

MAC protocols for ad hoc networks

Lecturer: Dmitri A. Moltchanov

E-mail: moltchan@cs.tut.fi

<http://www.cs.tut.fi/kurssit/TLT-2756/>

OUTLINE:

- Problems for MAC to deal with;
- Design goals;
- Classification of MAC protocols
- Contention-based protocols
- Contention-based with reservation mechanism
- Contention-based with scheduling mechanism
- MAC protocols for directional antennas
- Power control MAC protocols

1. Problems for MAC to deal with

Aim of MAC: provide fair access to shared broadcast radio channel.

Issues to deal with:

- Bandwidth efficiency:
 - must be maximized.
- Real-time traffic support:
 - should be provided.
- Synchronization:
 - sometimes needed, e.g. TDMA.
- Shared broadcast medium:
 - collisions must be avoided/minimized.
- Lack of central coordination:
 - fully distributed MAC design.

- Hidden terminal problem:
 - collisions \rightarrow inefficient bandwidth utilization.

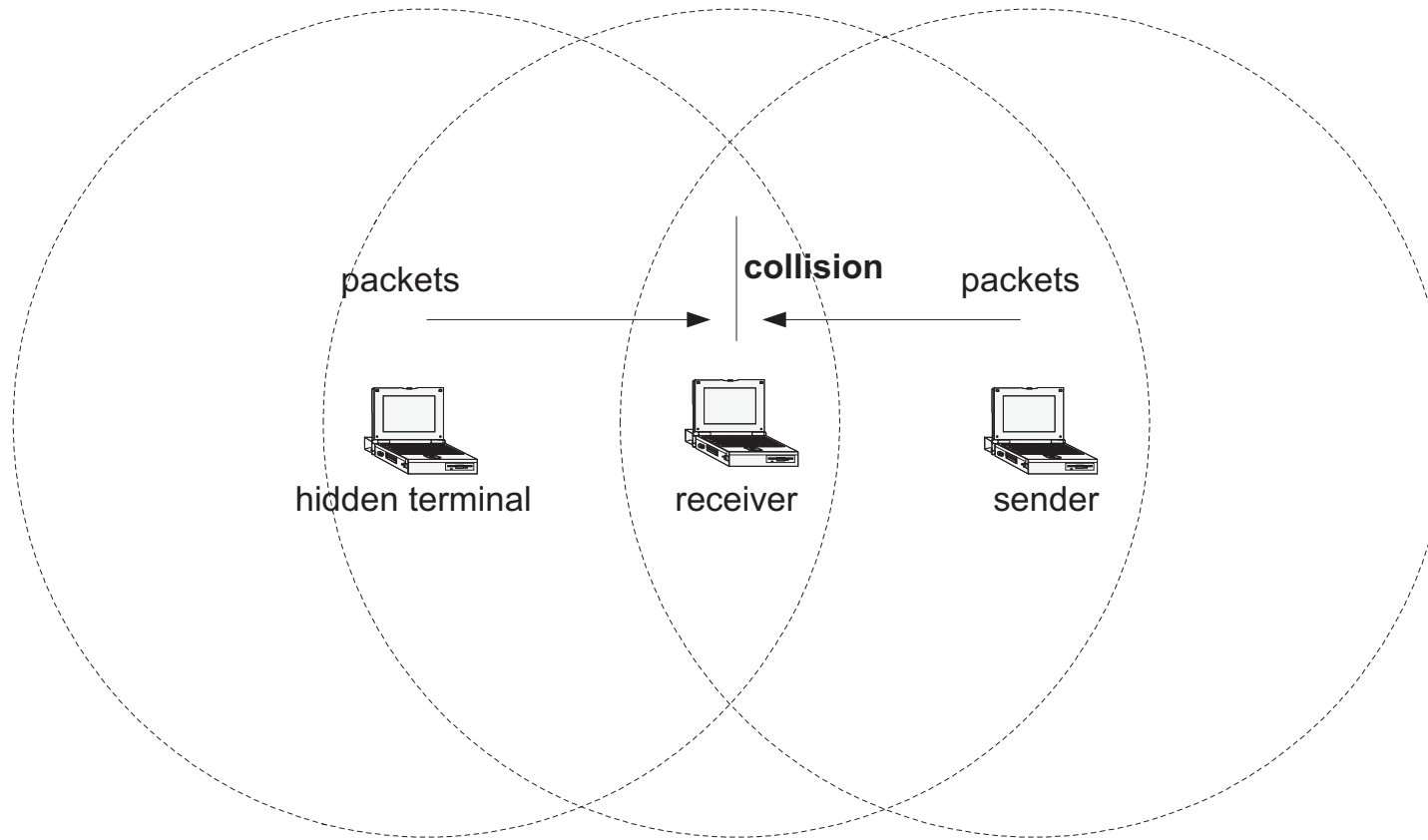


Figure 1: Illustration of the hidden terminal problems.

- Exposed terminal problem:
 - inability to transmit \rightarrow inefficient bandwidth utilization.

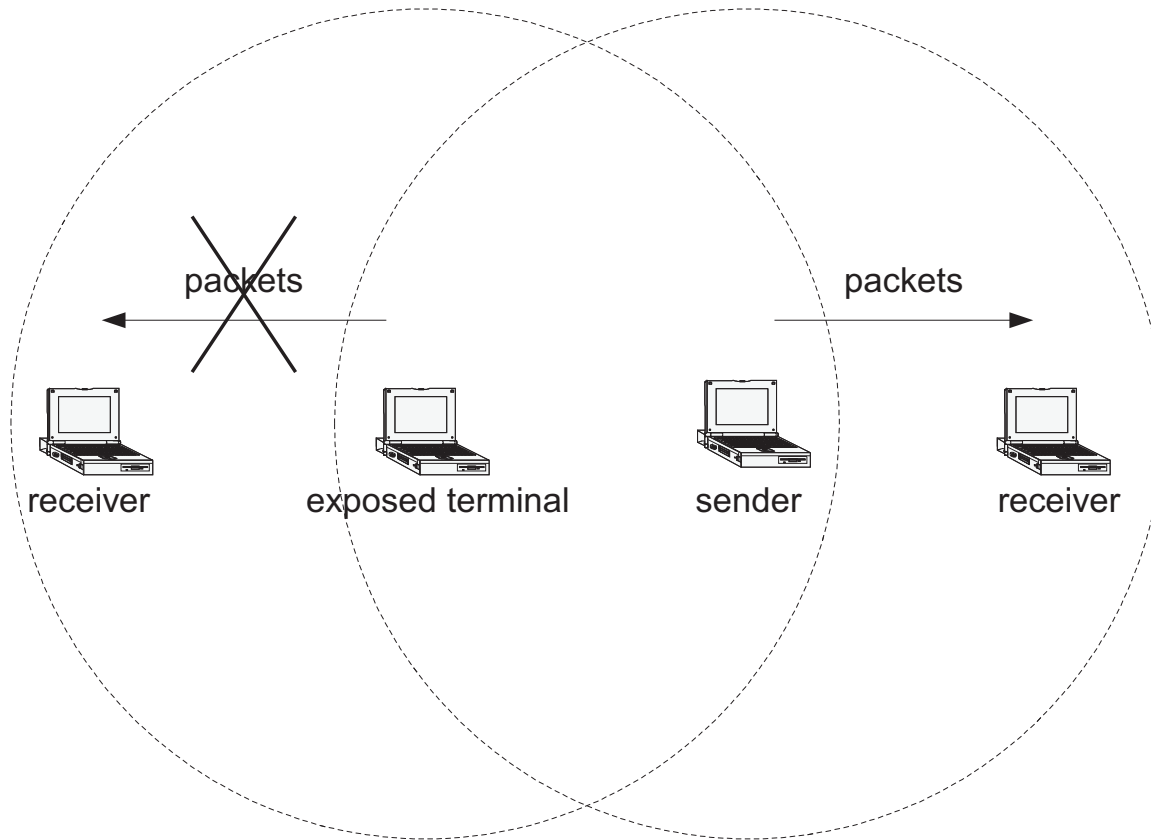


Figure 2: Illustration of the exposed terminal problem.

- Mobility of nodes:
 - loss of connectivity;
 - network partitioning;
 - bit errors.

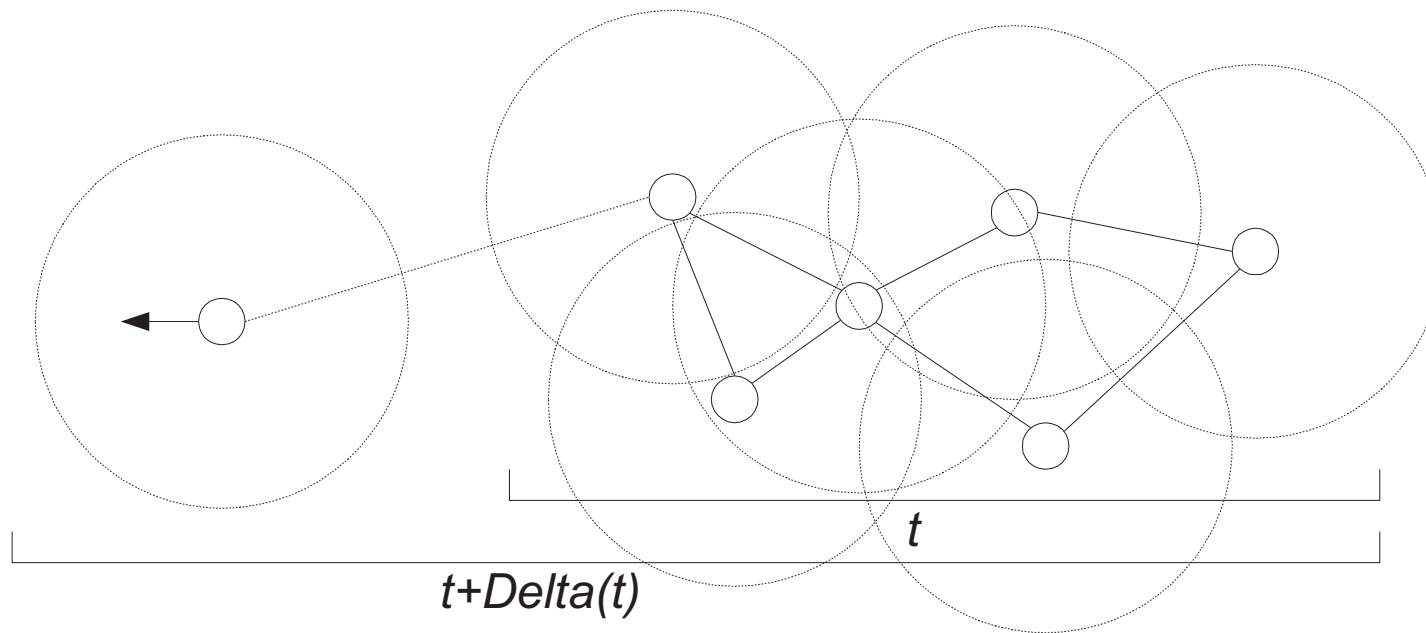


Figure 3: Network partitioning is one of the biggest problem to deal with at MAC sublayer.

2. Design goals

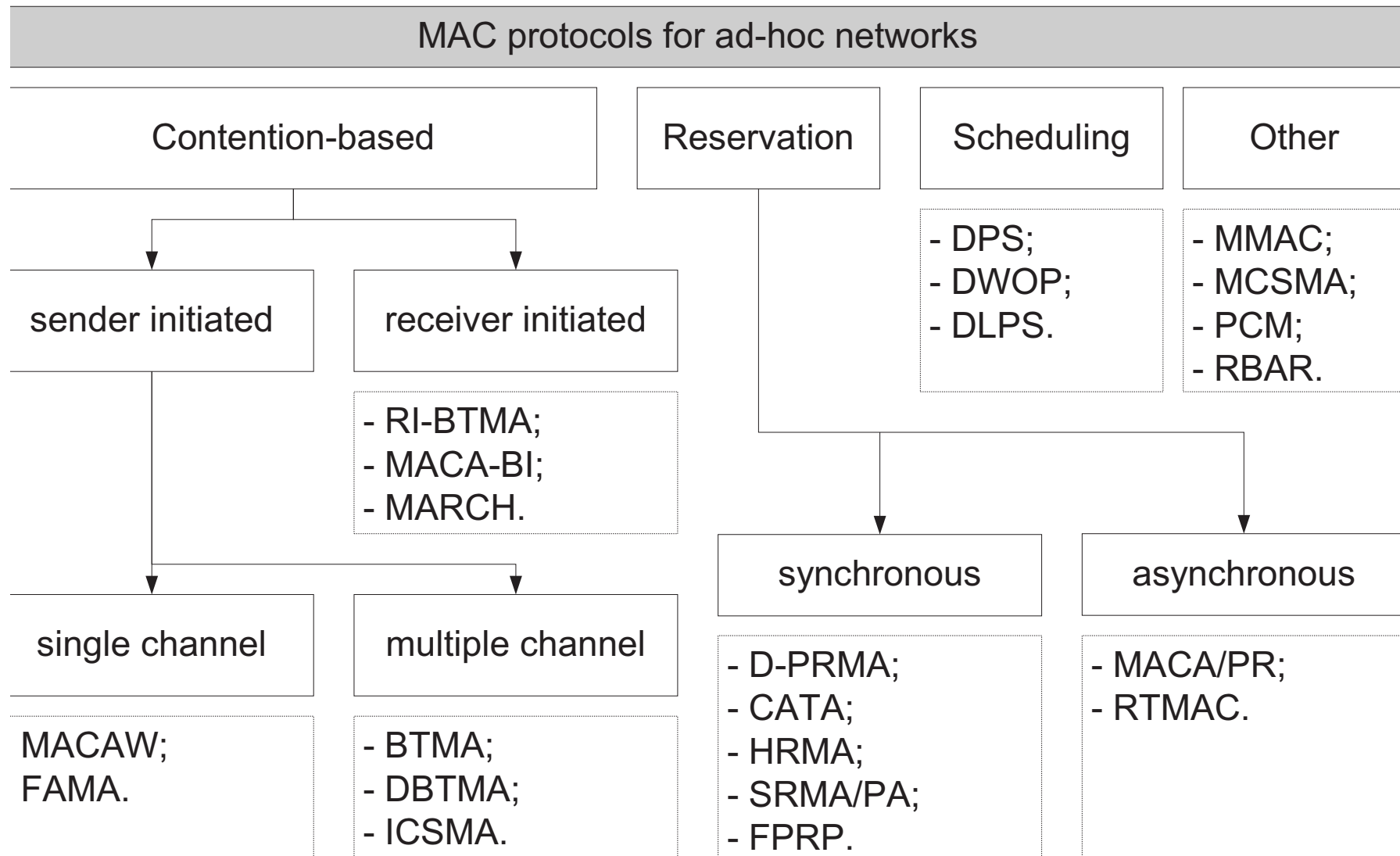
What we want from MAC protocol:

- allow fair access to the shared radio medium;
- operation of the protocol should be distributed;
- should support real-time traffic;
- the access delay must be minimized;
- available bandwidth must be utilized efficiently;
- fair bandwidth allocation to competing nodes;
- control overhead must be minimized;
- the effects of hidden/exposed terminals must be minimized;
- must be scalable;
- should minimize power consumption;
- should provide synchronization between nodes.

3. Classification of MAC protocols

MAC protocol for ad-hoc networks must be classified into:

- Contention-based protocols without reservation/scheduling:
 - no reservation of the bandwidth is made;
 - guarantees are not possible.
- Contention-based protocols with reservation mechanisms:
 - bandwidth for transmission is reserved in advance.
 - guarantees are possible.
- Contention-based protocols with scheduling mechanisms:
 - distributed scheduling between nodes is used.
 - guarantees are possible.
- Protocols that do not fall to any of these categories:
 - implement several features of different protocol groups or
 - use completely different approach



4. Contention based protocols w/o reservation/scheduling

The basic idea: contention for the resource, winning node transmits.

4.1. MACA protocol

CSMA operates as follows:

- the sender sense the channel for the carrier signal;
- if the carrier is present it retries to sense the channel after some time (exp. back-off);
- if not, the sender transmits a packet.

The following shortcomings are inherent to CSMA/CA:

- —: hidden terminal problem leading to frequent collisions;
- —: exposed terminal problem leading to worse bandwidth utilization.

To avoid it:

- virtual carrier sensing;
- RTS-CTS handshake before transmission.

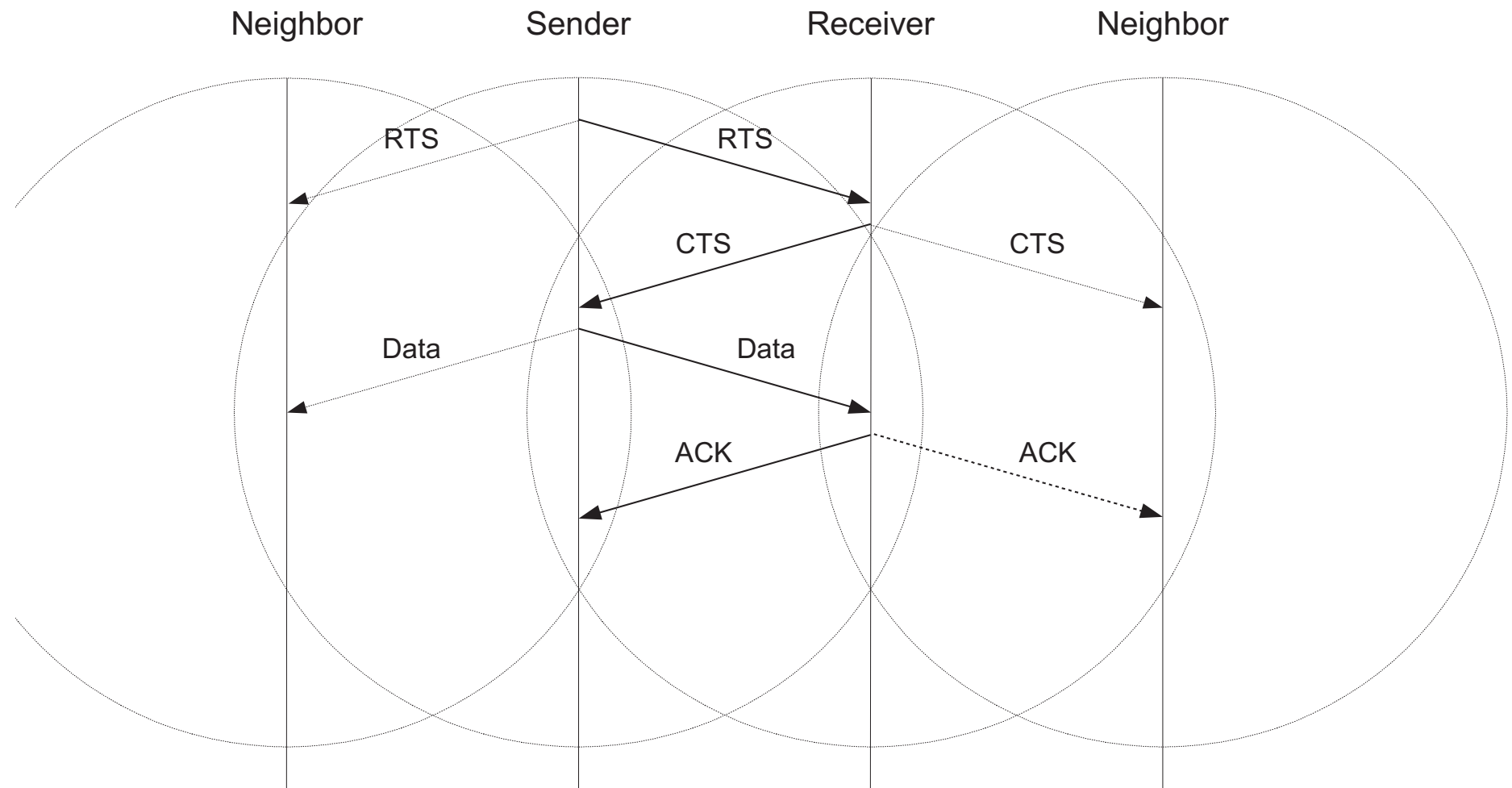


Figure 4: Packet transmission in MACA.

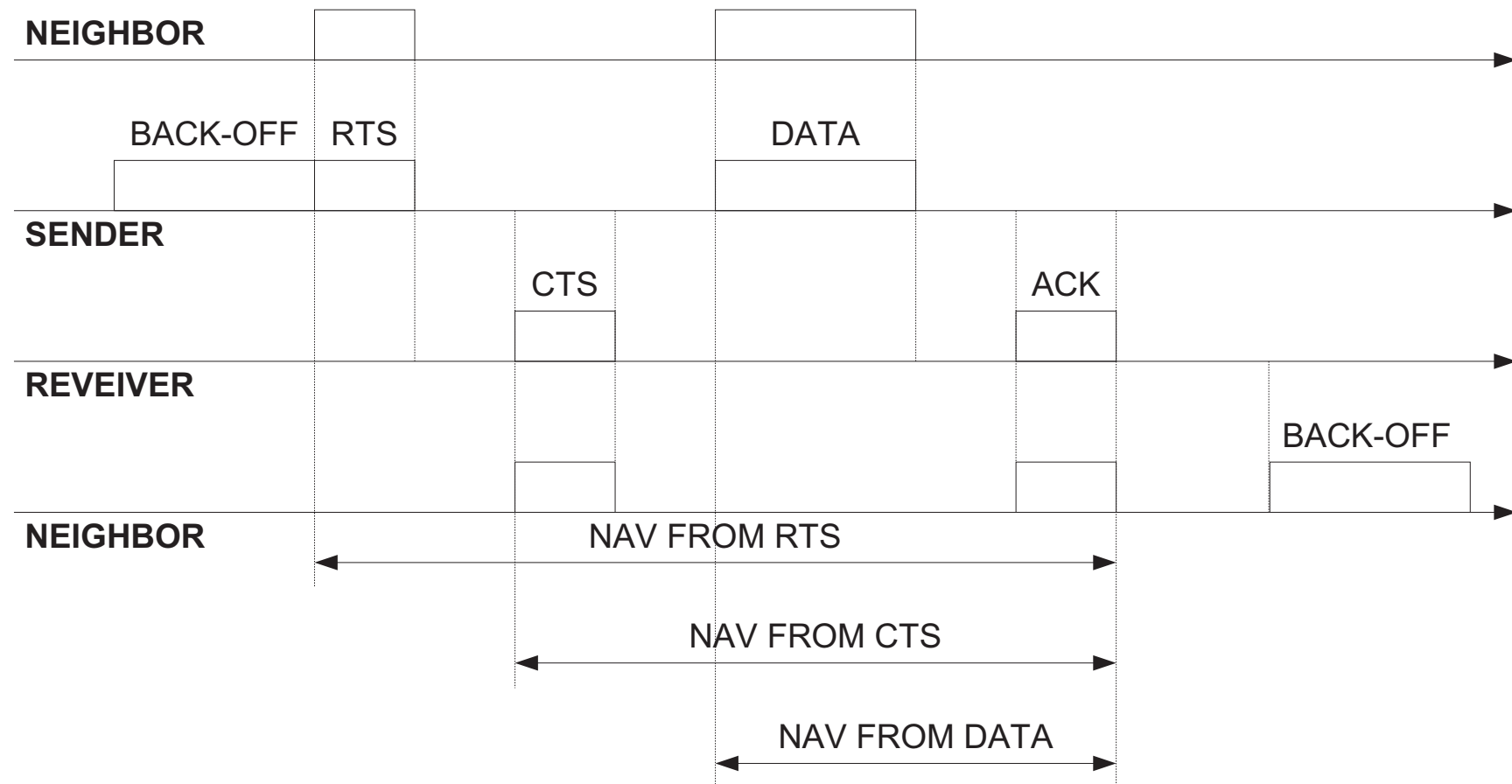


Figure 5: Usage of virtual carrier sensing.

NAV: network allocation vector – implementation of virtual carrier sensing.

If the transmission fails:

- contention window: $CW \times 2$;
- retransmission.

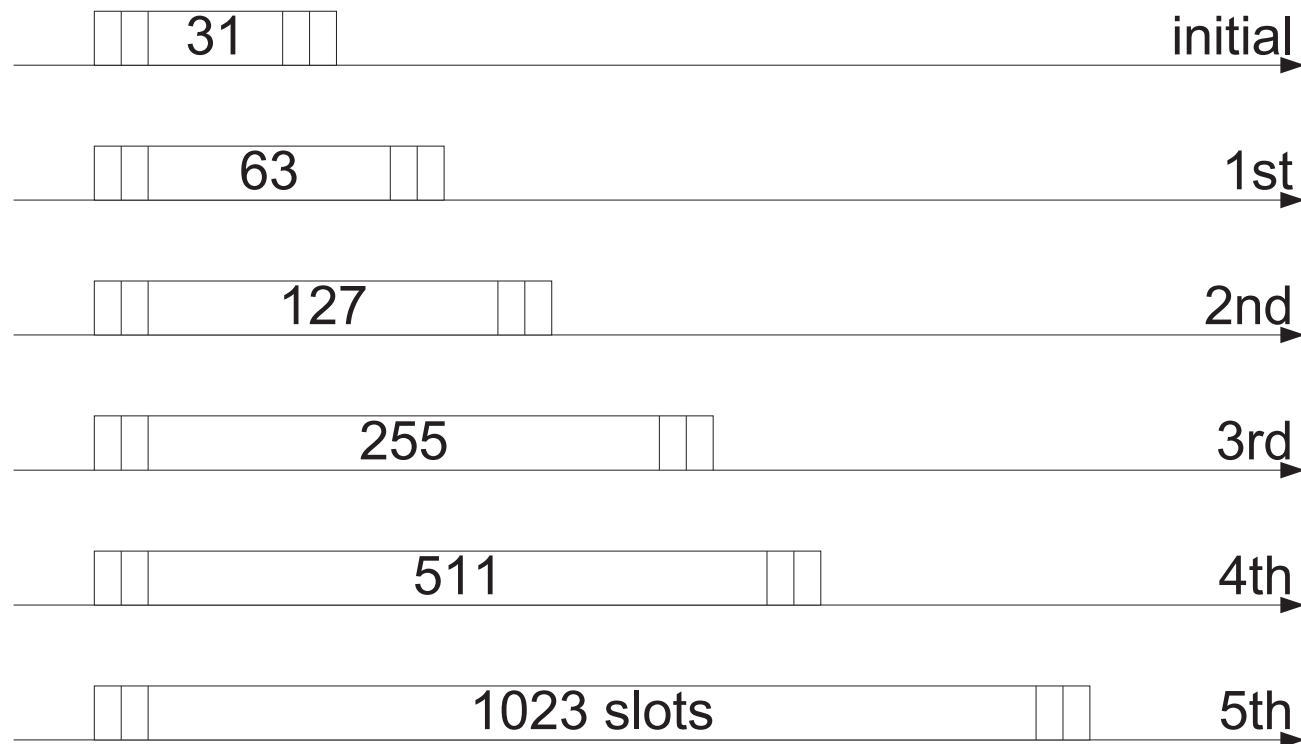


Figure 6: Evolution of the contention window with increasing of transmission attempts.

Problem 1 of MACA: starvation of flows:

- both S1 and S2 have the high volume of traffic, S1 seizes the channel first;
- packets transmitted by S2 get collided and it doubles CW ($CW = 2CW$);
- the probability that the node S2 seizes the channel is decreasing.

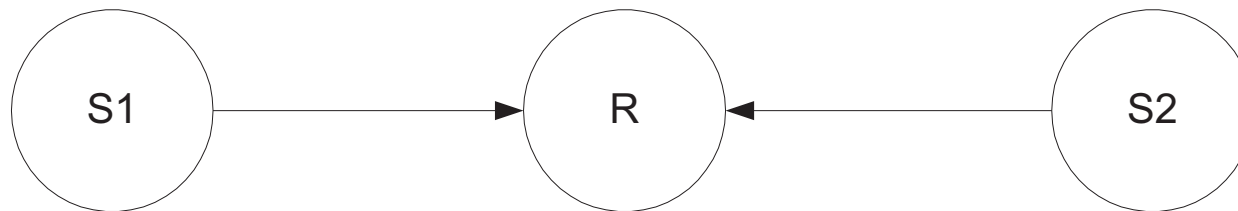


Figure 7: Starvation of the flow from S2.

Solution:

- the packet header contains the field set to the current back-off value of the transmitting node;
- a node receiving this packet copies this value to its back-off counter (fairness);
- $CW = CW_{\min}$ after every successful transmission.

Problem 2 of MACA: fast adjustment of CW:

- when a node successfully transmits a packet;
- when a collision is detected by a node.

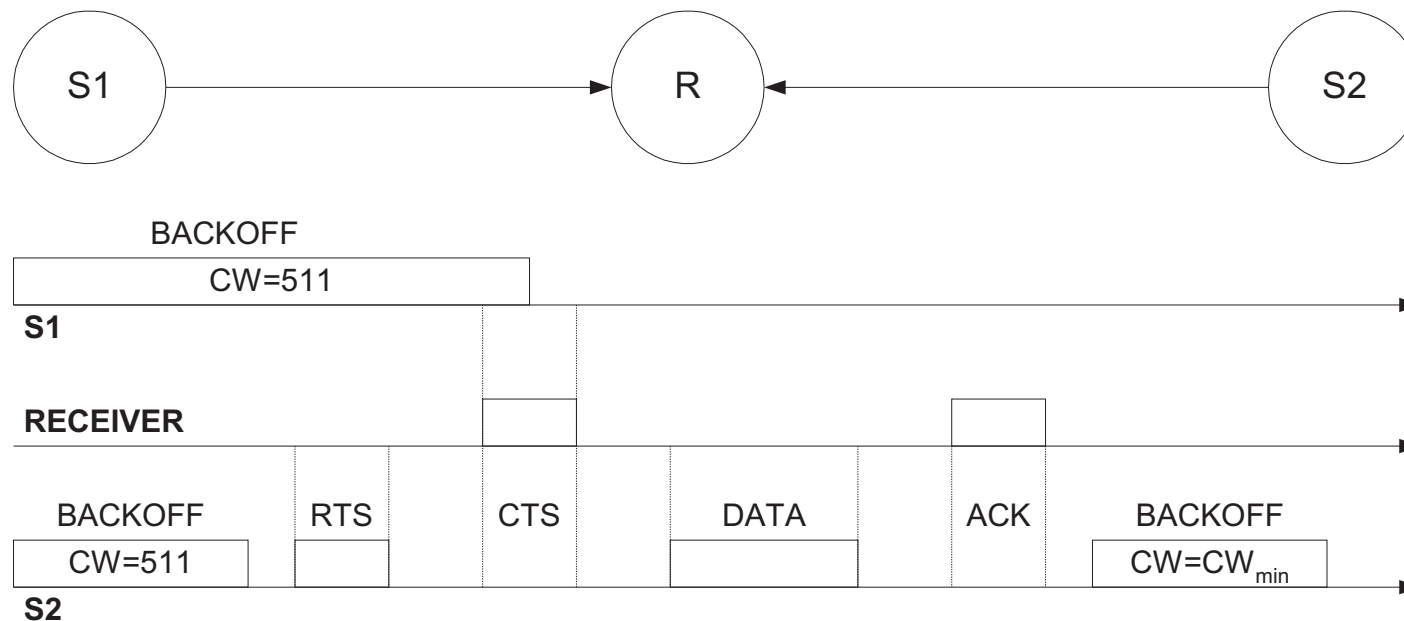


Figure 8: Rapid adjustments of the CW.

Solution: multiplicative increase when collision, linear decrease when success.

Problem 3 of MACA: an exposed node is free to transmit.

- node S2 hears RTS but not CTS (exposed node);
- S2 initiates transfer to R2;
- DATA from S1 and CTS from R2 may collide, CW unnecessary increases at S2.

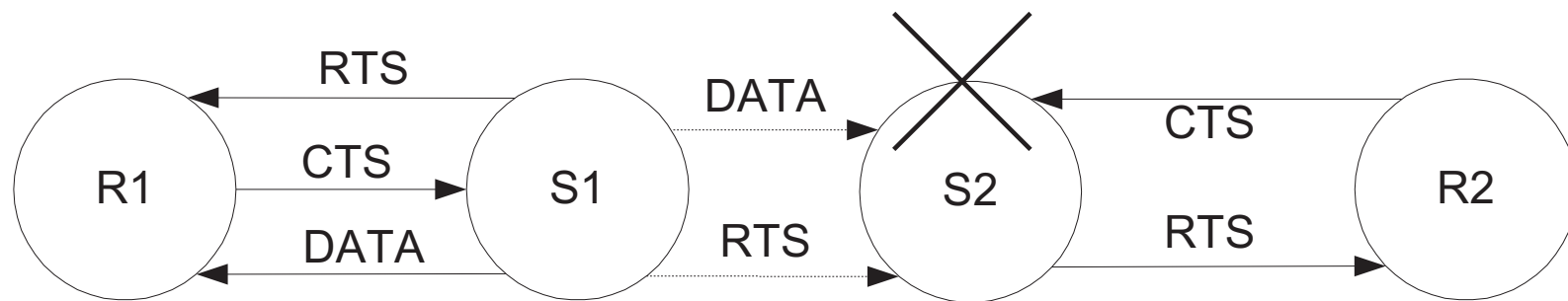


Figure 9: Problems with exposed node.

Solution: use of small data sending packet (DS) to update information.

Problem 4 of MACA: neighbor receivers problem:

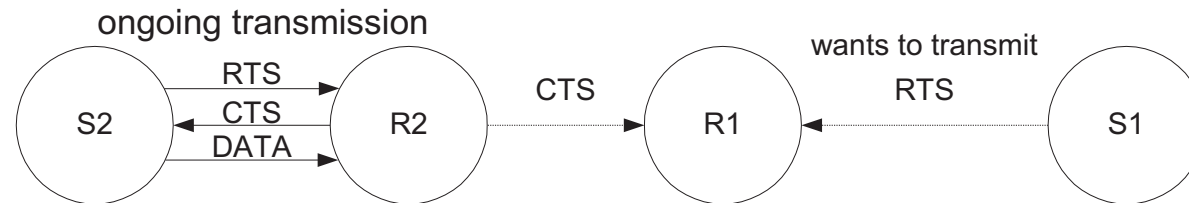


Figure 10: Illustration of the neighbor receivers problem.

Solution: usage of request-for-request (RRTS) to send packets:

- if R1 had received RTS (S1) and did not respond due to R2-S2 it backs off sends RRTS;
- R2 hears RRTS waits for successive RTS-CTS between S1 and R1;
- S1 hears the RRTS, transmits regular RTS and RTS-CTS-DATA-ACK takes place.

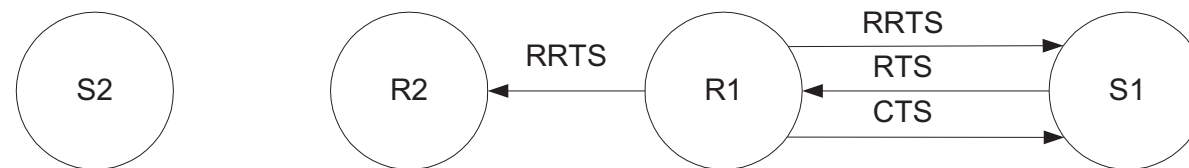


Figure 11: Solution of the neighbor receivers problem.

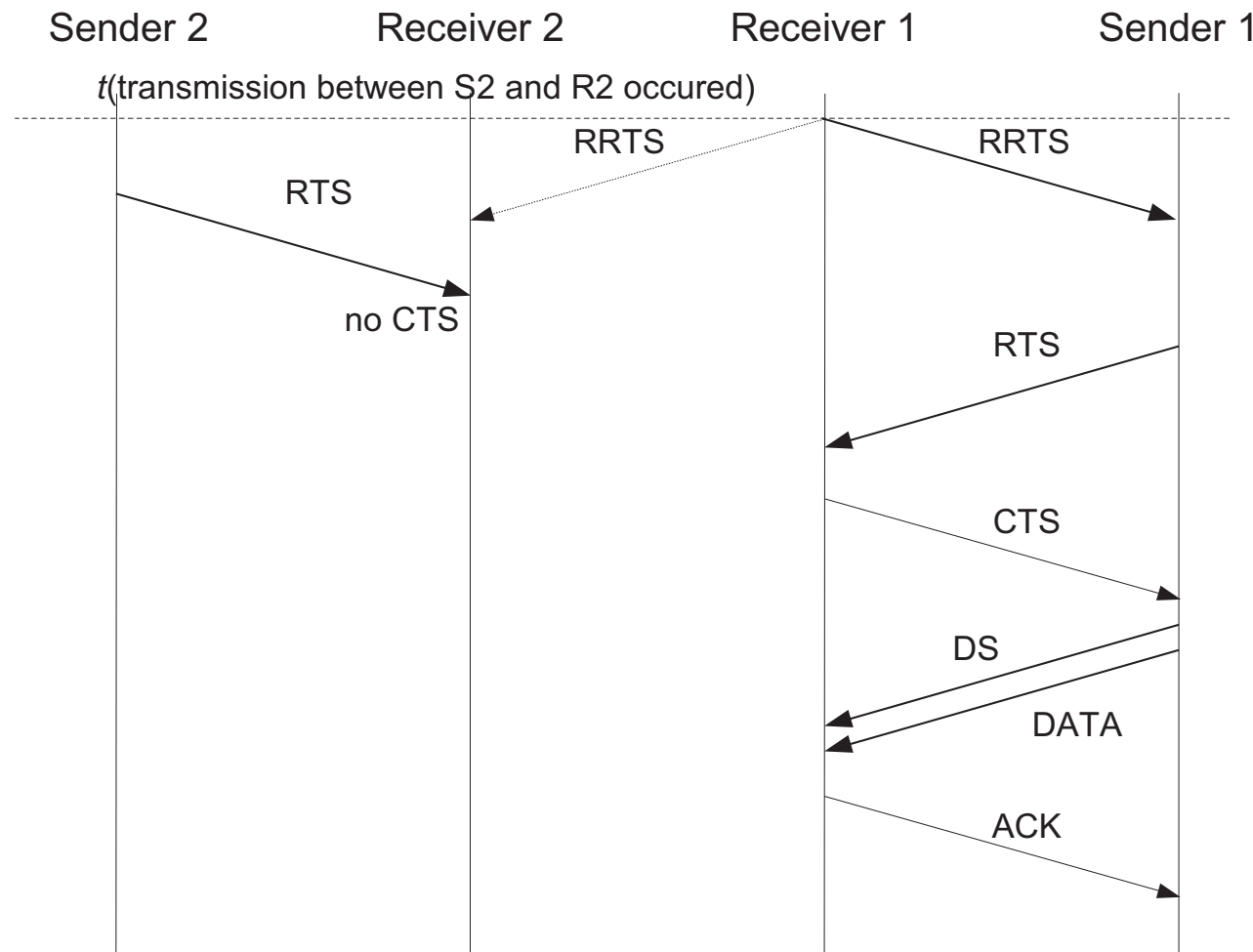


Figure 12: Packets exchange in neighbor receivers problem.

4.2. Busy tone multiple access protocol (BTMA)

Multichannel protocol where the channel is separated into:

- control channel: used for data transmission;
- data channel: used for busy tone transmission.

BTMA works as follows:

- a node senses the control channel to check whether the busy tone is active;
- if not, it turns on the busy tone signal and starts data transmission;
- if yes, a node waits for a random period of time and repeats the procedure;
- any node that senses the carrier on the incoming data channel also transmits a busy tone.

There are following advantages and shortcomings of the BTMA:

- +: simple enough;
- +: probability of collision is extremely low;
- -: bandwidth utilization is low (nodes are blocked in two-hop neighborhood).

4.3. MACA by invitation (MACA-BI)

Receiver-initiated MAC protocol providing the following extension to MACA:

- MACA: RTS-CTS-DATA-ACK;
- MACA-BI eliminates the need for CTS using the receiver's ready-to-receive (RTR) packet.

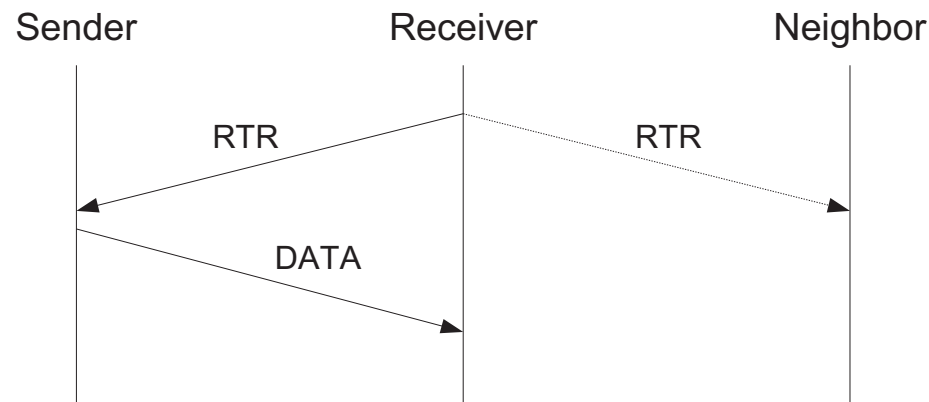


Figure 13: Transmission in MACA-BI.

- needs information about the traffic at neighboring nodes;
- this information is included into DATA packets.

4.4. Media access with reduced handshake (MARCH)

RTS packet is used only for the first DATA packet of the stream:

- nodes know about packet arrival at neighboring node listening to CTS signals;
- to relay packet, it sends a CTS packet to the concerned node.

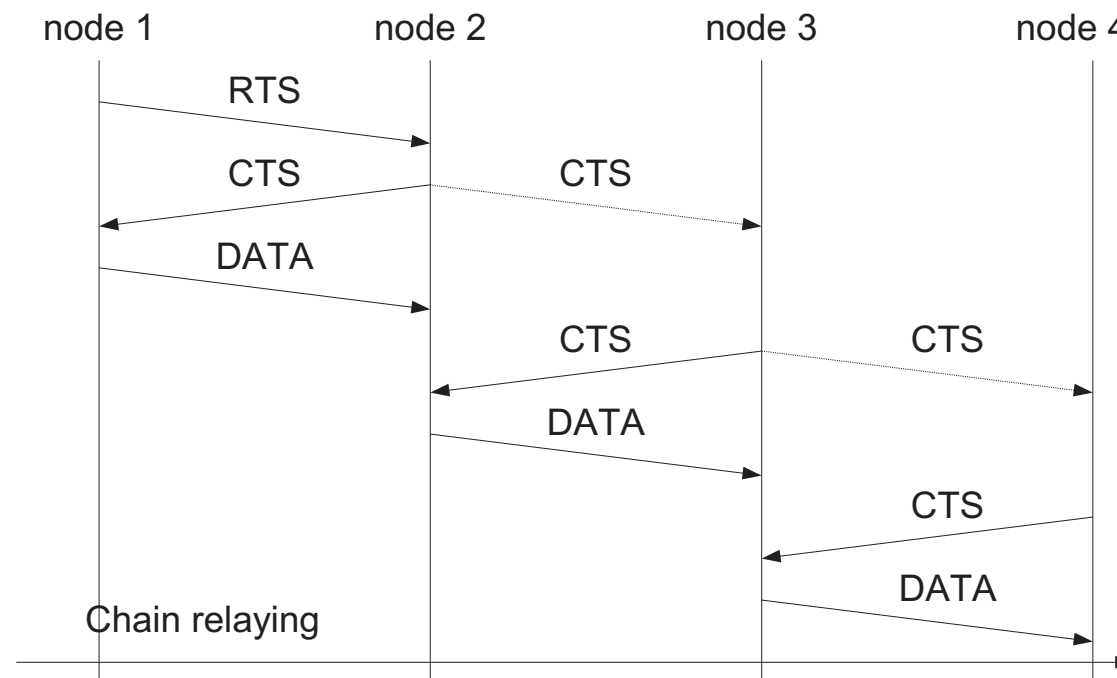
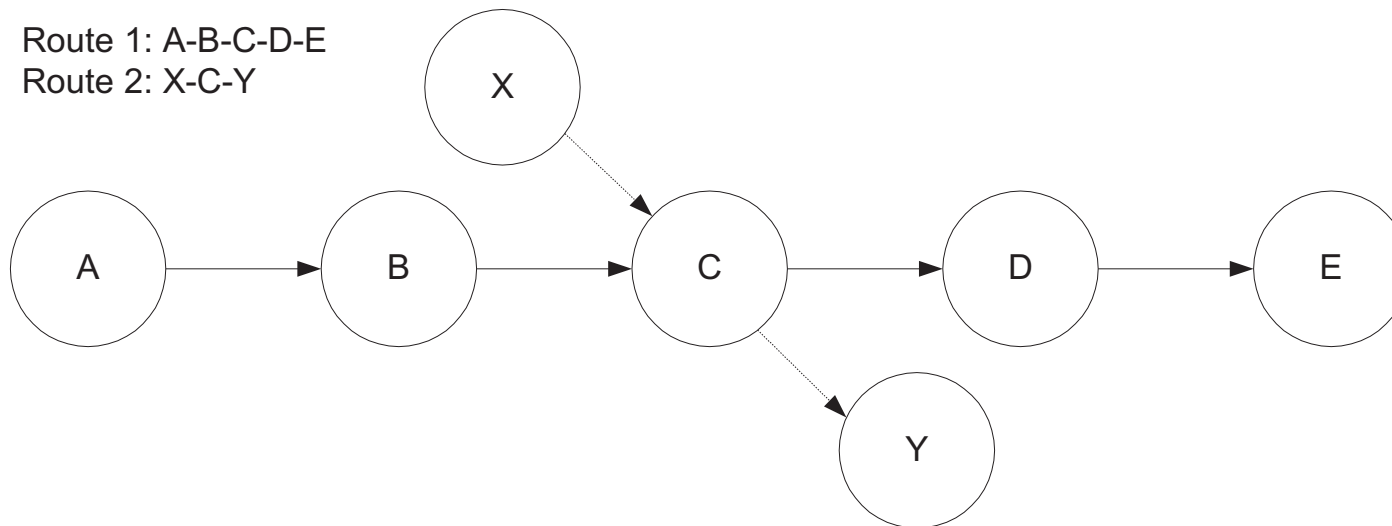


Figure 14: Relaying using the MARCH.

The CTS packet in MARCH carries the following information:

- the MAC address of the sender and the receiver node;
- route identification number R_{id} to distinguish between routes.



MARCH is characterized by the following advantages and shortcomings:

- +: very high throughput;
- +: very low control overhead;
- -: access to routing information is required → cross-layering!

5. Contention-based protocols with reservations

Use **bandwidth reservation techniques**:

- contention occurs here **only** at resource reservation phase;
- once bandwidth is reserved a node gets an exclusive access to the media.

5.1. Distributed packet reservation multiple access protocol (D-PRMA)

D-PRMA is a TDMA based scheme where the channel is divided into frames.

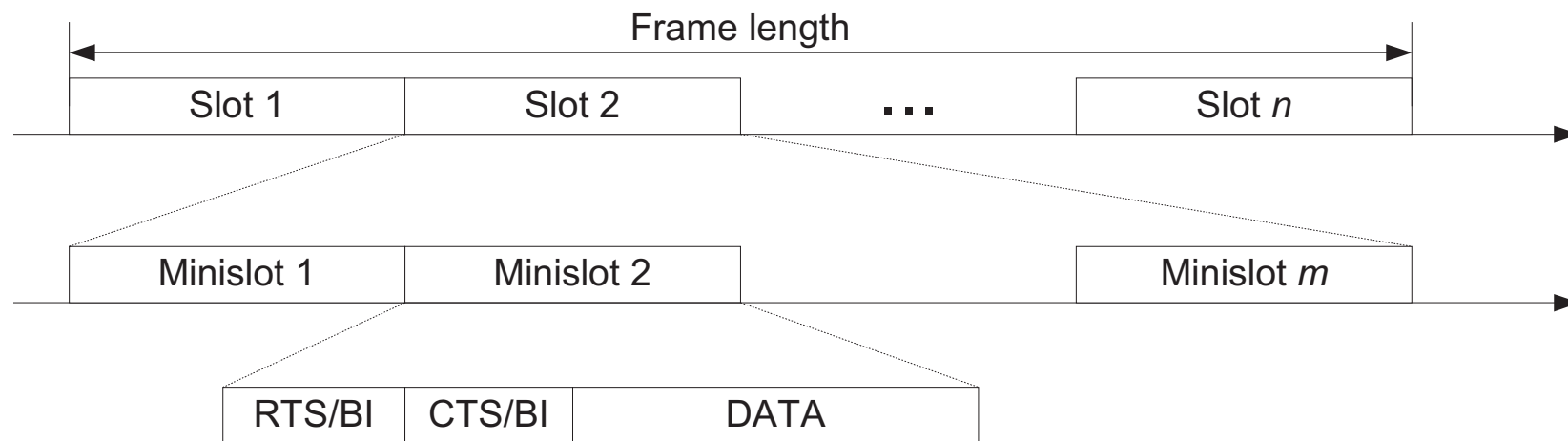


Figure 15: Frame structure in D-PRMA.

Slot reservation and overcoming the hidden terminal problem:

- Request to send / busy indication (RTS/BI) and clear to send / busy indication (CTS/BI).

The protocol operates as follows:

- nodes having a packet for transmission contend in the first minislot of each slot;
- the remaining $(m - 1)$ minislots in the slot are granted to the node that wins the contention;
- the same slot in subsequent frames is reserved for the this terminal, until it ends transmission;
- if no node wins the first minislot, the remaining minislots subsequently used for contention;
- within a reserved slot communication is performed using TDD or FDD.

Slot reservation mechanism performs as follows:

- a certain period in the beginning of each minislot is reserved for carrier-sensing;
- if a nodes detects a channel to be idle, it sends a RTS packet to destination using RTS/BI;
- receiver answers with CTS packets in the CTS/BI field of the same minislot;
- the sender upon receiving CTS, gets a reservation for current slot (all minislots).

To prioritize the voice traffic:

- **Rule 1:**

- voice nodes traffic are allowed to start contention from minislot 1 with probability 1.
- data nodes start contention from minislot 1 with probability < 1 ;
- for the remaining $(m - 1)$ minislots all nodes contend with probability 1.

- **Rule 2:**

- if the node winning the contention is the data node, only the current slot is reserved;
- if the node winning the contention is the voice node, subsequent slots are also reserved.

To make it real the following requirements must be satisfied:

Requirements for nodes other than a winning one:

- hidden and exposed terminals should be avoided;
- no contention:
 - no contention in remaining minislots;
 - no contention in the subsequent slots.

Requirement 1: (no contention in other minislots)

Hidden terminal problem:

- RTS packet do not suffer a collision due to carrier sensing (winning node transmits);
- a node hearing the CTS is not allowed to transmit in the remaining period of the slot.

Exposed terminal problem:

- A node hearing the RTS but not CTS is allowed to transmit.

Requirement 2: (no contention in other slots)

- the receiver and sender transmit a BI signal in minislot 1 of the reserved slot;
- when any node hears BI signal it does not contend in this slot;
- when the transmission is completed both sides stops transmission of BI signal.

Advantages and shortcomings:

- +: D-PRMA is best suited for voice applications;
- -: requires synchronization (TDMA).

5.2. Collision avoidance time allocation protocol (CATA)

The operation of CATA is based on the following principles:

- the receiver of a flow must inform the source nodes about the reserved slot;
- the source must inform destinations about interferences in the slot;
- usage of negative acknowledgements for reservation requests;
- control packet transmissions for distributing reservation information.

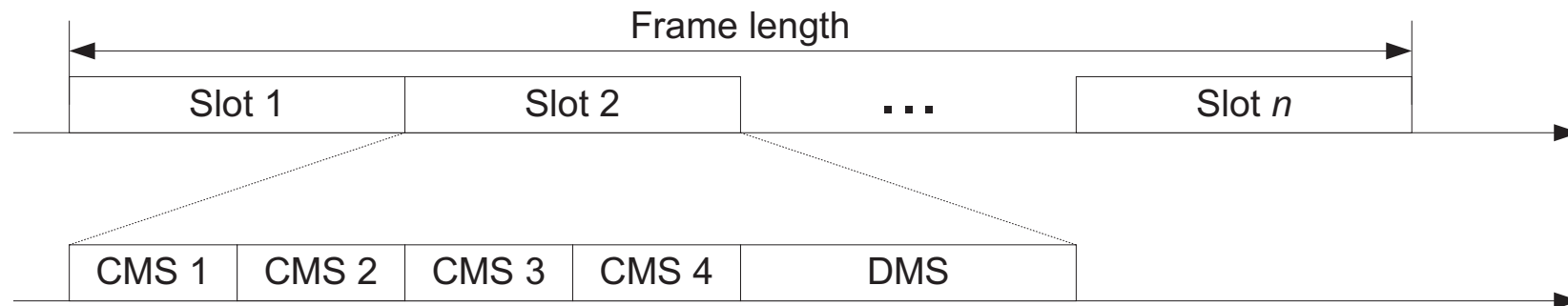


Figure 16: Frame structure of CATA.

- CMS – control minislot; DMS – data minislot.

The slot reservation is done as follows:

- the sender sense the channel to be idle in CMS 1, and transmits RTS in CMS 2;
- the receiver receives RTS in CMS 2 and responses with CTS in CMS 3;
- the sender transmits DATA in DMS part of the slot and in the subsequent slots;
- once the reservation is made the sender and receiver transmit NTS (not to send) in CMS 4.

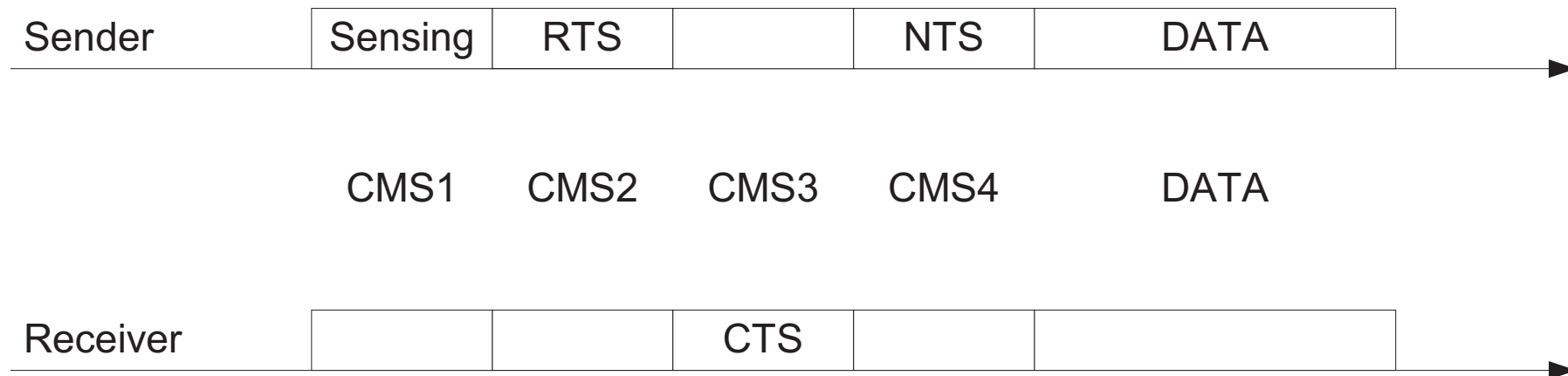


Figure 17: Slot reservation in CATA.

5.3. Hop reservation multiple access protocol

The following are the major features of this protocol:

- multichannel MAC protocol;
- half-duplex protocol;
- very slow FHSS (frequency hopping spread spectrum).

The channels are used as follows:

- there are L channels in the system;
- channel f_0 is used for synchronization;
- $(L - 1)$ channels are divided into M frequency pairs (f_i, f_i^*) , $i = 1, 2, \dots, M$;
- in general, there are M hops in the system.

Frequencies in a pair are assigned different functions:

- f_i : hop reservation packets (HP), RTS, CTS, and DATA packets;
- f_i^* : transmitting and receiving ACKs for packets transmitted at f_i .

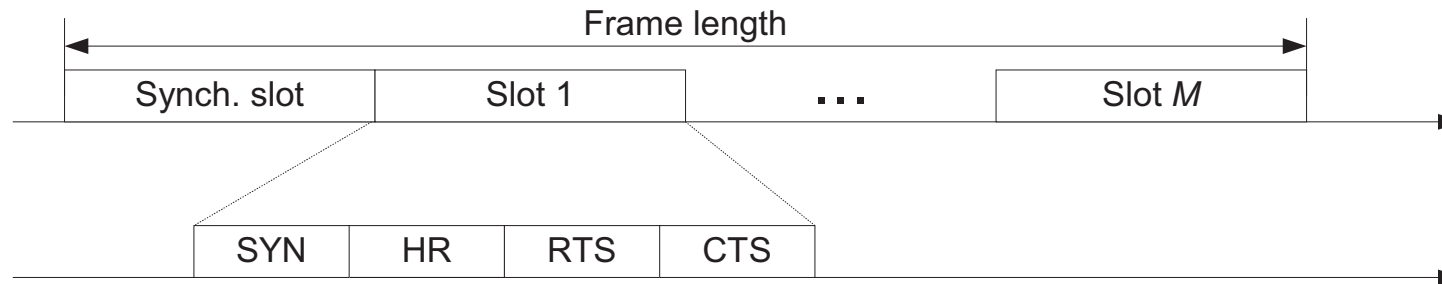


Figure 18: Frame structure of HRMA.

- each slot is assigned a separate frequency hop, one of M available;
- each time slot is divided into four periods:
 - SYN period: synchronizing packet;
 - HR period: HR packet;
 - RTS period: RTS packet;
 - CTS period: CTS packet.

All idle nodes hop together exchanging synchronization information:

- in f_0 and synchronization slot.

A node entering the network:

- to gather SYN and hopping information remains on f_0 for a long time;
- if these information is not received, a node:
 - broadcasts its own SYN information;
 - forms a one node system.

When a node receives data to be transmitted it:

- listens on HR period of the following slot;
- if it hears HR packet, it backs off for a random period of time;
- if the channel is free, it transmits RTS packet to a destination in RTS period;
- receiver replies with CTS, and waits for a DATA packet;
- if the source receives the CTS correctly, the reservation of the hop is OK;
- if not, the source backs off for a random time and repeats the process later;
- both source and receiver stays on the same frequency during the whole transmission;
- when the DATA packet is sent, source hops to f_i^* and waits for ACK.

5.4. Soft reservation multiple access with priority assignment

The following are two major objective of this protocol:

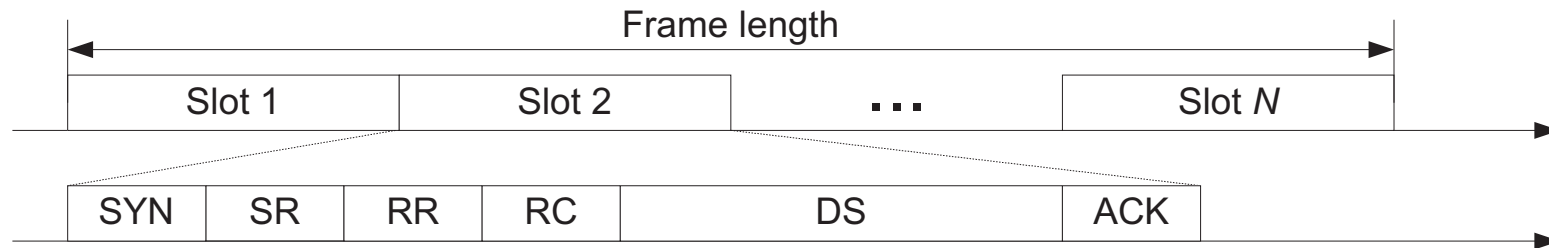
- support of real-time and non-real time applications;
- maximizing the multiplexing gain.

The following are two basic principle of SRMA/PA:

- collision-avoidance handshake mechanism;
- soft reservation mechanism for time slot reservation.

The following are the main features of SRMA/PA:

- unique frame structure;
- soft reservation capability for dynamic slot scheduling;
- dynamic and distributed priority assignment and update policies;
- time-constrained back-off algorithm.



SR – soft reservation (busy tone + priority), RR – reservation request, RC – reservation confirm.

Figure 19: Frame structure of SRMA/PA.

When a node has a packet to transmit:

- it determines whether slot is free using SR field;
- if SR is idle, a node transmits RR packet in the RR field;
- if SR is not idle, it carries a priority:
 - priority of a node is higher than the priority in SR: node takes control;
 - priority of a node is lower than the priority in SR: node backs off.
- Exchange of information: RR-RC-DS-ACK is similar to RTS-CTS-DATA-ACK of MACAW.

According to SRMA/PA a sender can be in the following modes:

- **idle state:** a node does not have any data to transmit;
- active state that can be classified into following:
 - **access state:** node is trying to reserve a slot for transmission;
 - **reserved state:** node has already reserved a slot for transmission.

Priority levels:

- are initially assigned based on two service classes:
 - voice (real-time, v);
 - data (non-real-time, d).
- when a node is in access state it is assigned priorities $p_d(n)$ and $p_v(n)$;
- when a node is in reserved state it is assigned priorities p_d^R and p_v^R ;

A voice node can take over a slot if:

$$p_v(n) > p_d^R, \tag{1}$$

where $p_v(n)$ is the access priority level of voice node after n reservation attempts.

Priorities of the terminals is updated following the algorithm:

- when a node enters the active state it is assigned a priority value $p_v(0)$ or $p_d(0)$;
- if the access attempt (sending of RR packet) is failed priorities are updated:

$$p_v(n+1) = p_v(n) + \Delta p_v, \quad p_d(n+1) = p_d(n) + \Delta p_d, \quad (2)$$

where Δp_v and Δp_d are priority increments for voice and data services.

- Δp_v and Δp_d is determined as follows:

$$\Delta p_v = \frac{\Delta p_v^R \tau_S}{\tau_r}, \quad \Delta p_d = \alpha l_Q, \quad (3)$$

- τ_S is the slot duration;
- τ_r is the residual lifetime for voice service;
- l_Q is the queue length;
- α is the scaling coefficient.

The following constraint ensures that the voice source always may get access:

$$p_d(0) < p_d(n) < p_d^R = p_d^{\max} < p_v(0) < p_v(n) < p_v^R = p_v^{\max}. \quad (4)$$

Collisions may still occur in RR field among nodes with the same priority. To avoid:

- *binary exponential back off algorithm:*
it doubles back off window every time a collusion occurs.
- *modified binary exponential back off algorithm:*
it divides the window into two regions of lengths:
 - N_{b1} to use for real time traffic;
 - N_{b2} to use for non-real-time traffic.

If the difference between maximum delay and the residual lifetime of the HOL packet:

- increases the limit T_l one of N_{b1} slots are chosen for back off;
- does not increase the limit T_l one of N_{b2} slots are chosen for back off.

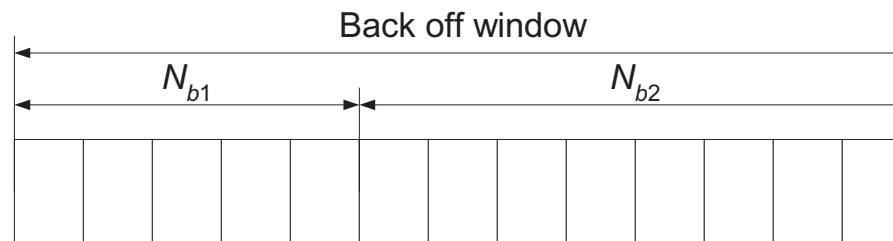


Figure 20: Back off window in SRMA/PA.

6. Contention-based protocols with scheduling mechanisms

Aim is on transmission scheduling at nodes considering metrics:

- delay targets of packets;
- traffic load at nodes;
- remaining battery power at nodes, etc.

6.1. Distributed priority scheduling (DPS)

This protocols is primarily based on IEEE 802.11 DCF using RTS-CTS-DATA-ACK mechanism.

The communication is as follows:

- RTS packet transmitted by a node carries priority index of the packet (delay, etc.);
- the receiver responds with CTS containing the priority tag and source ID copied from RTS;
- neighbors retrieve this information from RTS and CTS and make entry in scheduling tables;
- source sends DATA and receiver responds with ACK;
- after DATA and ACK is transmitted neighbor updates their scheduling tables.

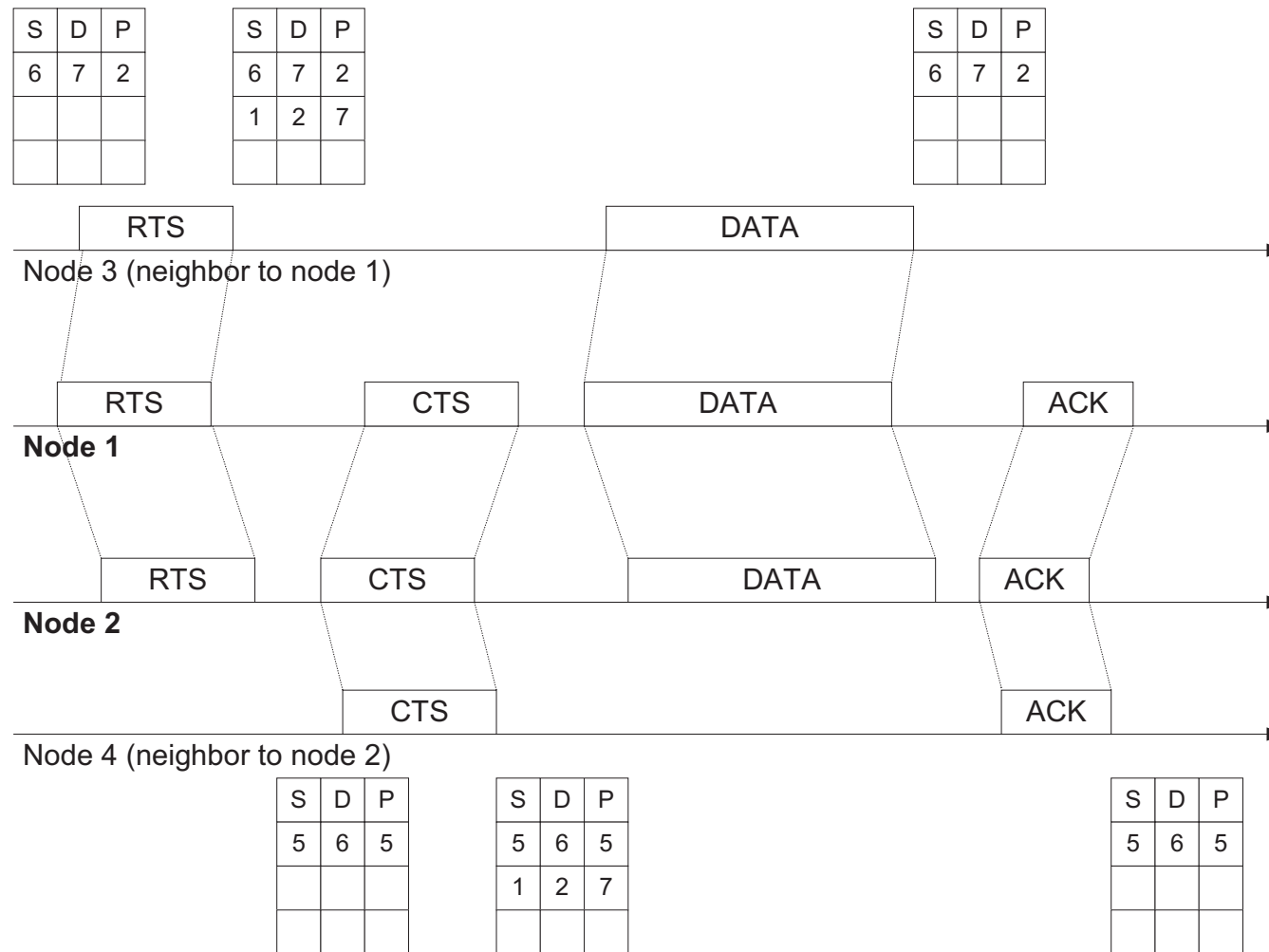


Figure 21: Packet exchange and scheduling tables update in DPS.

6.2. Distributed wireless ordering protocol (DWOP)

This protocol consists of two parts:

- MAC protocol;
- scheduling mechanism.

The scheduling mechanisms ensures that packets access medium according to:

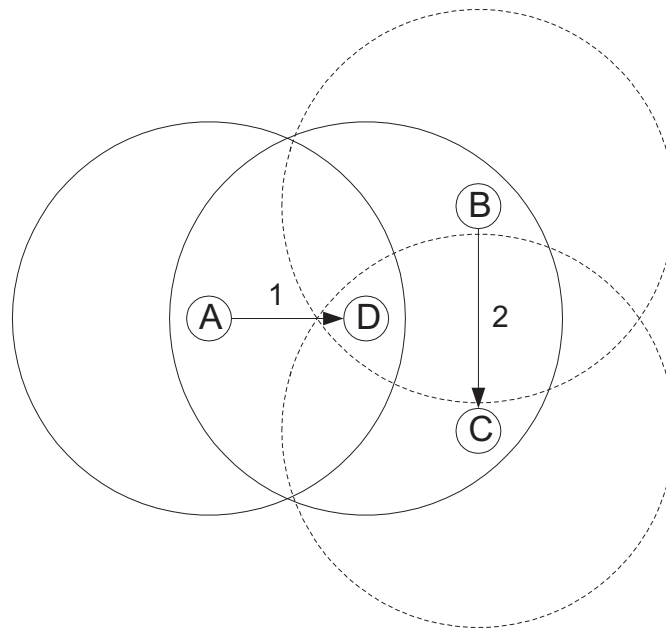
- First Come First Served (FCFS) scheduling discipline;
- virtual clock scheduling discipline;
- earliest deadline first scheduling discipline.

The basis is almost similar to DPS:

- control packets distribute information about the head-of-line packets at nodes;
- each node builds up a scheduling table;
- ST is built up according to arrival times of packets as in DPS.

The following is the major distinguished feature of DWOP is that a node:

- contends for channel only if its packet has smaller arrival time compared to all those in ST.

**Initial conditions:**

- Flow 2 has higher priority than flow 1;
- B and C are not within direct cov. of A;
- A is not aware that B has a higher priority.

Problem:

- A tries to get access;
- flow 2 receives an unfair share.

Figure 22: Asymmetry information problem in DWOP.

The **receiver participation** mechanism is used to overcome this problem:

- if the receiver finds that the sender is transmitting out of order:
 - violates the FCFS scheduling and sends the **out of order** notification in CTS/ACK packet.
- on receiving out of order notification the sender completes ongoing transmission and backs off.

Another problem: stale entries in ST:

- entry is deleted when DATA or ACK packets are received;
- if these packets get collided entry cannot be deleted.

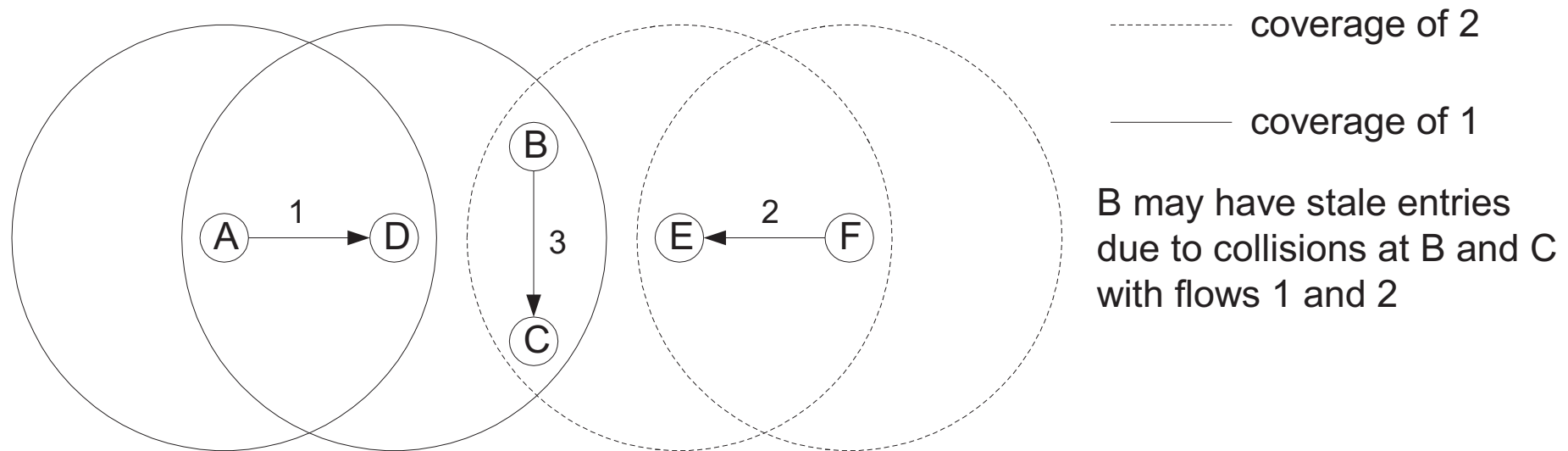


Figure 23: Problem of stale entries in ST.

Solution:

If packets with lower priority, than the node has, are transmitted it removes the oldest entry.

7. MAC protocols for directional antennas

The following advantages can be achieved using the directional antennas:

- reduced signal interference;
- increase in system throughput;
- improved channel reuse.

7.1. MACA for directional antennas

For this protocol the following assumptions are used:

- each node has only one radio transceiver;
- transceiver is equipped with M directional antennas;
- each antenna covers angle $2\pi/M$;
- transmissions by adjacent antennas never overlap;
- MAC layer is able to switch antennas individually or all antennas together.

Packet transmission is made using RTS-CTS-DATA-ACK.

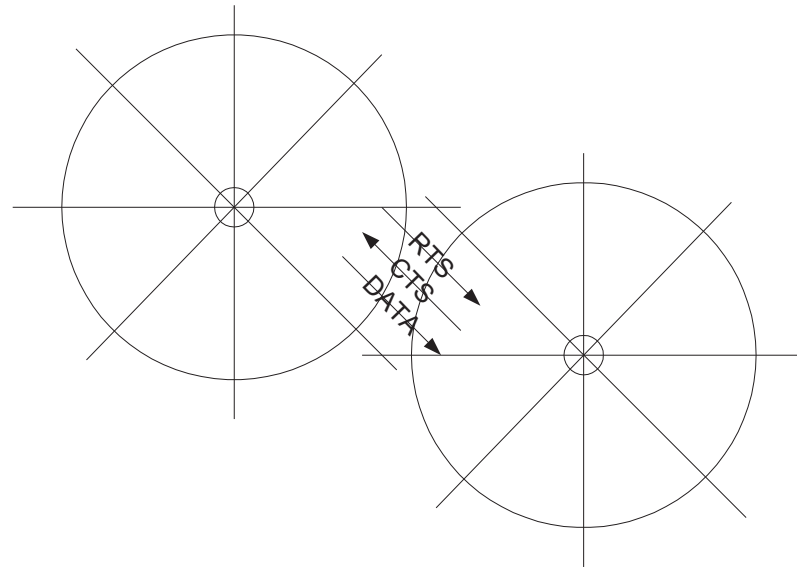


Figure 24: Packet transmission using directional antennas.

The main problem is to determine the direction of each other:

- idle node listens on all antennas;
- the sender transmits RTS using omnidirectional transmission;
- the receiver responds with CTS using omnidirectional transmission;
- both determines the antennas with the highest quality of the signal and switch them up.

7.2. Directional busy tone based MAC protocol

The major features of this protocol are as follows:

- it uses directional antenna consisting of N elements;
- for broadcast all elements are used;
- for unicast only one element is used;
- when a node is idle all elements sensing the channel;
- while receiving only one element receives the signal.

It operates as follows:

- a node senses the channel for presence of receiver busy tone (BT_r);
- if BT_t is not active, it sends RTS on all antennas elements;
- the receiver receives RTS and makes sure that BT_t is not present;
- then, the receiver transmits CTS directionally to the sender and turn on the BT_r ;
- the sender turns on the BT_t and sends the DATA packet.

7.3. Directional MAC for ad-hoc networks

There are two protocols in this group:

- DMAC-1;
- DMAC-2.

These protocols assume that node knows about its own location and location of its neighbors.

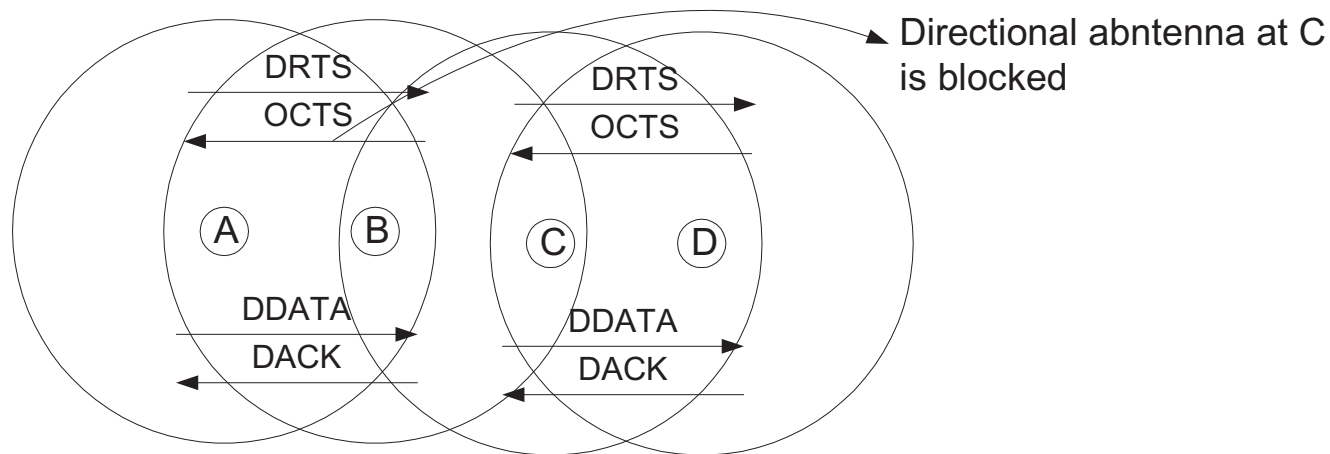


Figure 25: Operation of DMAC-1 protocol.

DMAC-1 protocol allows transmissions that are not possible using omnidirectional antennas.

DMAC-1 protocol may increase the probability of control packet collisions.

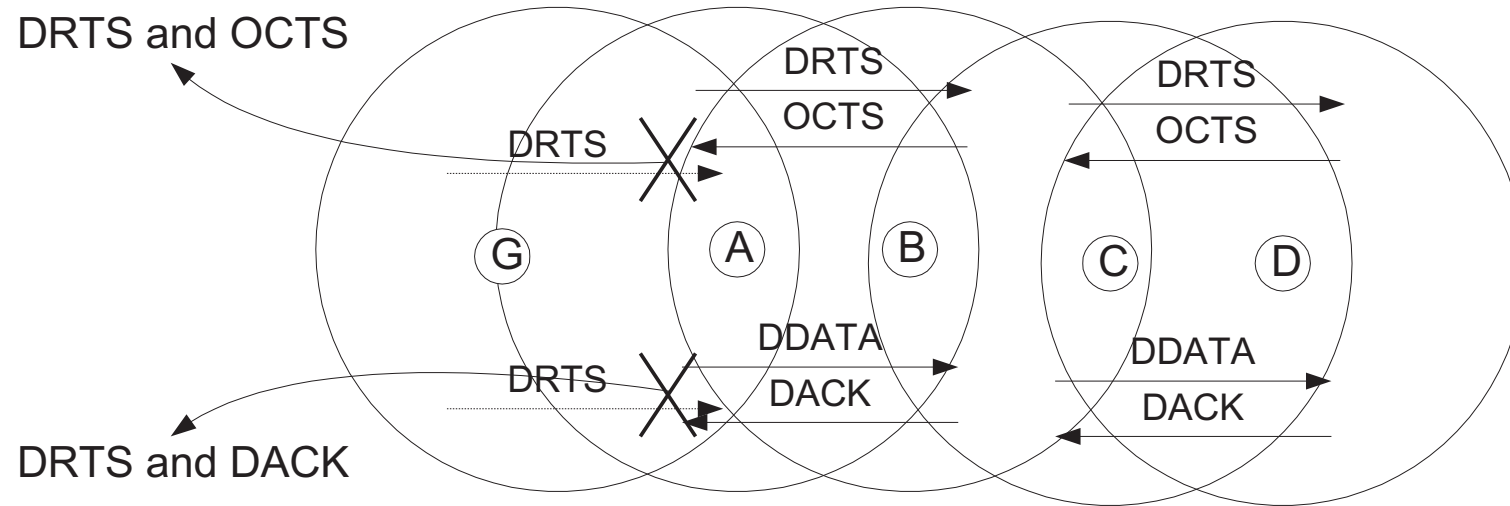


Figure 26: Problems with DRTS.

In DMAC-2 the sender may send either ORTS or DRTS based on the following:

- if none of directional antennas of the node are blocked, ORTS is sent;
- otherwise, DRTS packet is sent (if that antenna element is not blocked).

The problem in Fig. 26 is resolved e.g., node G is aware of transmission between A and B.

8. Power control MAC protocol

This protocol allows to vary a transmission range of nodes on a per-packet basis.

There are two modes of operation:

- BASIC protocol;
- PCM protocol.

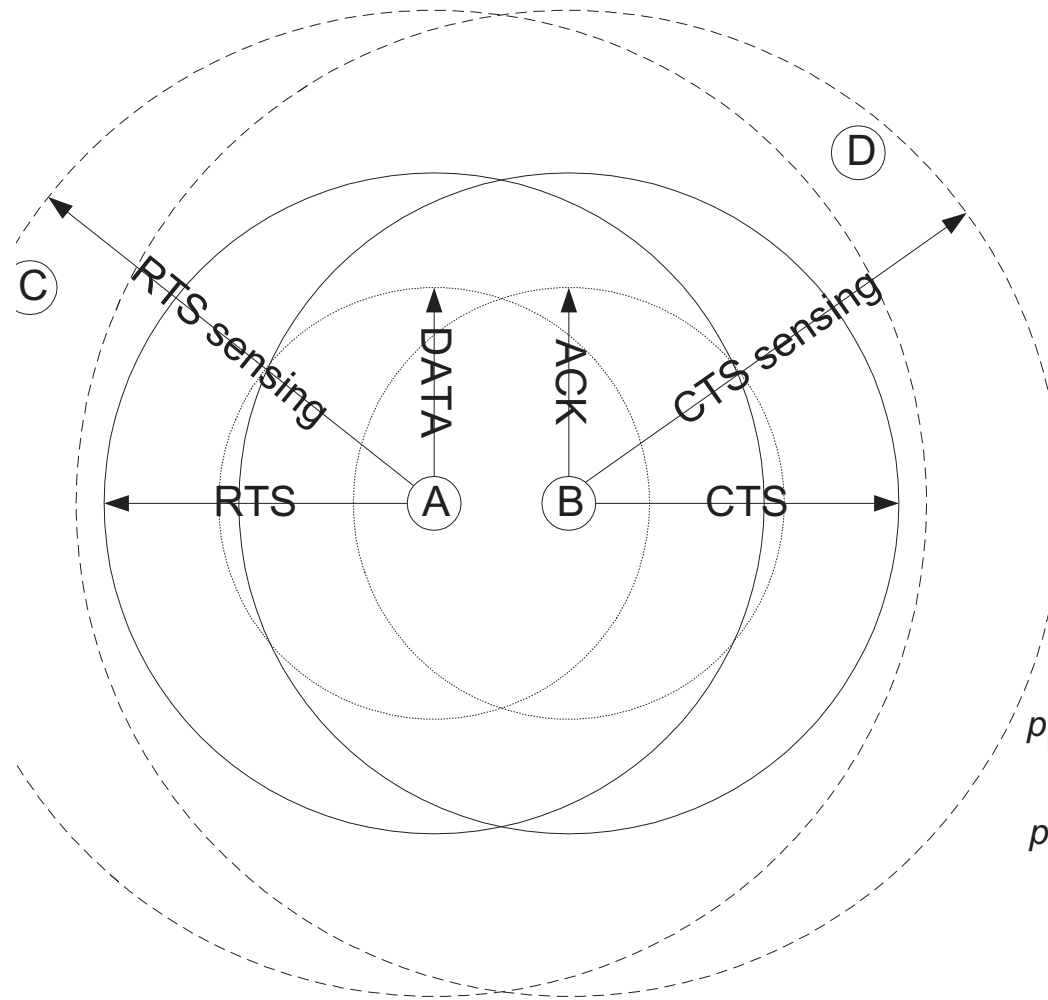
The BASIC protocol operates as follows:

- RTS and CTS packets are transmitted using the maximum power p_{\max} ;
- RTS-CTS packets are used to decide necessary transmission power for DATA and ACK packets:
 - **Method 1:** The receiver send CTS with estimated transmitted level $p_d < p_{\max}$;
 - **Method 2:** CTS is sent back using p_{\max} and the source calculates p_d based on p_{\max} :

$$p_d = \frac{p_{\max}}{p_r} Rx_{th}c, \quad (5)$$

where

- * Rx_{th} is the minimum required power and c is a constant
- * p_r is the received signal strength.



Node C sense carrier of RTS but not CTS;
Node D sense carrier of CTS but not RTS;

Both wait for extended IFS:
- C packet may collide with ACK;
- D packet may collide with DATA.

Solution: increase power to p_{\max} during
DATA packet transmission:

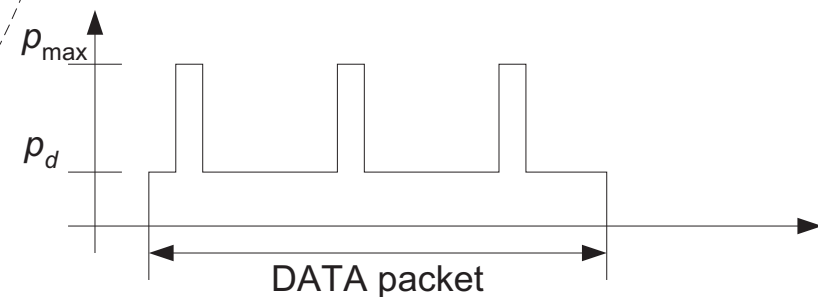


Figure 27: The major problem associated with BASIC protocol.