A Distributed Dynamic Channel Access Scheduling Method for Wireless Ad Hoc Network

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Abstract

Channel assignment and scheduling are very important and challenging topics in wireless Ad Hoc networks. In this paper, a distributed dynamic channel access scheduling method based on Time Division Multiplex Access (TDMA) is presented to resolve hidden terminal and exposed terminal problems. An exclusive control slot is used to allocate to each node after it gets access to the network in a common access slot. Traffic slots are dynamically scheduled for transmission of data packets. The hidden nodes are enabled to transmit packets and prohibited to receive packets, and exposed nodes are allowed to receive packets and avoided to transmit packets. Thus it is highly efficient of slot spatial reuse. Simulation results show that the proposed protocol is capable of providing collision-free transmission, and suitable for multimedia applications.

Keywords: Ad Hoc network, Channel Access, Dynamic Schedule, TDMA

1. Introduction

A Wireless Ad Hoc network consists of a set of mobile hosts without any infrastructure. There is no central node in the networks. All nodes are equal in status and forwarding packet to each other in multi-hop manner. In the multi-hop networks, each node shares the wireless channel with other nodes. However, the packets sent by a node are only received by its neighbor nodes, and the nodes which are not its neighbor nodes are unaware of it. This leads to hidden terminals and exposed terminals problems. How to design an efficient Medium Access Control (MAC) protocol is a challenging problem.

Due to the lack of a centralized control entity in ad hoc networks, the sharing of wireless channel among the ad hoc nodes must be organized in a decentralized manner. Some MAC protocols for wireless Ad Hoc networks have been proposed. According to the communication model, the channel access protocols can be divided into Asynchronous MAC protocols, Synchronous MAC protocols, and Hybrid MAC protocols.

Asynchronous MAC protocols usually adopt contention based scheme to access to the channel. All nodes contend for the common wireless channel when they have packets to be transmitted. Packet collision will inevitably arise as a result of random competition. Hence the collision avoidance is a key design issue. The typical asynchronous MAC protocols are: Carrier Sense Multiple Access (CSMA) protocol [1], Multiple Access Collision Avoidance (MACA) [2], IEEE 802.11 Protocol [3], Busy Tone Multiple Access (BTMA) [4], etc. These protocols are simple and perform well under the low payload condition. However, when the payload is increasing, the number of packet collisions is increasing accordingly. Therefore, the delay of the packets transmission will be a linear increased with the network payload.

Synchronous MAC protocols adopt channel reservation mechanism. Channel in synchronous protocols is composed of several time intervals (time slot) with equal duration. Packet delay and broadband distribution can be controlled by slot management, which is generated static or dynamical [5]. Each node communicate with each other in the time slot, hence the packet transmission is collision-free. Typical synchronous protocols are Time Division Multiple Access (TDMA) [6], Evolutionary TDMA (E-TDMA) [7], Five Phase Reservation Protocol (FPRP) [8], Hop-Reservation Multiple Access (HRMA) [9] and so on. In synchronous protocol, both packet delay and channel allocation can be controlled by slot management. So it achieves a fairly well operation performance under heavy load condition, but has a poor performance while the load is light.
Hybrid MAC protocols are the combination of both asynchronous MAC protocols and synchronous MAC protocols. The common hybrid protocols are Hybrid TDMA (HTDMA) [10], ADAPT protocol [11], ABROAD protocol [12] and so on. These protocols are nearly like competition protocol when the payload is light. On the other hand it is similar to reservation protocol under the heavy traffic.

The overview of the research work conducted in the field of MAC protocols for wireless Ad Hoc networks show that, synchronous protocols are the best choices for application such as audio and video transmission [13,14]. Meanwhile, the multi-channel TDMA scheme has the advantages of conflict-free, good in fairness, and high throughput. In this paper, a synchronous MAC protocol is designed for ad hoc networks. The proposed protocol combines the strategies of multi-channel TDMA and synchronous protocol.

The rest of this paper is organized as follows. Channel share manner of Ad Hoc Network is firstly given in Section 2. The MAC frame structure is presented in Section 3. Section 4 is proposed the channel access scheme. Then in Section 5, the control slot allocation method is provided. In Section 6, traffic slot assignment scheme is narrated. In Section 7, some simulation results are shown to evaluate the performance of our proposed protocol. Finally, the conclusion is given in Section 8.

2. Multi-hop Channel Share Manner

In multi-hop wireless Ad Hoc networks, a radio channel is spatially reused in different parts of the network. Channel access scheme plays an important role in coordinating channel access among the nodes. Because of the limited transmission distance of node in Ad Hoc networks, the message sent by node can only be received by the neighbor nodes, and the nodes that are not its neighbor nodes are unaware of it, which led to the "hidden terminal" and "exposed terminal" problems.

![Figure 1. Hidden terminal and Exposed terminal](image)

Hidden terminals refer to nodes that are within destination node’s coverage range while out of the source node’s coverage range. Since the hidden terminal can’t aware of the transmitting, it may send message to the same destination node, resulting in the message confliction at the destination node. The hidden terminal problem will increase the number of collisions, thus reducing channel utilization. As shown in Fig. 1 (a), any nodes C locate in the dashed area will be the hidden terminals for source node A. The existing of C may lead to a collision at destination node B when source node A send message to B.

Exposed terminal refers to the terminal which is at the sender's transmission range but not at the receiving node’s transmission range. As shown in Fig. 1 (b), node C is in the range of source node B, but not in the range of destination node A. When B is sending to A, C will delays its transmission, even if its destination is D which will not interfere with B’s transmission. In that case, C is an exposed terminal for B. Since the exposed terminal can aware of the sender's transmission, it delays its transmission, but it is not at the receiver's wireless coverage range, actually its transmission will not lead to conflict. The exposed terminal deals with the unnecessary delays to the node, leading to reducing the network capacity.

To avoid hidden terminal problem and exposed terminal problem, the protocol proposed in this paper is designed with multi-channel TDMA scheme.
3. MAC Frame Structure

3.1. Some Assumptions

Dynamic channel scheduling method based on TDMA schemes is an approach that adjusts the time slot assignments according to the traffic requirements of individual nodes. Before discussing the channel access protocol based on TDMA, we make some assumptions on the model of multi-hop wireless network.

1. All the nodes are synchronized in a global time slot reference;
2. Each node is assigned a unique MAC identifier (ID);
3. A node can only transmit or receive one packet during a time interval, but cannot do both at the same time;
4. Each node has no capture effect, so when receiving multiple transmission signals, it may lead to a collision;
5. Links are bidirectional.

3.2. MAC Frame Structure

In TDMA-based protocols, time is broken into frames, and a frame is further broken into slots. Each node acquires a time slot for communication through slot scheduling mechanism. Slots in a MAC frame divide into three categories: Control Slot, Traffic Slot and Access Slot. The frame structure is shown in the following Fig. 2.

![Figure 2. The Frame Structure](image)

Access Slot is a public channel. Every node gets access to the network randomly by a competitive manner in access slot. Control Slots are used to send control packets, which are exclusively allocated without spatial reuse when a node is joining in the network. The number of control slots is decided by the number of nodes in the network. Traffic Slots are used for data transmission. Each node applies for an idle traffic slot in its spatial control slot. Traffic is designed capable for spatial reuse, and dynamic schedule by control slots.

Since Control Slot of every node is absolutely non-conflicting, the hidden terminal and the exposed terminal problem in the ad-hoc network can be easily resolved by the control packets sending in control slots.

4. Channel Access Method

All nodes are joining to the network by sending apply information during the access slot. Since the Access Slot is a public slot for each node, competition and confliction problem may arise in this slot. Channel access scheme is described as follows:

Nodes in network are sending frame synchronization information (FRAME_SYNC) periodically, which are received by the access nodes. Node to be access to the network firstly checks whether the synchronization information (FRAME_SYNC) is sent by a legal node. If the synchronization information received is a legal one, the node to be access to the network will adjust its local time slot reference to the time at which the synchronization information is received, and sends an access request (ACCESS_REQ) to the network nodes after then. If the synchronization information received is illegal, it will drop the packet and wait for another one.
When the node in the network received an access request (ACCESS_REQ), it firstly identifies the legitimacy of the sending node. If the node to be access to the network is a legal one, the node in the network will sent an acknowledgment message (SEND_ACCESS_PERMIT) to the joining node for notifying that the access is successful. If the node to be access to the network is illegal, the node in the network will reject it.

The access request uses S-Aloha as its mechanism of competition to occupy the channel access. If to be access node receives a permit message (SEND_ACCESS_PERMIT) before the time out (ACCESS_ACK_WAIT_TIMEOUT), access is successful. Or else, it supposes that there is a collision with the access request (SEND_ACCESS_REQ), so it starts a random back-off counter and sends request (SEND_ACCESS_REQ) again after a period of time.

The process of channel access is shown in Fig. 3.

5. Control Schedule Scheme

5.1. Control Slot Allocation

After a node successful joining in the network, a unique Control Slot is acquired. Each node only uses its exclusively Control Slot to sent control packet without spatial reused, thus avoiding the control packet conflict with that of other nodes. The traffic slots are dynamic allocated by exchange of control packet sending in control slots.

5.2. Control Rules

The interaction control signals in control channel are: Request To Sent (RTS), Clear To Sent (CTS), Not Clear To Sent (NCTS), and acknowledgement (ACK). The state machine of a node in a business slot is shown in Fig. 4.

Before a packet transmission, a node should exchange handshake information by RTS and CTS. After a data transmission is finished, the receive node sends an ACK signal to the sending node to indicate that the packet is received properly. If an exposed terminal receives a RTS signal request to send packet, the exposed node will send a NCTS to inform the sending node that it is an exposed node, which is not allow to receive data. However, a hidden terminal will send a CTS signal in control slots.
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to allow the sending node for sending data. As the control slot is exclusively used by a node, it will not conflict with other packets, the hidden terminal can achieve data receiving.

Figure 4. State transition diagram of the MAC protocol

There are 7 states in Fig. 4, that is: IDLE, READY, SENDER, RECEIVER, HIDDEN, EXPOSED, and DEFER.

1. IDLE: the channel is idle, receive of sent traffic data are permitted.
2. READY: a node is ready for sending traffic data.
3. SENDER: a node is the sender of traffic data.
4. RECEIVER: a node is the receiver of traffic data.
5. HIDDEN: a node is a hidden terminal, which is not allowed to send data.
6. EXPOSED: a node is an exposed terminal, which is not allowed to receive data.
7. DEFER: a node is both in the coverage area of sending node and receiving node, which is allowed to neither send data nor receive data.

As the control packets sending in control slot is un-conflictive, hidden terminals are able to receive packet whereas transmit packets are avoided. Similarly, exposed terminals are enabled to transmit packets while receive packets are avoided. Thus high efficiency of slot spatial reused may be achieved.

6. Traffic Slot Allocation

Mechanism for traffic slots allocation is distributed coordinated by each node as there is no central node in the network. In order to increase network throughput, the proportion of the control slot and the traffic slot in a frame must be organized rationally. The use of the channel can be divided into three stages: Slot Reservation, Slot Occupation and Slot Release.

The main idea of traffic slot allocation scheme is: a node firstly calculates the number of its requiring slots according to its own data transmission requirements. And then, it applies for slots to transmit packets. If the application is successful, it will occupy the traffic slots in a frame for communication. After packet transmission is finished, it will release the traffic slots, which can be reapplied by other nodes in the following time.

6.1. Slot Applications

After successfully get access to the network, each node occupies a Control Slot independently, and the rest of channel can be dynamically used as Traffic Channel. The operation of Slot Reservation is realized through spatial Control Slot.

An idle traffic slot is choose before the source node sending slot reservation application, if the chose traffic slot is available in destination node, a reservation success message will be received. Otherwise,
if the chose Traffic Slot is occupied in destination node, a reservation fail message will be received. The source node chose another idle Traffic Slot to reserve.

In order to realize dynamical allocation in Traffic Slot, each node needs to maintain two lists which reflect the service condition of traffic channel: Sending Channel Usage List (SCUL) and Receiving Channel Usage List (RCUL).

![Figure 5. The Spatial reuse of Traffic Slot](image)

When sending station is going to transmit traffic packets, it chooses the channel used last time firstly, if the channel is busy, it chooses a free channel from list SUCL, and then makes an appointment. Once the receiving station receives this appointment request, it check that whether the sending channel which is chose by the sending station is free in its list RCUL, if so, it sends successful message to the sending station, else, sends failure message and the sending station would choose the traffic channel again. Spatial reuse of Traffic Slot of nodes in the network is shown in Fig.5.

### 6.2. Slot Occupations

In order to increase channel utilization, special reuse of traffic slot in a TDMA based Ad Hoc network is adopted. Classical method to achieve time slot spatial reuse is that, packet transmission and receive in all the nodes within the two hop range of transmitting node are prohibited. And the same time slot is allowed to be reused by a node outside the two-hop range of the transmitting node. As shown in Fig. 6.

![Figure 6. Compare of Slot Spatial Reuse](image)
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As discussed how packet arises in wireless Ad Hoc network, it is obviously that packet transmitted by the hidden stations may generate the second type of collision. However, when the hidden node only receives data, the packet collision does not arise. Therefore, when a node is sending packet, there is no need to forbid the transmitting and receiving behavior completely within two-hop nodes. As long as allocation scheme prohibit the neighbor nodes within one-hop range of the transmitting node to receive data, and prohibit the neighbor nodes within one-hop range of receiving node to transmitting data, packet can be successful transfer without collision. An example is shown in the Fig. 5.

Supposed that node A is transmitting packets to node B, obviously, node E is an exposed node of node A. In the proposed slot allocation scheme, node E is allowed to transmit traffic packets to node H at the same traffic slot by exchanging the control signal. Similarly, node C is a hidden station of node A. Because of having the special control channels, node C can achieve receiving the data packets from node F at the same slot.

Compared with the classical slot allocation method, the proposed slot assignment scheme allows the exposed terminal to transmit packet, and also allows the hidden terminal to receive packet. Thus spatial reuse rate is improved. It can be achieved by the introduction of private control channels.

### 6.3. Slot Releases

When there is not any packet to be sent in a node, or the slot occupied by a node is more than it needed for a period of time in the future, the Traffic Slot should be released in order that it can be reuse by other nodes.

If a node wants to release a Traffic Slot, it only needs to broadcast a frame which indicates the releasing action. The broadcast frame including the number and position of the slots it wants to release.

### 7. Simulation Experiment

#### 7.1. Simulation Model

There are 36 nodes scatter in the area according to grid position, as shown in Fig. 7. There are 25 control slots and 55 traffic slots are included in a frame structure.

![Figure 7. Topology of Simulation Network](image)

It is supposed that there has only one transmission buffer in each node to cache data packets. The packet generated in each node is independent, and also with the identically probability distribution. Assumed that the number of new packets arrive at each node is subjected to Poisson distribution. The data arrive rate is \( \lambda \) packets per slot period. The probability function for the number of arrival packets in a slot period is:

\[
P(X = k) = \frac{\lambda^k e^{-\lambda}}{k!}
\]  

(1)
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Assumed that the length of one packet is subjected to negative exponential distribution, and the average length equals to $\mu$ slot length. The probability function for the length of one data packet is:

$$p(Y = l) = \begin{cases} \mu e^{-\mu l} & l \geq 0 \\ 0 & l < 0 \end{cases}$$

(2)

We also assume that there has neither bit error nor capture effect in the transmission channel. If there have many packets transmitted to one and the same destination node at the same time, collision may occur and the destination node would receive no packets.

7.2. Throughput Simulation

Assume that the average length of every packet lasts only one time slot, and the number of packets generated in a node during a slot is subjected to the Poisson distribution. The average numbers of transmission nodes in a business slot, compared with the average packet arrived rate in different coverage radius is shown in Fig.8.

Assume that the average length of every packet is subject to the negative exponential distribution, and only one packet generated in a node during a slot time. The average numbers of transmission nodes in a business slot, compared with the average packet length in different coverage radius is shown in Fig.9.

Figure 8. Throughput Simulation with Different Packet Arriving Rate

Figure 9. Throughput Simulation with Different Packet Length
7.3. Transmission Delay Simulation

Assume that the average length of every packet lasts only one time slot, and the number of packets arrived in a node subject to the Poisson distribution. Fig. 10 shows the average time interval of two transmission packets as a function of the average packet arriving rate with different coverage radius.

![Figure 10. Delay Simulation with Different Packet Arriving Rate](image)

Assume that the average length of every packet is subject to negative exponential distribution, and only one packet generated in a node during a slot time. The average time interval of two transmission packets as a function of the average packet length with different coverage radius is shown in Fig. 11.

![Figure 11. Delay Simulation with Different Packet Length](image)

8. Conclusions

A distributed dynamic channel access scheduling method based on TDMA for wireless Ad Hoc Networks is proposed in this paper. Nodes access to the network in the access slot, and an exclusive control is allocated subsequently. Data packets are transmitted by dynamic schedule in the traffic slots. As it using multi-channel TDMA scheme, conflict free packet transmission is realized. The proposed method allows the exposed terminal to transmit packet, and also allows the hidden terminal to receive
packet. Hence spatial reuse rate is improved. Simulation results show that the protocol achieves high throughput and less transmission delay.

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10. References


