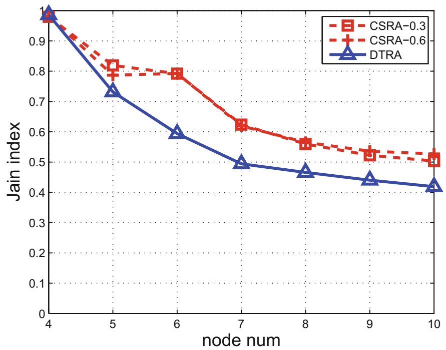

Fig. 5. Comparison of Jain's index varying with node number.

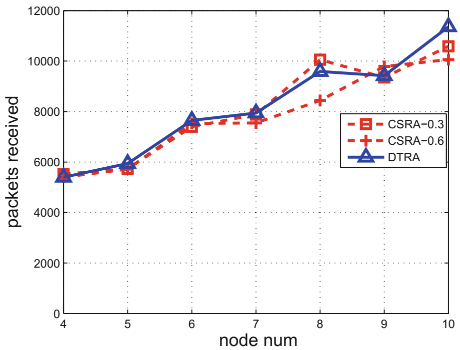

Fig. 6. Comparison of packets received varying with node number.

index of the proposed CSRA outperforms DTRA. From Fig. 6, it can be found that the throughput of these two protocol are close to each other.

5 Conclusion and Future Work

In order to solve the unfairness problem in DTRA, in this paper, we propose a Classified Slot Re-allocation Algorithm, shorted as CSRA. It classifies the data slots in data transmission phase according to the status of the slots into four types, and the re-allocation order is given as the free slots, the sending slots and the neighbour link transmitting slots. The simulation results show that CSRA can achieve an obvious advantage in term of fairness while keeping little performance loss in term of throughout. In the future, how to vary the re-allocation threshold of different types of slots will be studied.

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