MAC protocols, contention-based with reservation and scheduling

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1. Introduction

Ad hoc wireless networks are comprised of mobile nodes that exchange packets by sharing a common broadcast radio channel. Due to the limitations of this channel, the bandwidth to be shared among the nodes is limited. Therefore, the aim in these networks is to be able to utilize the bandwidth efficiently, and guarantee fairness to all nodes. As we know, wireless networks differ enormously from wired networks; furthermore, ad hoc wireless networks have even more specific characteristics, such as node mobility, power constraints. Thus, new protocols are needed for controlling access to the physical medium. The unique properties of the ad hoc networks make the design of a media access control (MAC) protocol more challenging.

This paper sets on giving a brief outline of the MAC protocols for ad hoc networks, focusing on contention-based algorithms with reservation and scheduling.

2. Design issues

Following are the main issues one should have in mind when considering designing a MAC protocol for ad hoc wireless networks.

Bandwidth efficiency: The scarcity of bandwidth resources in these networks calls for its efficient usage. To quantify this, we could say that bandwidth efficiency is the ratio of the bandwidth utilized for data transmission to the total available bandwidth. In these terms, the target will be to maximize this value.

Quality of service support: Providing QoS in these networks is very difficult, due to the high mobility of the nodes comprising them. Once a node moves out of another node's reach, the reservation in it is lost. On the other hand, in these networks QoS is sometimes extremely important, for example in military environments. Therefore, QoS should be provided somehow, despite the characteristics of ad hoc networks.

Synchronization: Some mechanism has to be found in order to provide synchronization among the nodes. Synchronization is important for regulating the bandwidth reservation.

Hidden and exposed terminal problems: The reason for these two problems is the broadcast nature of the radio channel, namely, all the nodes within a node's transmission range receive its transmission.

Hidden terminal problem – two nodes that are outside each-other's range perform simultaneous transmission to a node that is within the range of each of them, hence, there is a packet collision.
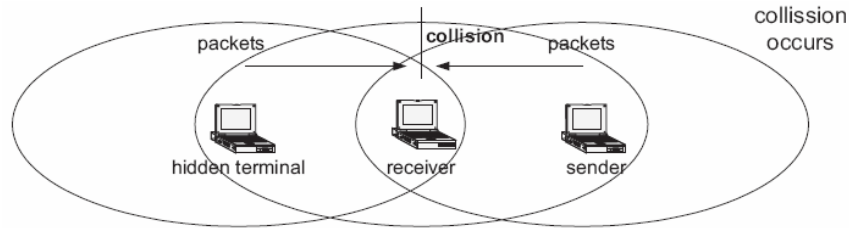
Figure 1: Example of the hidden terminal problem

Exposed terminal problem – the node is within the range of a node that is transmitting, and it cannot transmit to any node.
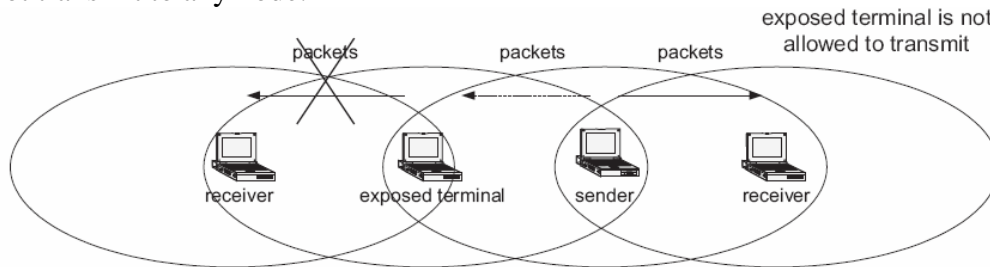

Figure 2: Example of the exposed terminal problem

Hidden nodes mean increased probability of collision at a receiver, whereas exposed nodes may be denied channel access unnecessarily, which means underutilization of the bandwidth resources.

Error-prone shared broadcast channel: In radio transmission, a node can listen to all traffic within its range. Therefore, when there is communication going on no other node should transmit, otherwise there would be interferences. Access to the physical medium should be granted only if there is no session going on. Nodes will often compete for the channel at the same time; therefore, there is high probability of collisions. The aim of a MAC protocol will be to minimize them, while maintaining fairness.

No central coordination: in ad hoc networks, there is no central point of coordination due to the mobility of the nodes. Therefore, the control of the access to the channel must be distributed among them. In order for this to be coordinated, the nodes must exchange information. It is the responsibility of the MAC protocol to make sure this overhead is not a burden for the scarce bandwidth.

Mobility of nodes: The mobility of the nodes is one of its key features. The QoS reservations or the exchanged information might become useless, due to node mobility. The MAC protocol must be such that mobility has as little influence as possible on the performance of the whole network.

Signal propagation delay: Signal propagation delay is the amount of time needed for the transmission to reach the receiver. If the value of this parameter is considerable, a node may start transmitting, when in fact, transmission from other nodes is taking place, but it has not reached the node yet. The ad hoc networks that utilize synchronization, therefore, will have to expand the time slot to accommodate the propagation delay.

Hardware constraints: Most radio-receivers are designed in such a way that only half-duplex communication can take place. When a node is transmitting, the power level of the outgoing signal is higher than any received signal; therefore, the node receives its own

transmission. Here, we can also add hardware switching time – time needed to shift from one mode to the other.

3. Design principles for a MAC protocol in ad hoc networks

The operation of the protocol should be distributed through all the nodes.

The protocol should provide QoS support for real-time traffic.

The average delay for packet transmission should be as small as possible.

The bandwidth should be utilized efficiently.

Each node must have a fair share of the available bandwidth.

Control overhead should be minimized.

The hidden and exposed terminal problems should be minimized.

The protocol must be scalable to large networks.

Power control mechanisms are needed for efficient management of the energy consumption of the nodes.

Adaptive data rate control should be provided – a node controls the rate of outgoing traffic in relation also to the network load and to the status of the other nodes.

Directional antennas are encouraged, the advantages are reduced interference, increased spectrum reuse, and reduced power consumption.

Time synchronization between the nodes should be provided.

4. Classification of MAC protocols for ad hoc networks

Several criteria can be used for the classification of MAC protocols, such as time synchronization, initiation approach, and reservation approach. Ad hoc network protocols can be classified into three basic types [1]:

- Contention-based protocols;
- Contention-based protocols with reservation mechanisms;
- Contention-based protocols with scheduling mechanisms;

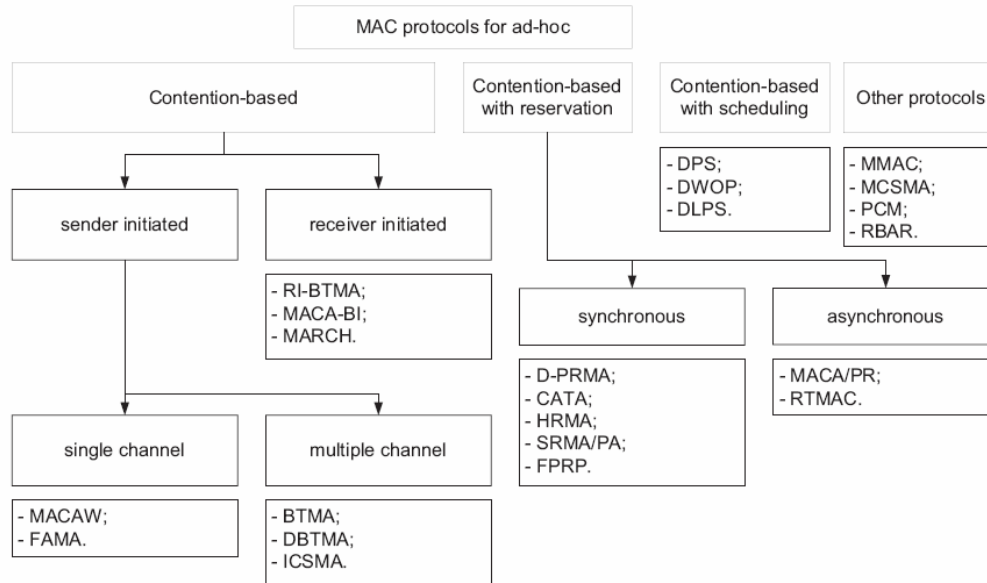There are also some MAC protocols outside the above categories.

MAC protocols for ad-hoc

Contention-based

Contention-based with reservation

Contention-based with scheduling
- DPS;
- DWOP;
- DLPS.

Other protocols
- MMAC;
- MCSMA;
- PCM;
- RBAR.

sender initiated

receiver initiated
- RI-BTMA;
- MACA-BI;
- MARCH.

synchronous
- D-PRMA;
- CATA;
- HRMA;
- SRMA/PA;
- FPRP.

asynchronous
- MACA/PR;
- RTMAC.

single channel
- MACAW;
- FAMA.

multiple channel
- BTMA;
- DBTMA;
- ICSMA.

Figure 3: Classification of the MAC protocols for ad hoc networks

General definition of contention-based protocols

Here, the channel access policy is based on competition. Whenever a node needs to send a packet, it tries to get access to the channel. These protocols cannot provide QoS, since access to the network cannot be guaranteed beforehand.

General definition of contention-based protocols with reservation mechanisms

These protocols provide bandwidth reservation ahead; therefore, they can provide QoS support. These can be further subdivided into:

- Synchronous protocols: there is time synchronization among all nodes in the network, the nodes in the neighborhood are informed of the reservations;
- Asynchronous protocols: no global synchronization is needed. Relative time is used for the reservations.

General definition of contention-based protocols with scheduling mechanisms

There can be packet scheduling at the nodes, or node scheduling for access to the channel. Node scheduling should not treat the nodes unfairly. Some of these protocols consider battery power in their node scheduling.

5. Contention-based protocols with reservation mechanisms

Even though these protocols are contention-based, the contention takes place only during the bandwidth reservation phase.

5.1. Distributed Packet Reservation Multiple Access (D-PRMA) Protocol

According to [1], D-PRMA is based on TDMA. The time division of the channel is done into frames, then further into slots, then further into minislots. Each minislot contains two control fields, RTS/BI – Request To Send / Busy Indication and CTS/BI – Request To Send / Busy Indication.
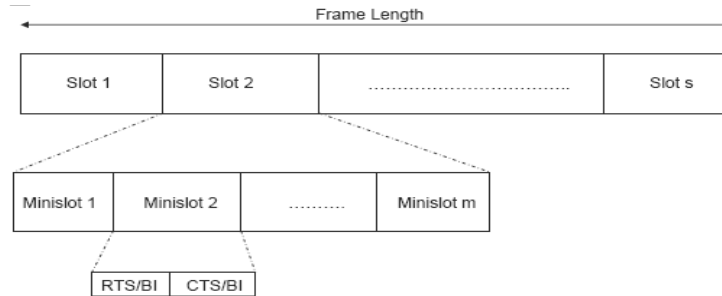
Figure 4: Time Division in the D-PRMA protocol

The mechanism of competition for slots is such that a certain period at the beginning of every slot is reserved for carrier-sensing. The nodes compete for the first minislot in each slot. The winning one transmits a RTS packet through the RTS/BI part of the first minislot. The receiver responds by sending a CTS packet through the CTS/BI field. Thus, the node is granted all the subsequent minislots [1].

In addition to that, this very same slot in the subsequent frames is reserved for the same node, until it ends its transmission. Within a time slot, communication between the source and destination nodes is done either by Time Division Duplexing (TDD), or by Frequency Division Duplexing (FDD).

There are two rules for the reservation, which prioritize voice traffic:

-   Contention for the first minislot is done with probability 1 for voice traffic, and a smaller probability for other traffic.
-   The reservation of a minislot brings reservation of the subsequent slots only if the winning node is a voice one.

5.2. Collision Avoidance Time Allocation (CATA) Protocol

In this protocol, time is divided into frames, each frame into slots, and each slot into 5 minislots. The first four minislots are control ones, CMS, only the fifth is used for data transmission, DMS, and it is longer than the other ones.
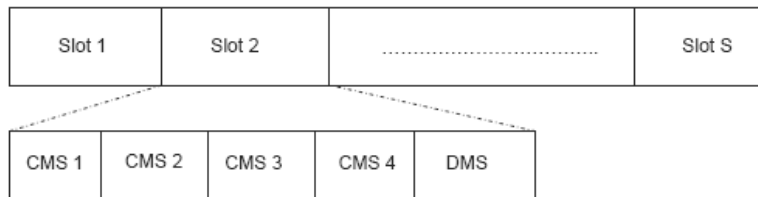

Figure 5: Time Division in the CATA protocol

CATA supports broadcast, unicast, and multicast transmissions at the same time. CATA has two basic principles:

-   The receiver of a flow must inform other potential source nodes about the reservation of the slot, and also inform them about interferences in the slot.
-   Negative acknowledgements are used at the beginning of each slot for distributing slot reservation information to senders of broadcast or multicast sessions.

The CMS1 and CMS2 are used to inform neighbors of the receiving and the sending nodes accordingly about the reservation.

The CMS3 and CMS4 are used for channel reservation [1].

CATA provides support for collision-free broadcast and multicast traffic.

5.3. Hop Reservation Multiple Access (HRMA) Protocol

HRMA is a time slot-reservation protocol where each slot is assigned a separate frequency channel. A handshake mechanism is used for reservation to enable node pairs to reserve a frequency hop, thus providing collision-free communication and avoiding the hidden terminal problem [1].
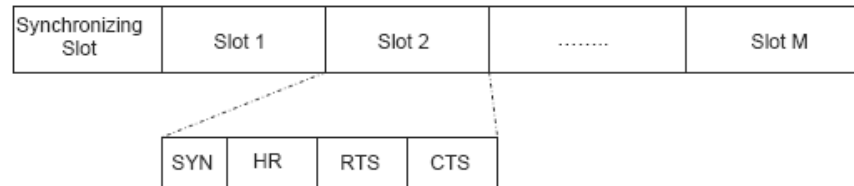

Figure 6: Time Division in the HRMA protocol

One frequency channel is a dedicated synchronizing channel where nodes exchange information. The remaining frequency channels are paired, one channel in each pair is used for reservation and data packets, and the other one is used for acknowledgements. As mentioned above, each time slot has a frequency channel. The time slot is divided into four periods, each period is reserved for sending a particular kind of packet or its acknowledgement, depending on which frequency channel of the pair this time slot belongs to.

After the handshaking is over, the two nodes communicate by sending data and ACKs on the very same frequency channels.

When a new node wants to join the network, it listens to the dedicated frequency and gathers information. When a node wants to send data, it listens to the Hop Reservation (HR) period. If there is a packet there, it tries again after a random amount of time, otherwise it sends a RTS packet, and waits for the CTS acknowledgement packet in the CTS period of the corresponding frequency channel.

5.4. MACA with Piggy-backed Reservation (MACA/PR) Protocol

There are three main components of this protocol:

- A MAC protocol;
- A reservation protocol;
- A QoS routing protocol.

MACA/PR differentiates between real-time packets and best-effort packets; it provides bandwidth to real-time traffic.

Time is divided into slots that are asynchronous in nature and have different lengths. Each node records the transmit and receive reservations of its neighbors in a reservation table.

A node that wants to transmit a non-real-time packet finds a free slot in the table. Then it waits for the same slot the next time around. If it is still free, it sends a RTS packet in the slot, expects a CTS packet, then sends the data and receives the acknowledgement still in the same slot. The RTS and CTS packets contain in them the amount of time that the data transmission is going to take place. In this way, the neighbors of the source and destination nodes can update their tables.
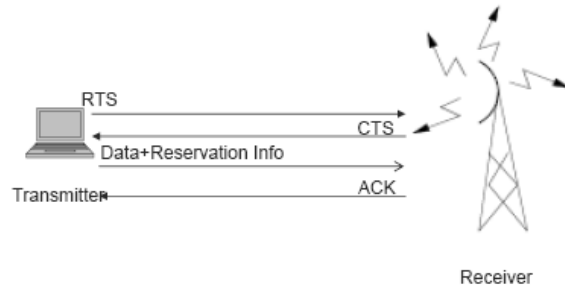
Figure 7: Packet exchange in MACA/PR

For real-time traffic, the first part is identical until the first data packet is sent. Each data packet contains information about the reservation of the next data packet. This information is piggy-backed to it. Each acknowledging packet also contains this information. Thus, the neighbors of both communicating nodes can update the information. When the sender receives the acknowledgement, it makes sure that the reservation was successful.

If several acknowledgements do not come, the sender assumes that the reservation has been lost and restarts the whole procedure. The acknowledgement refreshes the reservation; unrefreshed ones are simply dropped from the reservation table. The nodes exchange the information in their reservation tables; this eliminates the hidden terminal problem.

This mechanism works as a TDM for real-time traffic, while best-effort packets are transmitted in the empty slots.

When a new node joins the network, at first it learns about it by receiving the reservation tables from the neighbors. Then it behaves just like the others.

Advantage: global synchronization not required.

Drawback: the RTS-CTS-DATA-ACK exchange takes place in the same slot in different cycles; therefore, random empty slots are not utilized.

6. Contention-based protocols with scheduling mechanisms

These protocols handle packet scheduling at the nodes and scheduling of the nodes. Rather than aiming to provide node or flow level fairness, the target here is an ordering mechanism to achieve either QoS differentiation or fairness. In other words, the objective is to design a distributed MAC protocol in which, packets are serviced to the maximum extent possible in the order defined by a reference scheduler.

6.1. Distributed Priority Scheduling (DPS)

DPS uses the RTS-CTS-DATA-ACK packet exchange mechanism. The RTS packet contains the priority label for the DATA packet that is to be transmitted. The corresponding CTS contains it also. Neighbor nodes receiving the RTS packet update their scheduling tables with the node and its priority. When the DATA packet is sent, it contains piggy-backed information about the priority of the next packet from this node and its priority, so the other nodes can record this information. Finally, when the acknowledgement comes, the nodes delete the entry for the data packet that is being acknowledged [1].

This mechanism enables the nodes to evaluate their priority in relation to the priority of the other nodes.

6.2. Distributed Wireless Ordering Protocol (DWOP)

The purpose of this protocol is to achieve a distributed FIFO schedule among multiple nodes in an ad hoc network.

When a node transmits a packet, it adds the information about the arrival time of queued packets. All nodes overhear this information and record it in their local scheduling table. This information helps a node establish its relative priority in relation to the partial list of the nodes within its range, associated with their arrival times. According to DWOP, a node should contend for channel access only when it has the lowest arrival time of all the nodes within its range [2].

Entries in the table are deleted when the node hears the ACK packet. In case these ACK packets are not heard, we end up having false entries in the tables. This can be detected if a node notices other packets with lower priority being transmitted; it can solve the problem by deleting the oldest entry.

In case not all the nodes are within radio range of each-other, incomplete table information will lead to collisions, and will prevent a pure FIFO scheduling from happening [1,2].

7. Conclusions

The issues associated with the design of a MAC protocol for wireless ad hoc networks are: node mobility; an error- prone, broadcast and shared channel; time-synchronization; bandwidth efficiency; QoS support.

8. References

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[3] Alexander Tyrrell, Gunther Auer and Christian Bettstetter: Firefly Synchronization in Ad Hoc Networks