Directional Antenna based Time Division Scheduling in Wireless Ad hoc Networks

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Abstract—Conventional omni-antenna ad hoc MAC protocols, such as the IEEE 802.11, use RTS/CTS mechanism to avoid collision but waste much space by reserving the wireless media over a large area. Using directional antenna is a good solution to increase spatial reuse, however, packet collision caused by hidden nodes and deafness problems are serious. Recently, many schemes based on directional antenna in ad hoc networks have been proposed, however, most of the schemes have not solved the hidden node and deafness problem completely.

In our paper, in order to solve these problem, a node self scheduling based MAC protocol is proposed. For guaranteeing the transmission of data, we let all the nodes overhear control messages at a fixed period periodically. Through utilizing these overhear periods, our proposed scheme can efficiently reduce hidden node problem and the deafness problems, which is a specific problem in directional antenna based network. Through simulation results, we have found that our scheme performs better than conventional protocol in the static Ad hoc network with respect to throughputs and end to end delays. That is, our proposed scheme provides a good method to solve hidden nodes, deafness problem and also reduce much interferences to guarantee the data transmission in wireless Ad hoc networks.

I. INTRODUCTION

Using directional antenna in Ad hoc network is an important issue these years, since directional transmission can provide many benefits, such as higher gain, lower interferences and enhanced capacity. Similar to the IEEE 802.11 DCF, directional antenna based scheme also uses network allocation vector (NAV) table to record channel reservation duration for all directions around the node. We call the NAV used in directional antenna based networks as DNAV. In the directional antenna based networks, nodes within the same transmission range can start two different transmission works at the same time which is impossible in omni-antenna based networks. This high spatial reuse is the reason why antenna based networks can give an incredible performance enhancement than omni-antenna based networks.

Although using directional antenna can support numerous benefits, there are still many new problems challenging us. When using the directional antenna, packets are transmitted only toward the direction of desired destination. That is, most neighbors around the transmitter are not able to aware any ongoing transmission of the transmitter. This can be a big trouble for future transmission process. Because of no awareness of neighbor’s behavior, if a node initiates a transmission to the neighbor which is receiving data at the same time, collision will happen, which makes its neighbor fail in receiving data. We call this problem a hidden node problem.

In the other aspect, if a node initiates RTS to its neighbor which is transmitting data to another direction at that time, its neighbor cannot be aware of the RTS. Upon no answer from the intended destination, this node will lengthen its backoff window and retransmit RTS multiple times until destination node becomes idle and respond the RTS by sending CTS. This problem is called deafness problem. How to effectively solve these two problems is an important issue in wireless ad hoc networks.

The rest of this paper is organized as follows. In section II, we introduce some related works. In section III, we describe the proposed protocol based on self-scheduling node and simulation results are presented in section IV. This paper concludes with a summary and the future work in the last section.

II. RELATED WORK

In the past, a variety of schemes [2] were proposed to solve hidden node/deafness problems in directional antenna based ad hoc networks. The authors of CRM [3] provided a conception of circular transmission control message. In their scheme, RTS is transmitted in a circular sweeping way which can prevent hidden node problems around the sender. MDA [4] is an enhanced CRM, where RTS and CTS are both transmitted in a circular way at the same time. In their schemes, hidden node problem can be solved in certain level, but multiple transmissions of RTS/CTS cause overhead and deafness problem is still left, which decreased the performance of the system significantly. Besides these researches, there are some other proposed schemes such as SDMAC [5], DMAC [6], which can solve the overhead problem, but deafness and hidden node problems were also still not solved. MMAC [7] is a scheme that uses multi-hop RTSs to establish links between distant nodes and then transmits CTS, DATA, and ACK over a
single hop. Their scheme utilized the directional antenna gain to attain the increased spatial reuse.

Also, there are some schemes based on two channels to solve the hidden and deafness problem [8]. In [8], authors tried to solve these problems, however, additional RFA-ACK’s transmission makes their protocol complicated. In busy-tone multiple access (BTMA) scheme [9], data receiver initiates busy tone that makes stations who heard it defer transmission, so collision is avoided. DBTMA [10] is a scheme where two busy tones such as transmit-busy tone and receive-busy tone are used to resolve data collision. Although above two channel schemes can solve hidden node and deafness problems, due to continuing busy tones, high spatial reuse cannot be realized. Also, there are some directional antenna based algorithms discussed in WLAN networks, such as [11].

III. PROPOSED SCHEME

Ad hoc network is a self-configuring network that nodes connect each other to form arbitrary topologies, and the networks topology may change rapidly and unpredictably. Thus, management of ad hoc networks by certain node is difficult and even impossible. Ad hoc networks should take into account the scheduling method. Motivated by this consideration, in this paper, we propose to apply self scheduling node mechanism to reduce packet collision in wireless ad hoc networks. We consider the method to exchange the control messages during the pre-defined period. During this pre-defined period called control messages exchanging period, resources are scheduled by self scheduling nodes so that channel for each data communication in next data transmission period can be reserved. Thus, during data communication period, data packet can be transmitted by reserved channel. The proposed self scheduling node algorithm allocates the channel for each data communication and hence data collision can be reduced. Our scheme is based on some assumptions and new definitions as follows. First of all, we assume that direction changing of antenna is quickly enough and transmission power for both control and data packets are same. Here are new definitions:

- Tiny message (TM): A message which is small enough just is used to indicate duration of the channel reservation. We set the size of it to be 120bit, the same as CTS.
- Data transmission permission period (DP): Period for DATA transmission. All data should be transmitted only in DP period.
- Time slot assigning period (TP): Period for exchanging control message. Each new data communication is based on the control message exchanging during the TP period.
- Basic period (BP): Total period of TP + DP is called as a BP. Length of BP is fixed and known to every node.
- Busy Node Sector Sequence: The node whose status is transmitting or receiving mode before TP period will change their sector by following sequence: sector 1 → sector 2 → sector 3 → sector 4. We call this sequence as Busy Node Sector Sequence.
- Idle Node Sector Sequence: The node whose status is idle mode before TP period will change their sector by following sequence: sector 3 → sector 4 → sector 1 → sector 2. We call this sequence as Busy Node Sector Sequence.

Sector antenna is a kind of directional antenna. We split the circle around every antenna into 4 sectors equally and a number is assigned to each sector. All the nodes in idle status overhear and change their antenna’s sector quickly to sense signal coming from each direction. Thus, if a node receives a message in some sector X, this node will assume that if it responds the message in sector X, the message sender can receive the response message also. Based on this assumption, following packet transmission can be done successfully by transmitting through sector X without knowing the exact location of neighbors. In the conventional scheme, all RTS and CTS are always transmitted sector by sector to reserve channel for each data communication. Different from the conventional schemes, every new transmission starts without transmitting RTS and CTS in circular sweeping way, but is sent directly to the destination in our proposed scheme. The reason of this is that each new data communication has reserves channel during TP period. TP is a fixed overhear period defined by negotiation among nodes in the same group. If a common start time of TP is identified, every node in this group will stop ongoing work but do the control message exchanging whenever TP begins. The nodes whose pre-status is transmitting or receiving mode will be in the role of self scheduling node during TP and change sector based on Busy Node Sector Sequence. And the nodes whose pre-status are idle mode will be in the role of being scheduled and change sector to receive control messages based on Idle Node Sector Sequence. Detail operation will be discussed in follow algorithms.

A. Group Initialization Algorithm

Ad hoc network is a distributed network with no central node. In order to design scheduling method in ad hoc network, we let the nodes staying close to each other form temporary group. During each TP period, the nodes whose pre-status is transmitting or receiving mode in the group execute the self scheduling job, and the node whose pre-status is idle mode will be scheduled by self scheduling nodes. Because TP, DP and BP are fixed length durations, the main problem when initializing a group becomes a synchronization problem. That is, algorithm how to make nodes in the same group have the common start time of TP, DP and BP is needed.

The process of Group Initialization Algorithm is shown in Fig. 1. Assume that there are several nodes in the turn off status, and after some time later, they will be turned on and want to communicate with other nodes. The turn on time of each node may be different and once waking up, nodes will overhear for a period of BP to look for if any nodes near it are transmitting. We let node A wake up earliest among them and start to overhear right after turning on. The waking up time of Node B and C is between the time A wakes up and the time A finishes its overhear periods. Overhearing for a duration of BP is long enough for every new waking up node, because if there are some other nodes transmitting around overhearing node, during a BP, a TP period must begin and TM messages sent by the transmitting node must be received by overhearing node.
Therefore, if no message arrives during an overhear period \( BP \), it means that no node is doing transmitting job around \( A \) and no longer overhear is necessary. So, after overhearing during a \( BP \) period, since no message arrives during a \( BP \), node \( A \) will assume that there is no node doing transmission around it and sends a beacon to search idle nodes around it. A temporary start time of next \( TP \) is given in the beacon, and when temporary start time of next \( TP \) begins, node \( A \) sends \( TM \) message sector by sector based on Busy Node Sector Sequence. The channel reservation duration will be indicated in header of \( TM \) message. For example, \( TM \) sent in sector 1 indicates in its header that the channel is reserved until \( T_1 \) arrives and \( TM \) message sent in sector 2 indicates that channel is reserved until \( T_2 \) arrives. Since idle nodes respond \( TM \) in a sector only when the sector’s channel reservation duration expires indicated in received \( TM \), the expired time of channel reservation duration also means \( TM \) response time.

When beacon is sent out by node \( A \), node \( A \)’s neighbor nodes \( B \) and \( C \) who just wake up and overhear will receive the beacon and get the temporary start time of next \( TP \). If temporary start time of next \( TP \) begins, node \( B \) and \( C \) will change their antenna sector based on Idle Node Sector Sequence waiting for \( TM \)’s arriving. The reason for applying different sector sequences to busy node and idle node is to make sure the direction of transmitter and receiver towards each other when control messages are exchanged. If \( TM \) is successfully received, node \( B \) and \( C \) check the channel reservation duration indicated in the header of \( TM \) first and then respond the \( TM \) message when the indicated duration expires. Since node \( B \) is located in sector 1 of node \( A \) and node \( C \) is located in sector 2 of node \( A \), node \( B \) and \( C \) respond at time \( T_1 \) and \( T_2 \), respectively. Certainly, node \( A \) also changes its antenna to sector 1 and 2 at time \( T_1 \) and \( T_2 \) to receive the responses. As a result, node \( A \) will successfully receive two different transmission requests from \( B \) and \( C \) without packet collision. And then, node \( A \) chooses one of the responses (from node \( B \)) to initiate communication. Because there is no response until maximum waiting time expires, the other node (Node \( C \)) will come back to idle mode and update its DNAV to prevent the usage of this sector until next \( TP \) begins.

Until now, a new group is set up, the channel for data communication in next \( DP \) is reserved and the temporary start time of \( TP \) becomes a real start time of the first \( TP \) for this new group. This real start time of the first \( TP \) means that all the nodes in this group has the common start time of the first \( TP \), and after every \( BP \) time length, a new \( TP \) will begins. During common \( TP \) period, all the nodes in the group will join the work of exchanging control messages and the channel for next data communication will be reserved during each \( TP \). The nodes whose status are transmitting or receiving node will do self scheduling by sending \( TM \) messages, and the node whose status is idle mode will obtain response time slot from self scheduling nodes.

The DNAV in our scheme is modified and an example is shown in Table I. In the DNAV, channel reservation duration of each sector is recorded, and the total transmission times of each sector are also recorded. These records help self scheduling nodes choose proper nodes to transmit in the next \( DP \) period.

The nodes with small communication times have the highest priority, which means the sector with the smallest communication times will be chosen to communicate first. So fairness problem can be solved. As we know, guaranteeing fairness in multi-hop network is a challenging and important issue. In our scheme, by applying self scheduling node method, fairness can be guaranteed even in multi-hop case.

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**TABLE I**

<table>
<thead>
<tr>
<th>Sector</th>
<th>Channel reservation duration</th>
<th>Communication frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IDLE</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>220us</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>IDLE</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>1038us</td>
<td>2</td>
</tr>
</tbody>
</table>

**B. Joining algorithm of New Member**

Ad hoc is a dynamic network that we cannot estimate when and where some new members will come in. The algorithm of making new members join in a new group should be introduced. We discuss two cases about how a new member can accurately match sync with a new group and then join a communication group. The topology is shown in Fig. 2 and node \( A \), \( B \) and \( C \) form a group where \( A \) is sending data to \( B \).

The first case is that a new member (node \( D \)) comes in a new group and resides near a idle node (node \( C \)). Node \( D \) may be a member of other groups before coming to this new group and after getting out of its old group, node \( D \) periodically transmits beacon to try to connect to the nodes around it. Sometime later, node \( D \) may come into this new group near node \( C \). Since node \( C \) is in idle status, \( D \) will not receive any message from \( C \),
which let D assume that no node around it is transmitting data now. Hence, node D sends beacon periodically as usual. Node C, which is in the overhear period, will receive the beacon sent by D. By utilizing the beacon sent by D, node C informs D of matching this group’s sync by returning another beacon to D. The detail procedure is as follows. At first, node C receives a beacon from D. Because only the nodes who do not belong to any group will send beacon, node C judges that a new member is trying to get connection through this receiving sector. So, node C will wait for the TM messages sent by D in the sector where beacon has arrived. Node D sends TM message when the temporary start time of TP included in the beacon starts. After receiving TM, node C gets the response time indicated in the header of TM message. When the response time expires, node C returns a beacon to node D to inform node D of the group’s existence and to request sync matching. When node D successfully receives the beacon from C, node D can quickly match sync of the group and join into this new group. Since next TP has not arrived and node C and D are both idle, node D can initiate transmission with C as a new member of this group.

C. Sector Contention Algorithm

Ad hoc is a network whose topology is changed dynamically. We should consider the case that more than one node exist in the same sector of the same node, which also means that, a node uses the same sector to communicate with more than one node. Thus, a sector is shared by several nodes and how to schedule the medium usage of the common sector without packet collision should be considered. In this part, we’d like to show how nodes in the same sector of a node contend and share the common sector of a node. As shown in Fig. 3, in sector 2 of node A, there are existing two nodes C and D. Assume that right after A and B finish data transmission, a new TP begins.

Node A normally transmits TM sector by sector based on Busy Node Sector Sequence. In the aspect of node D and C, since they are in the same sector 2 of node A, they will receive TM message at the same time through the same sector, and thus get the same response time (end time of channel reservation for each sector). When the response time for TM expires, node C and D respond TM of node A at the same time. As a result, there is collision in the sector 2 of node A. Collision happened in sector 2 indicates that there may exist more than two nodes in sector 2 which are not recorded in the DNAV. In our scheme, collision problem may always be solved first, which can make future transmission more reliable. So, after all the responses for TM have arrived, node A will send a TM in sector 2. Node C and D who received a TM again right after responding TM will choose a backoff time to start contention procedure. Backoff
time is chosen randomly smaller than window size. 
BackoffTime = Random(0,CW indow)*aSlotTime. CWindow equals basic contention window (BasicCW) for the first contention. If first contention procedure fails, node A will send TM again to tell node C and D double the window size and contend again. The procedure will be repeated continuously until node A receives both none interfered responses from C and D. Node A will record the different addresses of two nodes in DNAV used for future self scheduling and choose one of the responded node (node C) to communicate. The other responded node (node D) updates its DNAV table and comes back to idle status if no response arrives before Max Waiting Time expires. If next TP period arrives, node A assigns different response time slots for two nodes in the sector 2, which can avoid packet collision. Through this method, control messages can be exchanged without collision and data communication can be guaranteed in the DP period.

D. Operation Procedure

In this section, we show whole general operation of our proposed scheme. Every new data transmission is based on the time slot assigned by self scheduling nodes in TP period. In Fig. 4, five nodes A, B, C, D, E exist and B is transmitting data to A. During node B is transmitting data to node A, a TP begins. The communication from B to A will be stopped for a TP period. Node A, which is in transmitting status, becomes the self scheduling node and assigns different response times to node C, D and E such as t1, t2, and t3 separately indicated in TM message. When the data transmission from B to A is finished, the self scheduling node A will change its antenna to the proper sector to receive corresponding TM. That is, node A will change its antenna to sector 2, 2 and 3 at time t1, t2, and t3 respectively to wait for the responses. And the idle nodes C, D, E will respond TM at time t1, t2, and t3 in sector 4, 4, 1. Since all the responses are scheduled at different time slot, control messages collision is avoided. After successfully receiving all response messages from all the sectors, node A will check its DNAV table shown in Table II and choose the node with smallest communication times. Since communicating times of node C in sector 2 is the fewest, node A chooses node C as the next communication node. In a word, based on the self scheduling method, not only collision can be avoided, but also fairness problem can be solved.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Channel reservation duration</th>
<th>Communication frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ON</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>IDLE</td>
<td>Address 1 (Node C): 3</td>
</tr>
<tr>
<td>3</td>
<td>IDLE</td>
<td>Address 2 (Node D): 4</td>
</tr>
<tr>
<td>4</td>
<td>IDLE</td>
<td>5</td>
</tr>
</tbody>
</table>

IV. SIMULATION RESULTS AND DISCUSSION

A. Simulation Environments

We evaluate the performance of proposed MAC protocol compared with WLAN and MMAC scheme. The simulation parameters are listed below.

- Antenna Beam Width = 90 degree
- Data speed = 1 Mbps
- RTS size = 160 bit
- CTS size = 120 bit
- ACK size = 120 bit
- TM size = 120 bit
- BP length = 16000 us
- TP length = 2700 us

We only consider the case that channel is stable and nodes have no mobility. Network topology of two predefined routings is shown in Fig. 5. Transmission range of DO neighbors is larger than two hops but smaller than three hops, and the distance from source to destination is not larger than DD transmission range. In the case of MMAC, direct transmission from source to destination needs DO neighbors’ help.

We chose OPNET as a simulator tool to evaluate our proposed scheme. As we know, the end-to-end performance of network applications depends on complex interactions among applications, servers, and networks. OPNET’s Application Performance Management ensures that applications will perform effectively in real environments. Thus, we implemented the OPNET based simulator of proposed scheme by extending the wireless lan project in OPNET simulator.

The node module of OPNET is shown in Fig. 6. We added the directional antenna at the end of transmitter and receiver to realize the sector antenna’s performance. The left one is node module of source and destination, and the right one is the relay.
node module. Source node generates traffic, relay node just relays packet, and the destination node collects results.

The process module of OPNET is shown in Fig. 7. When the self interrupt of TP happens, all nodes in each process transit to TP-CENTER process and control messages exchanging will start. The nodes executing TRANSMIT process will be in the role of self scheduling node, and nodes executing IDLE and DEFER process will be in the role of being scheduled and response time will be assigned by self scheduling nodes. TM-SEND is the process for transmitting and receiving TM message and sector of antenna will be changed according to different sector sequences. Sector changing based on Busy Node Sector Sequence will be applied to nodes transited from TRANSMIT process to TP-CENTER process and Idle Node Sector Sequence will be applied to nodes transited from IDLE or DEFER process to TP-CENTER process. When TP is over and DP starts, all the nodes will come back to former process. Here, nodes transited from TRANSMIT process to TP-CENTER process will transit to DEFER process first waiting for a SIFS period and then transit to TRANSMIT process to transmit data.

B. Results and Discussion

1) End to end Throughput: We evaluated the end to end throughput and end to end delay of our proposed scheme. Fig. 8 is the simulation result of end to end throughput. We evaluate the case of multi-hop, so we only focus on the destination nodes' performance. Through this figure, we can find that when traffic is low, collision is few and the advantage of self scheduling node is not obviously, but as the load is increasing, much more collisions happen and the effect of our scheme is obvious.

In fact, in the case of single cell, the saturated throughput of WLAN is about 70 percent of the maximum data rate. The maximum data rate in our simulation environment is 1Mbps, thus saturated throughput is assumed to be 700kbps in single cell case. But multi-hop case like our topology is different from single cell under our assumption that transmission range is larger than two hops and smaller than three hops. Under this assumption, if one node is transmitting packets, at least two other nodes are prevented from data transmission at the same time. Also, in our simulation, two routing paths are crossed. Thus, utilization will be decreased to about 15 percent compared with single cell case. Thus, throughput of multi-hop case also will be decreased to about 15 percent compared with single cell. In the case of MMAC, since directional antenna is used, although two nodes are within 2 hops (the same transmission range each other), these two nodes can transmit packet at the same time when transmitting direction is different. Therefore, since two directions are possible at the same time, the throughput of MMAC may increase by about two times compared with WLAN in multi-hop case. In case of our proposed scheme, since we applied a scheduling method which makes spatial reuse more effectively and also reduces the collision, the throughput could be increased much more compared with MMAC.

2) End to End Delay: The other objective we focus on is the end to end delay. We define end to end delay as the time interval between packet generation time in the source and the packet arrival time in the destination. The simulation result is shown in Fig. 9. Through this figure, we can find that delay increases abruptly. The time point when delay goes to infinite is different for those three schemes and the WLAN is earliest,
and proposed scheme is latest. WLAN is a scheme based on omni-antenna in which spatial reuse is very low. Thus, the number of packets that can be transmitted at the same time is so limited compared with MMAC and proposed scheme based on directional antenna. The delay of WLAN increases abruptly when the throughput is saturated at 100 kbps traffic load. In the case of MMAC, although directional antenna is used, since MMAC does not consider about hidden node and deafness node problem, packet collision caused by these problems can increase packets’ delay. But in our proposed scheme, since we use a self scheduling node which can reduce packets collision, we can guarantee the smallest delay compared with WLAN and MMAC.

In our scheme, we only considered the condition that all the nodes have no mobility. In real wireless ad hoc environment, nodes are dynamic. Especially, in the military field, mobility must be supported. How to support nodes with mobility is the next research topic we will focus on. Also, in this research, we have shown only performance result for specific network topology which is not general. We will try to obtain a general performance result by applying different network topologies.

V. CONCLUSIONS

Packet collision issues in directional antenna based ad networks are very important. A good collision reduction method can improve the performance of system much by using directional antenna. In our paper, we proposed self scheduling node method to reduce packet collision in directional antenna based wireless ad hoc networks. We divide time into two parts such as time slot assigning period (TP), and the data transmission period (DP). All new data communications are based on self scheduling node in which collision can be reduced much more. Through OPNET simulation, we proved the enhancement in the view of the end to end throughput and delay compared with WLAN and MMAC.

REFERENCES