

# Chapter 6: MAC Protocols for Ad Hoc Wireless Networks

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# Outline

- Issues in designing a MAC protocol
- Contention-based protocols
- Contention-based protocols with reservation mechanisms
- Contention-based protocols with scheduling mechanisms
- Other protocols
- Summary

# Issues in Designing a MAC Protocol

- Bandwidth Efficiency
- QoS support
- Synchronization
- Hidden and Exposed Terminal Problems
- Error-Prone Shared Broadcast Channel
- Distributed Nature/Lack of Central Coordination
- Mobility of Nodes

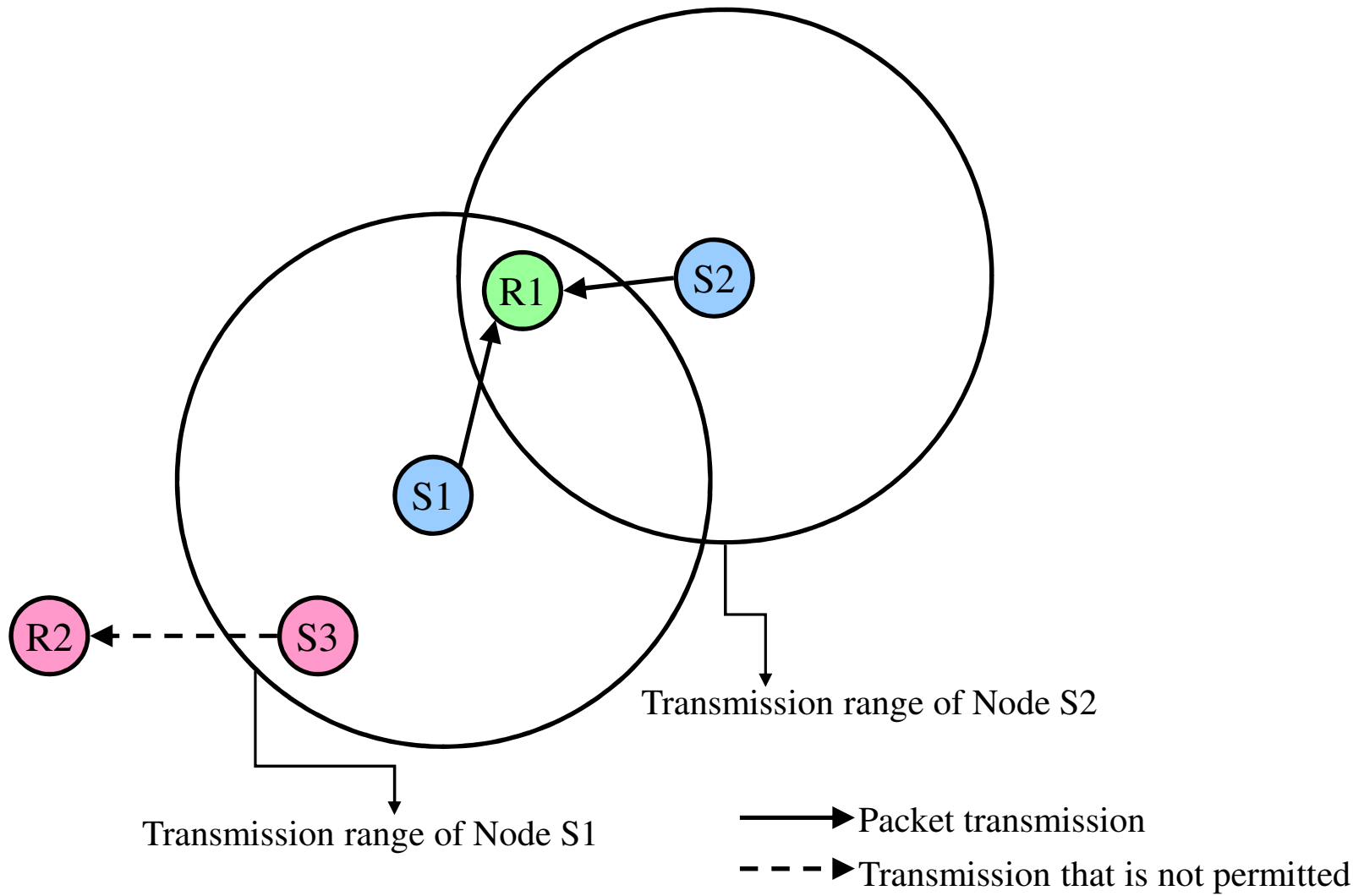


Figure 6.1 Hidden and exposed terminal problems

# Design Goals of a MAC Protocol

- Provided QoS support for real-time traffic
- Low access delay
- Bandwidth (BW) efficiently used
- Fair allocation of BW to nodes
- Low control overhead
- Scalable to large networks
- Support power control and time synchronization
- Adaptive data rate control

# Classifications of MAC Protocols

- Contention-based protocols
  - A node does not make any resource reservation a priori
  - It cannot provide QoS guarantee
- Two types of random access
  - Sender-initiated protocols
    - Single-channel sender-initiated protocols
    - Multi-channel sender-initiated protocols
  - Receiver-initiated protocols

## Classifications of MAC Protocols (cont.)

- Contention-based protocols with reservation mechanisms
  - Support real-time traffic
  - Reserve bandwidth a priori
  - Synchronous protocols
    - Global time synchronization is difficult to achieve
  - Asynchronous protocols
    - Not require global synchronization
- Contention-based protocols with scheduling
  - Packet scheduling at nodes and
  - Scheduling nodes for access to the channel

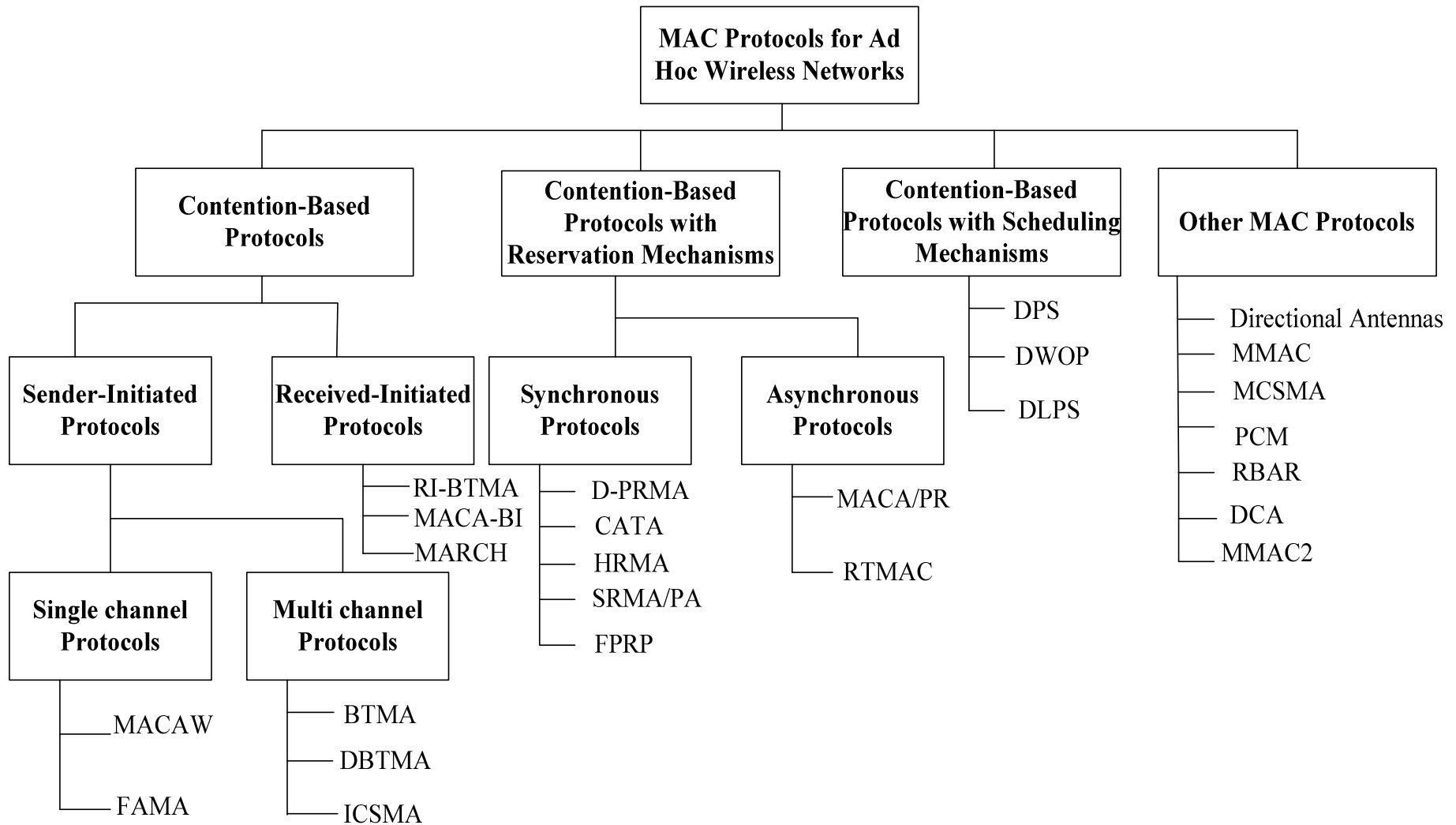


Figure 6.2: MAC protocols for ad hoc network



# Contention-Based Protocols

# MACA Protocol

- Multiple access collision avoidance protocol proposed by Karn in 1990
- MACA does not make use of carrier-sensing
- Request-to-send (RTS), clear-to-send (CTS), DATA messages
- Use binary exponential back-off (BEB) algorithm for retry
- Both the RTS and CTS packets carry the expected duration of the data packet transmission

## MACA Protocol (cont.)

- A node near the receiver (overcome hidden node problem)
  - Hearing the CTS packet, defers its transmission till the receiver receives the data packet
- A node near the sender (overcome exposed node problem)
  - A node that only hears the RTS is free to transmit simultaneously when the sender is transmitting data

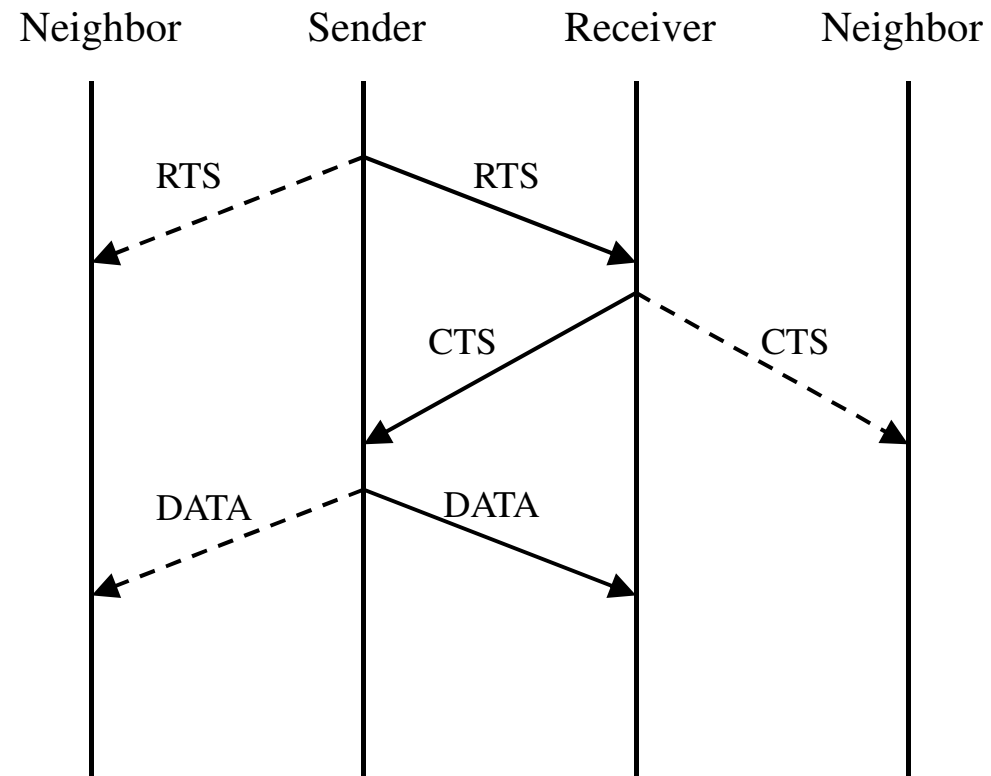


Figure 6.3 Packet transmission in MACA

# MACAW Protocol

- Back-off mechanism used in MACA starves flows (See Figure 6.4)
- Back-off algorithm has been modified by Bharghavan in 1994
  - Packet header has an additional field carrying the current back-off counter value of the transmitting node
  - A node receiving the packet copies this value into its own back-off counter

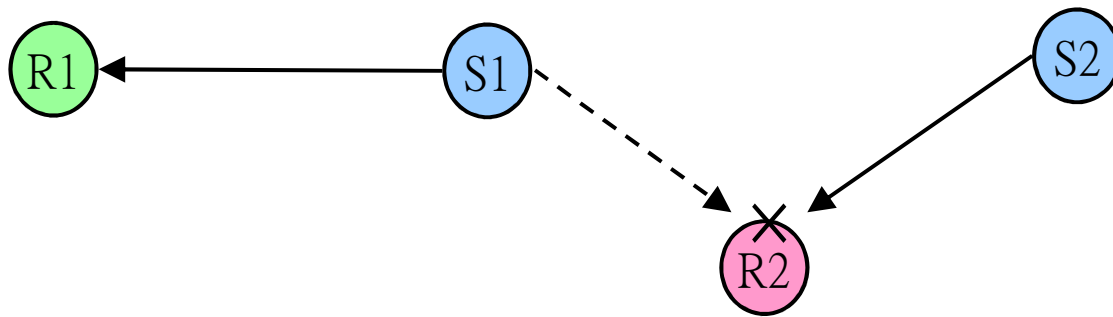


Figure 6.4 Example topology

## MACAW Protocol (cont.)

- To prevent large variations in the back-off values
  - A multiplicative increase and linear decrease (MILD) is used in MACAW
    - Collision: back-off is increased by a multiplicative factor (1.5)
    - Successful: back-off is decreased by one
- Implement per flow fairness as opposed to the per node fairness
  - Multiple queues at every node (running back-off algorithm independently)

## MACAW Protocol (cont.)

- An extra control packet ACK used in MACAW
  - If ACK is not received by sender, the sender would retry by transmitting an RTS for the same packet
  - The back-off counter is incremented
  - The receiver, instead sending back a CTS, sends an ACK for the packet received
- Exposed node problem (see Figure 6.5)
  - Before transmitting the data packet, the source node transmits the data-sending (DS) packet to ensure RTS-CTS exchange successful





Figure 6.5 Example topology

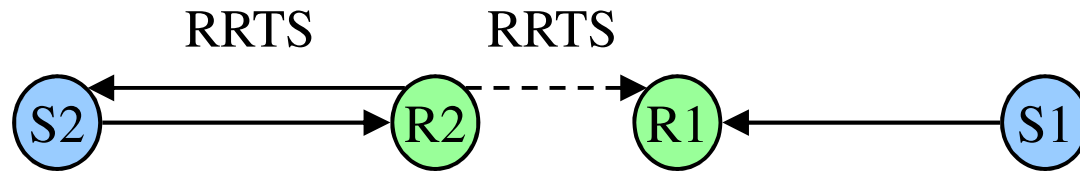


Figure 6.6 Example topology.

## MACAW Protocol (cont.)

- Another control packet: request for request to send (RRTS), See Figure 6.6
  - Synchronization information needs to be propagated to the concerned nodes
  - If a node had received an RTS previously for which it was not able to respond because there exists on-going transmission, then it waits for the next contention period and transmits RRTS
- Figure 6.7 shows the operation of the MACAW protocol
  - RTS-CTS-DS-DATA-ACK

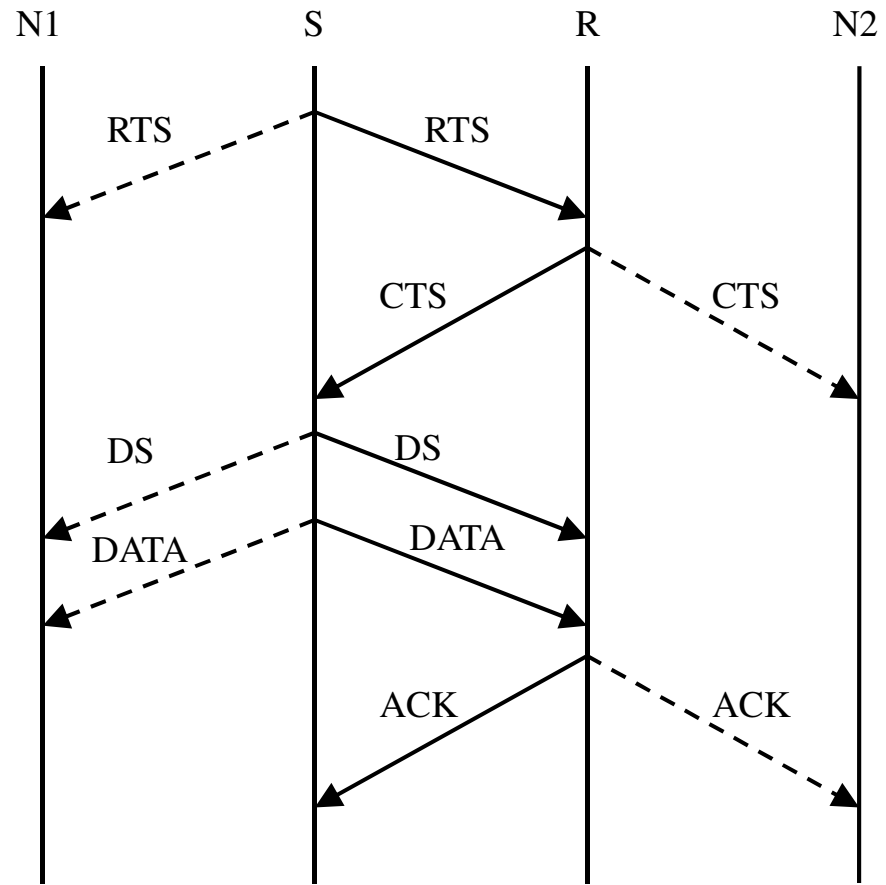


Figure 6.7 Packet exchange in MACAW.

# FAMA: Floor Acquisition Multiple Access Protocols

- Channel access consists of a carrier-sensing operation and a collision avoidance
- Carrier-sensing by the sender, followed by the RTS-CTS control packet exchange.
  - Data transmission to be collision free, the duration of an RTS must be at least twice the maximum channel propagation delay
- Two FAMA protocol variants
  - RTS-CTS exchange with no carrier sensing (**MACA**)
  - RTS-CTS exchange with non-persistent carrier sensing (FAMA-NTR)

# FAMA-NTR

- Before sending a packet, the sender senses the channel
- If channel is busy, the sender back-off a random time and retries later
- If the channel is free, the sender sends RTS and waits for a CTS packet
- If the sender cannot receive a CTS, it takes a random back-off and retries later
- If the sender receives a CTS, it can start transmission data packet
- In order to allow the sender to send a burst of packets, the receiver is made to wait a time duration  $\tau$  seconds after a packet is received

# BTMA: Busy Tone Multiple Access Protocols

- The transmission channel is split into:
  - Data packet transmissions: a data channel
  - Busy tone signal: a control channel
- When a node is ready for transmission, it senses the channel to check whether the busy tone is active
  - If not, it turns on busy tone signal and starts data transmission
  - Otherwise, it reschedules the packet for transmission after some random rescheduling delay.
- When a node is transmitting, no other node in the two-hop neighborhood of the transmitting node is permitted to simultaneously transmit (See Figure 6.8)

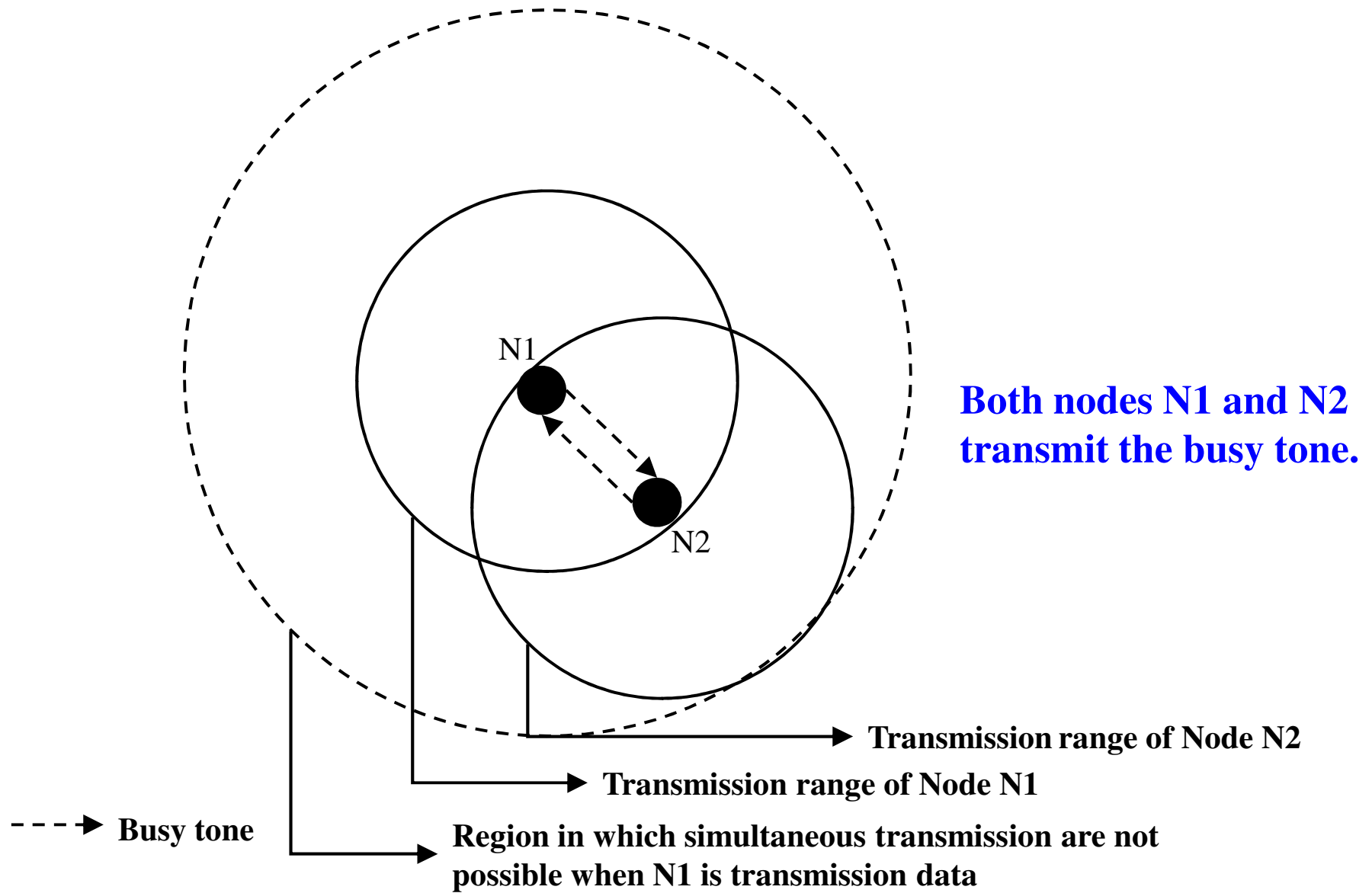


Figure 6.8 Transmission in BTMA.

# DBTMA: Dual Busy Tone Multiple Access Protocol

- The transmission channel is divided into:
  - The data channel → data packet transmission
  - The control channel → RTS, CTS, busy tones
- Use two busy tones on the control channel,  $BT_t$  and  $BT_r$ .
  - $BT_t$  : indicate that it is transmitting on the data channel
  - $BT_r$ : indicate that it is receiving on the data channel
  - Two busy tone signals are two sine waves at different frequencies



# DBTMA: Dual Busy Tone Multiple Access Protocol (cont.)

- When a node is ready to transmit a data packet (See Figure 6.9)
  - First sense the channel to determine whether the  $BT_r$  signal is active
    - No  $BT_r$  signal  $\rightarrow$  transmit RTS packet
  - On receiving the RTS packets, checks whether the  $BT_t$  tone is active
    - No  $BT_t$  signal  $\rightarrow$  Sending CTS packet and turn on the  $BT_r$  signal
  - Sender: receive CTS  $\rightarrow$  turn on  $BT_t$  signal  $\rightarrow$  start data  $\rightarrow$  turn off  $BT_t$  signal
  - Receiver: receive data  $\rightarrow$  turn off  $BT_r$  signal
- DBTMA has better network utilization than RTS/CTS based protocol (why?)

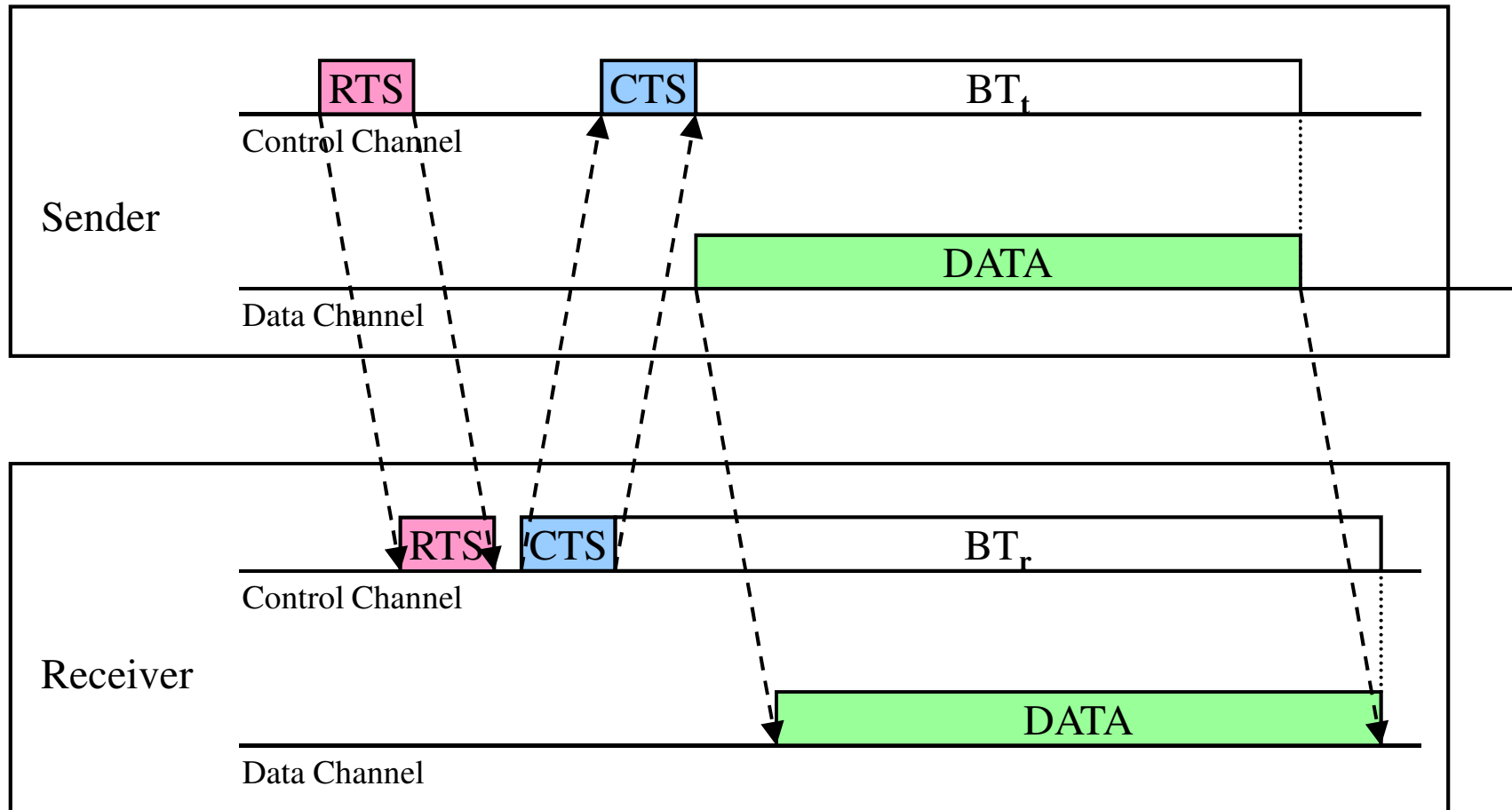


Figure 6.9 Packet transmission in DBTMA.

# RI-BTMA: Receiver-Initiated Busy Tone Multiple Access Protocol

- The available bandwidth is divided into two slotted channels:
  - The data channel → data packet transmission
    - Only if it finds the busy tone to be absent on the control channel
  - The control channel → busy tone signal
- Data packet: a preamble and the actual data packet
- The busy tone serves two purposes:
  - Ack the sender the successful of receiving preamble
  - Inform the nearby hidden nodes the impending transmission

# RI-BTMA: Receiver-Initiated Busy Tone Multiple Access Protocol (cont.)

- The operation of the RI-BTMA protocol (See Figure 6.10)
- Two types
  - the basic protocol
    - No backlog buffers  $\rightarrow$  packets that suffer collisions cannot be retransmitted
  - the controlled protocol
    - Backlogged mode  $\rightarrow$  backlog buffer is non-empty
      - Backlog buffers: transmitting a backlogged packet in the next idle slot with a probability  $q$  (why?)
    - Non-backlogged mode  $\rightarrow$  transmitting a non-backlogged packet in the next idle slot with a probability  $p$  (why?)

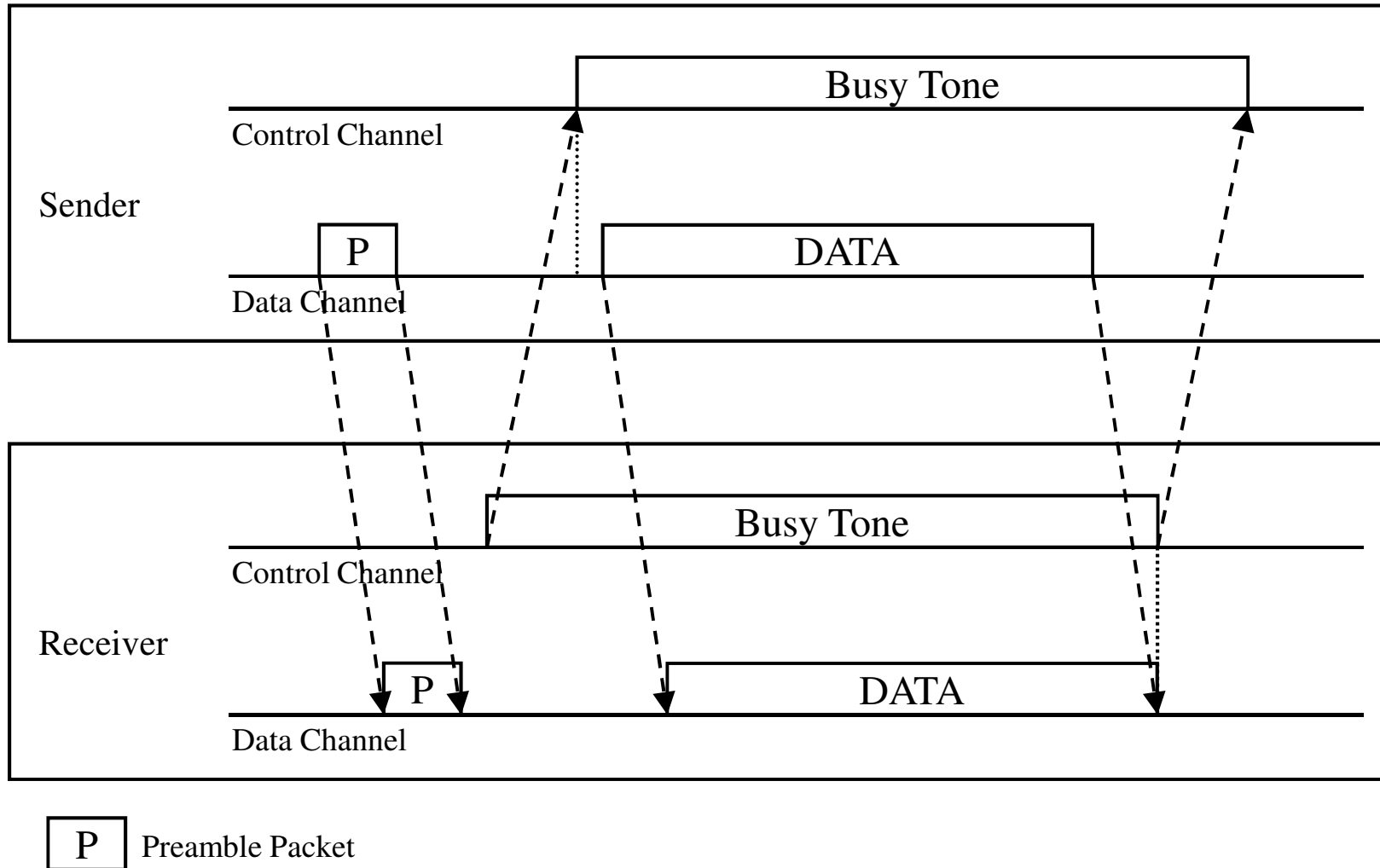


Figure 6.10 Packet transmission in RI-BTMA.

# MACA-BI: MACA-By Invitation

- MACA-BI is a receiver-initiated MAC protocol
  - Reduced the number of control packets in MACA protocol (uses three-way handshake mechanism)
- Receiver sends ready to receive (RTR) → Sender responds by sending a DATA packet (See Figure 6.11)
- The receiver needs to estimate the average arrival rate of packets
- Problems:
  - Receiver may not have an exact knowledge about the traffic rates
  - The protocol allowing the sender to declare its backlog through the RTS control packet, if an RTR packet is not arrived within a given timeout
  - Hidden terminal problem is overcome in MACA-BI
  - However, the hidden terminal problem still affects the control packet transmission
    - RTR packets can collide with DATA packets (See Figure 6.12)

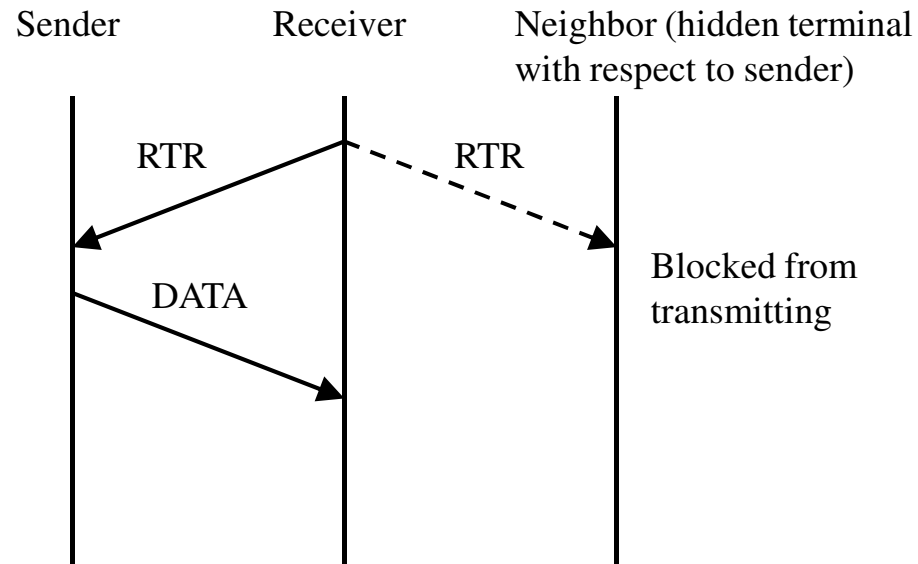
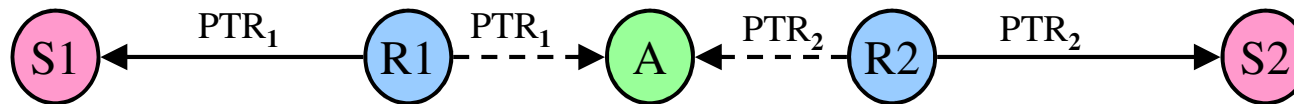


Figure 6.11 Packet transmission in MACA-BI



S1, S2 — Sender nodes

R1, R2 — Receiver nodes

A — Neighbor node

Figure 6.12 Hidden terminal problem in MACA-BI

# MARCH: Media Access with Reduced Handshake

- MARCH does not require any traffic prediction mechanism
- The RTS packet is used only for the first packet of the stream
  - MACA:  $RTS \rightarrow CTS \rightarrow DATA \rightarrow RTS \rightarrow CTS \rightarrow \dots$
  - MARCH:  $RTS \rightarrow CTS_1 \rightarrow DATA \rightarrow CTS_2 \rightarrow DATA \rightarrow \dots$  (See Figure 6.13)
- The CTS packet: MAC address of the sender, receiver, and the route identification number ( $RT_{id}$ ) (See Figure 6.14)
- The  $RT_{id}$  is used to avoid misinterpretation of CTS packets and initiation of false CTS-only handshake
- For example, when node  $Y$  received a CTS with  $RT_{id} = \text{route } 1$ , it does not respond (See Fig. 6.14)
- The throughput of MARCH is significantly high when compared to MACA, while the control overhead is much less



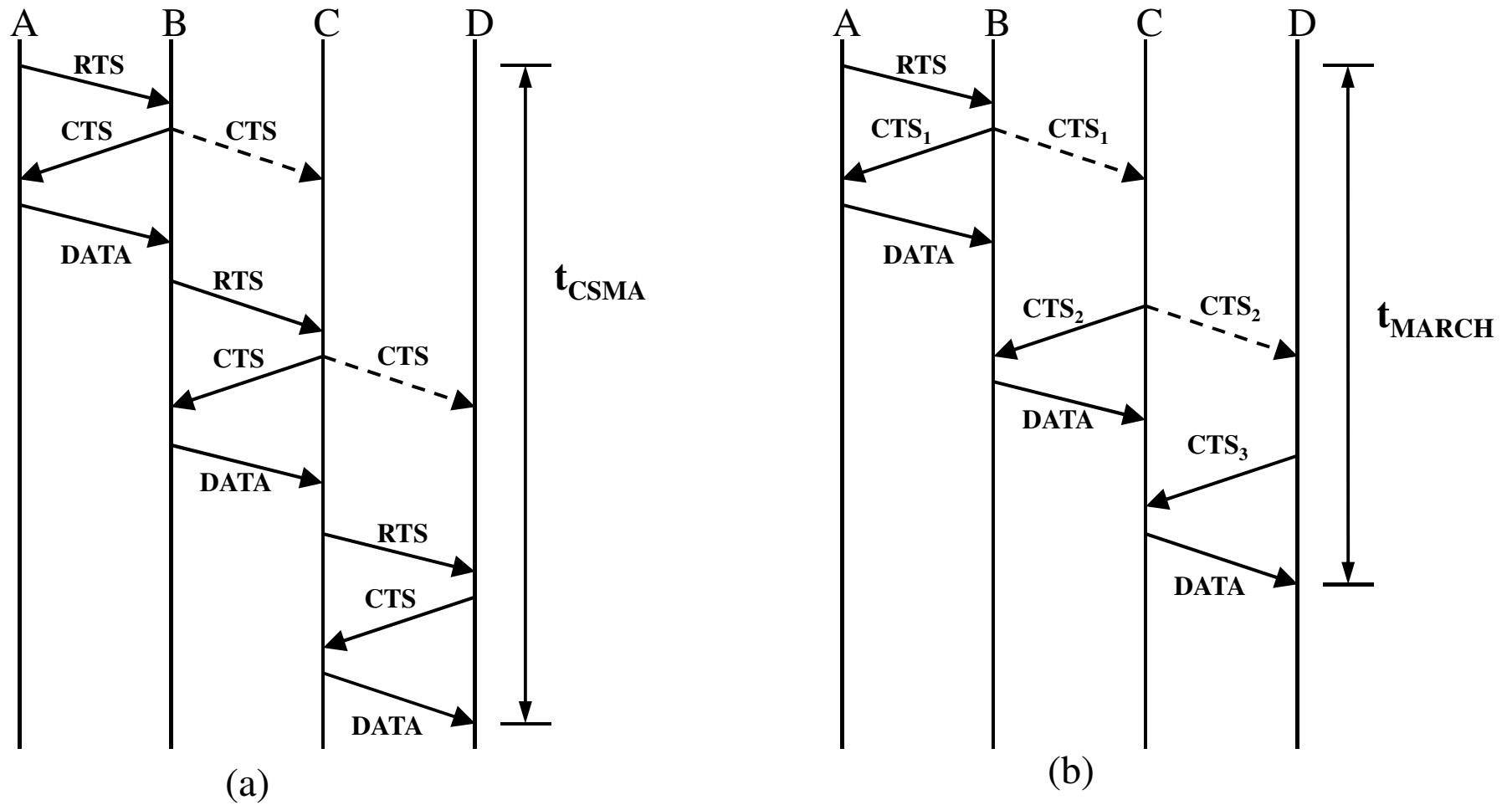


Figure 6.13 Handshake mechanism in (a) MACA and (b) MARCH

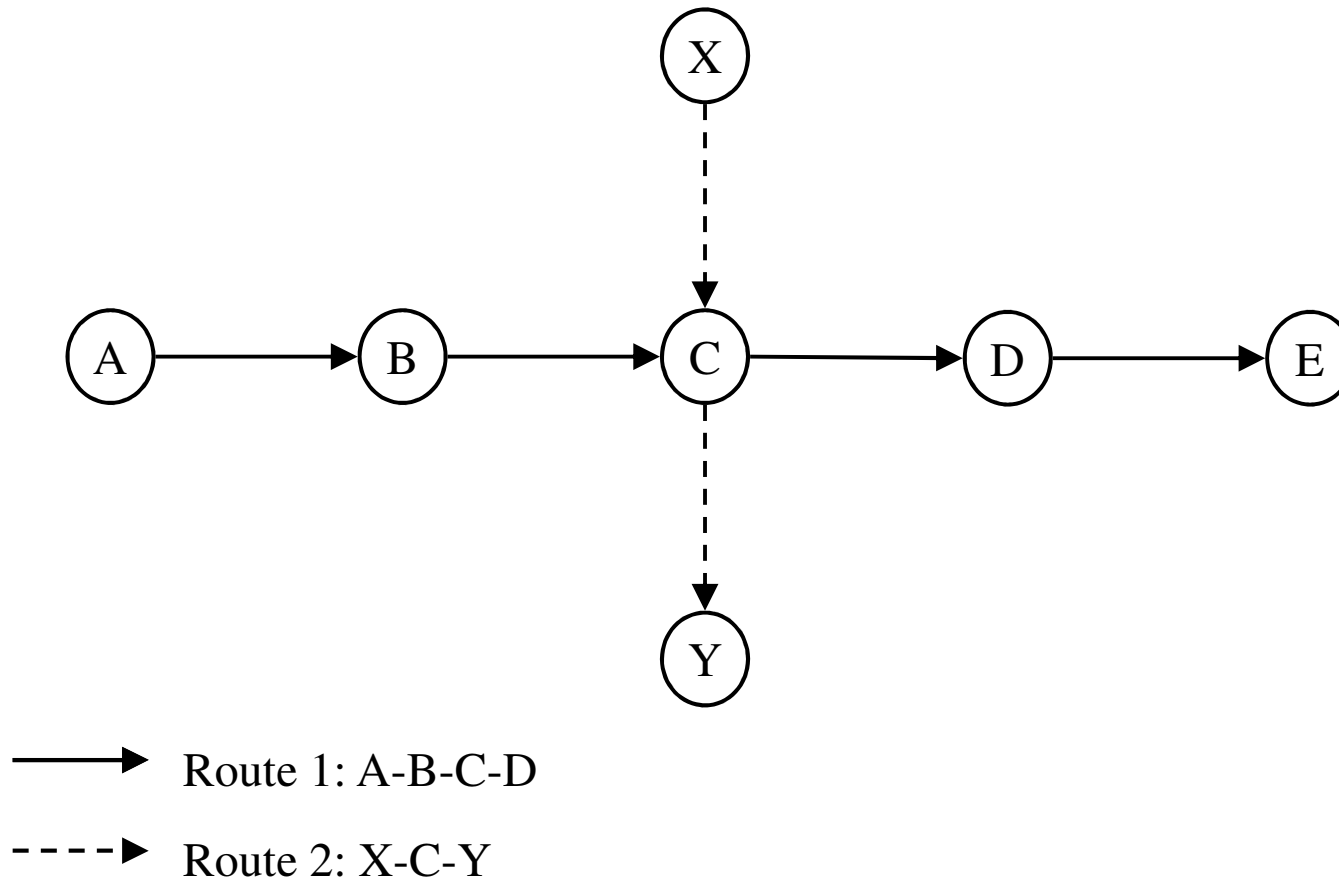


Figure 6.14 Example Topology

# Contention-Based Protocols with Reservation Mechanisms

# D-PRMA: Distributed Packet Reservation Multiple Access Protocol

- The channel is divided into fixed and equal sized frames along the time axis. (See Figure 6.15)
- The RTS/BI and CTS/BI are used for slot reservation and for overcoming the hidden terminal problem
- If a terminal wins the contention through mini-slot 1, the extra  $(m - 1)$  mini-slots of this slot will be granted to the terminal as the payload
  - For voice node, the same slot in each subsequent frame can be reserved until the end of its packet transmission
- In the other cases, the extra  $(m - 1)$  mini-slots are continuously used for contention, and the winner of this contention will be granted the reservation of the same slot

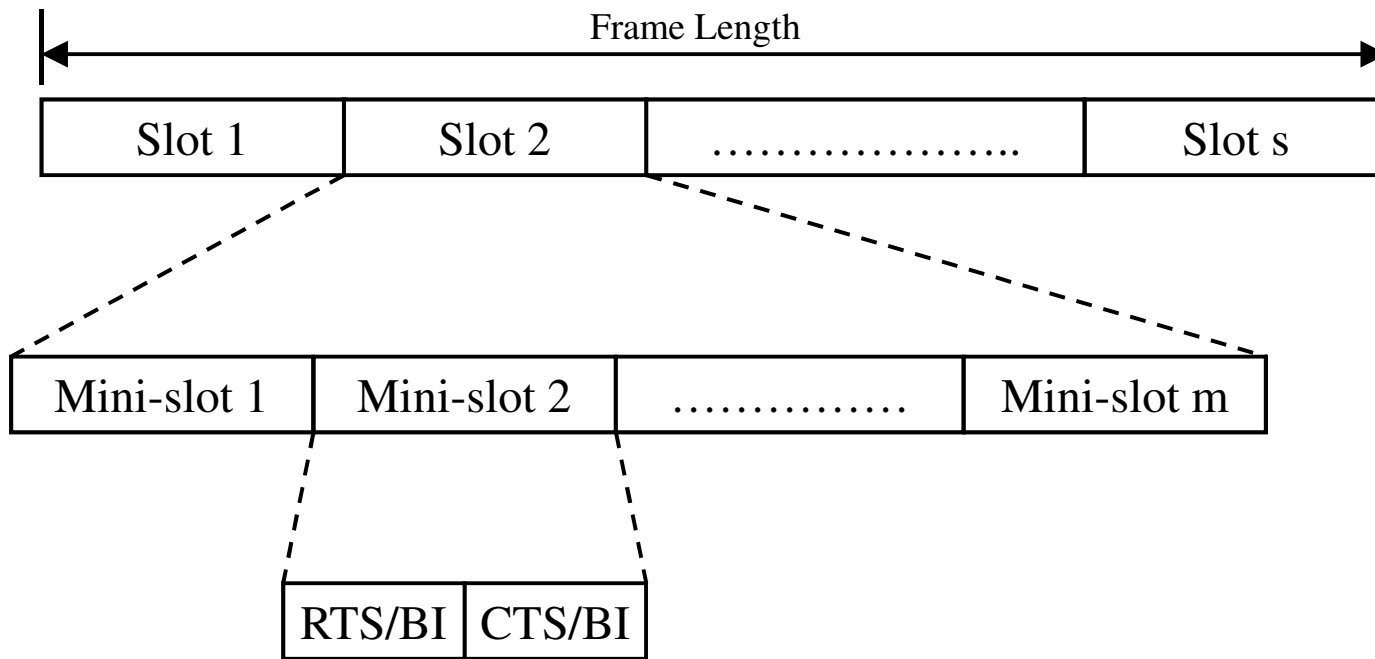


Figure 6.15 Frame structure in D-PRMA

# D-PRMA (cont.)

- To prioritize voice terminals over data terminals
  - Voice terminals starts contenting from mini-slot 1 with probability  $p = 1$  while data terminals can start such content with  $p < 1$
  - Both voice and data terminals can content through the extra  $(m - 1)$  mini-slots with probability  $p < 1$
  - Only the winner of a voice terminal can reserve the same slot in each subsequent frame until the end of packet transmission while the winner of a data terminal can only use one slot
- Problems:
  - When a terminal wins the contention in mini-slot 1, how to prevent other terminals in the same slot for contention ? **(Use RTS/CTS)**
  - How to prevent a terminal from contending for a reserved slot in each subsequent slot ? (Transmit a busy indication (BI) signal RTS/BI (receiver) **(why?)** and CTS/BI (sender) in mini-slot 1)

# CATA: Collision Avoidance Time Allocation Protocol

- Support broadcast, unicast, and multicast transmissions simultaneously
- Each frame consists of  $S$  slots and each slot is further divided into five mini-slots
  - CMS1: Slot Reservation (SR)
  - CMS2: RTS
  - CMS3: CTS
  - CMS4: not to send (NTS)
  - DMS: Data transmission

# CATA (cont.)

- Each node receives data during the DMS of current slot transmits an SR in CMS1
- Every node that transmits data during the DMS of current slot transmits an RTS in CMS2
- CMS3 and CMS4 are used as follows:
  - The sender of an intend reservation, if it senses the channel is idle in CMS1, transmits an RTS in CMS2
  - Then the receiver transmits a CTS in CMS3
  - If the reservation was successful the data can transmit in current slot and the same slot in subsequent frames
  - Once the reservation was successfully, in the next slot both the sender and receiver do not transmit anything during CMS3 and during CMS4 the sender transmits a NTS



# CATA (cont.)

- If a node receives an RTS for broadcast or multicast during CMS2 or it finds the channel to be free during CMS2, it remains idle during CMS3 and CMS4
- Otherwise it sends a NTS packet during CMS4
- A potential multicast or broadcast source node that receives the NTS packet or detecting noise during CMS4, understands that its reservation is failed
- If it find the channel is free in CMS4, which implies its reservation was successful
- CATA works well with simple single-channel half-duplex radios

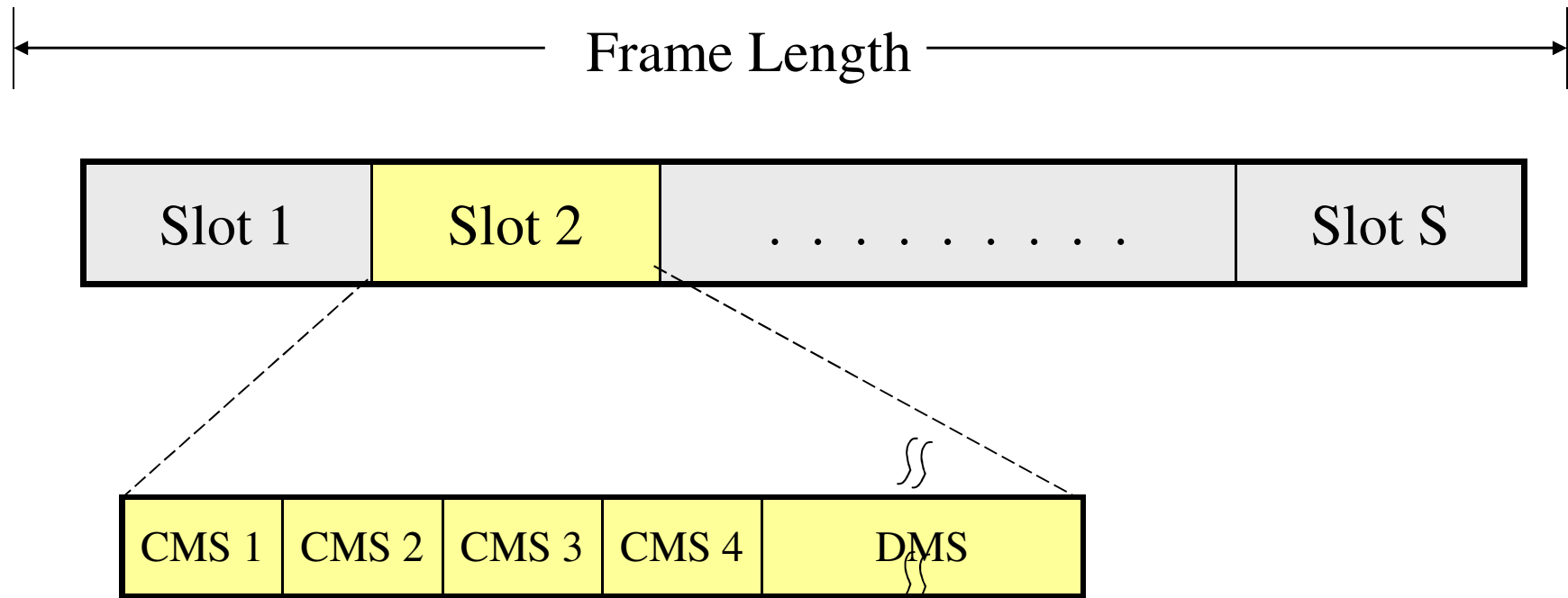


Figure 6.16. Frame format in CATA.

# HRMA: Hop Reservation Multiple Access Protocol

- HRMA is a multi-channel MAC protocol, based on half-duplex very slow frequency hopping spread spectrum (FHSS) radios
- Each time slot is assigned a separate frequency <sup>$M = \lfloor \frac{(L-1)}{2} \rfloor$</sup>  channel (See Figure 6.17)
- Assumptions
  - $L$ : frequency channels
  - $f_0$ : dedicated synchronized channel frequency
  - The remaining  $L - 1$  frequencies are divided into frequency pairs denoted by

$$(f_i, f_i^*), i = 1, 2, 3, \dots, M$$

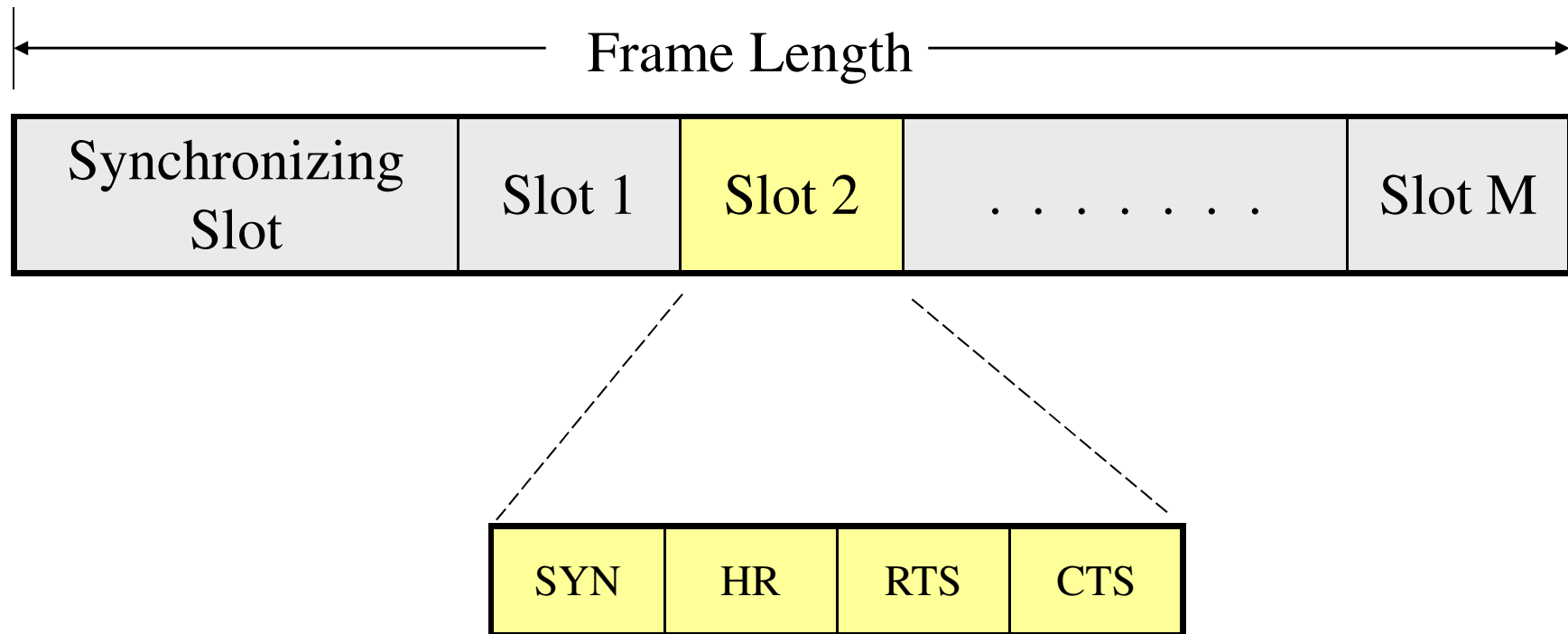
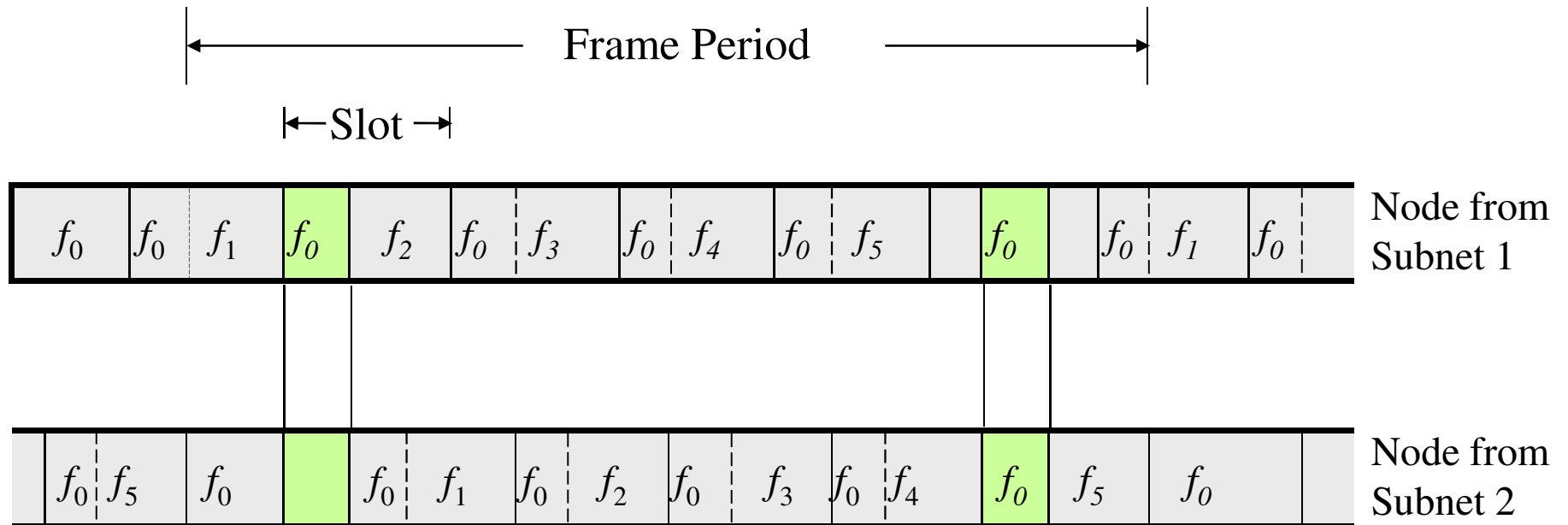


Figure 6.17. Frame format in HRMA .

## HRMA (cont.)

- Hop reservation (HR), RTS, CTS, DATA :  $f_i$
- ACK:  $f_i^*$
- All idle nodes hop to the synchronizing frequency  $f_0$  and exchange synchronization information
- Synchronizing slot: used to identify the beginning of a frequency hop and the frequency to be used in the immediately following hop
- Any two nodes from two disconnected networks have at least two overlapping time period of length  $\mu_s$  on the frequency  $f_0$  (See Figure 6.18)

If  $\mu$  is the length of each slot and  $\mu_s$  is the length of the synchronization period on each slot, then the dwell time of  $f_0$  is  $\mu + \mu_s$



$f_0$  synchronizing frequency

$M = 5$

Figure 6.18. Merging of subnets.

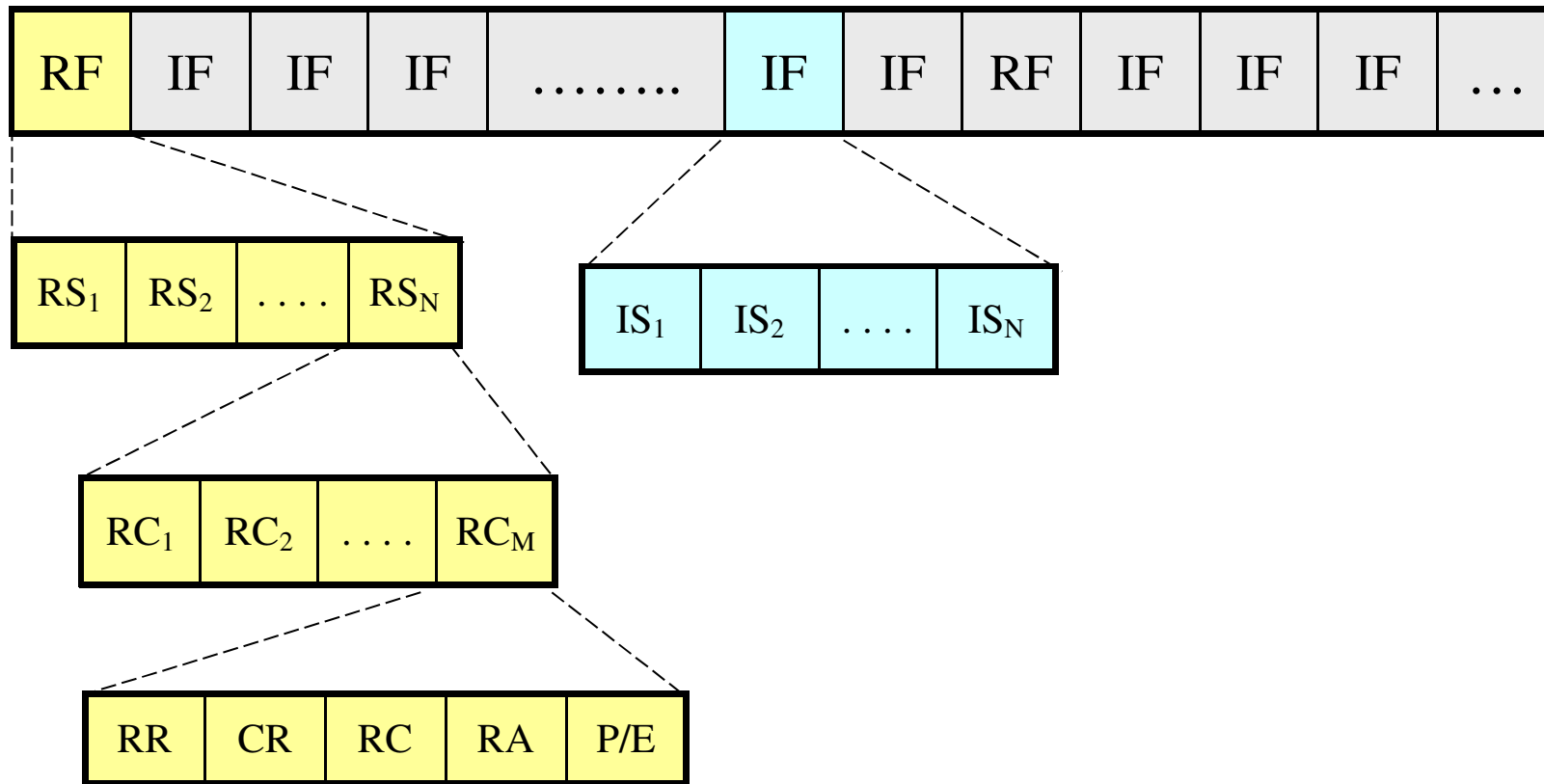
# HRMA (cont.)

- A node ready to transmit data, it senses the HR period of the current slot
  - If the channel is idle during HR period, it transmits an RTS during RTS period and waits for CTS during CTS period
  - If the channel is busy during HR period, it backs off for a randomly multiple slots
- Suppose the sender needs to transmits data across multiple frames, it informs the receiver through the header of the data packet
  - The receiver node transmits an HR packet during the HR period of the same slot in next frame to informs its neighbors
  - The sender receiving the HR packet, it sends an RTS during the RTS period and jams other RTS packets
  - Both the sender and receiver remain silent during the CTS period

# FPRP: Five-Phase Reservation Protocol

- FPRP is a single-channel TDMA-based broadcast scheduling protocol:
  - need global time synchronization
  - fully distributed and scalable
  - reservation process is localized; it involves only two-hop neighbors
  - No hidden terminal problem
- Time is divided into frames: reservation frame (RF) and information frame (IF) (see Figure 6.21)
  - Each RF has  $N$  reservation slots (RS) and each IF has  $N$  information slots (IS)
  - Each RS is composed of  $M$  reservation cycles (RCs)
  - With each RC, a five-phase dialog takes place
- Corresponding to IS, each node would be in one of the following three states: transmit (T), receive (R), and blocked (B)





Five-phase reservation dialog

Figure 6.21. Frame structure in FPRP.

# FPRP: Five-Phase Reservation Protocol (cont.)

- Five-phase protocol:
  - **Reservation request:** send reservation request (RR) packet to dest.
  - **Collision report:** if a collision is detected by any node, that node broadcasts a CR packet
  - **Reservation confirmation:** a source node won the contention will send a RC packet to destination node if it does not receive any CR message in the previous phase
  - **Reservation acknowledgment:** destination node acknowledge reception of RC by sending back RA message to source
  - **Packing and elimination:** use packing packet and elimination packet
- An example is shown in Figure 6.22

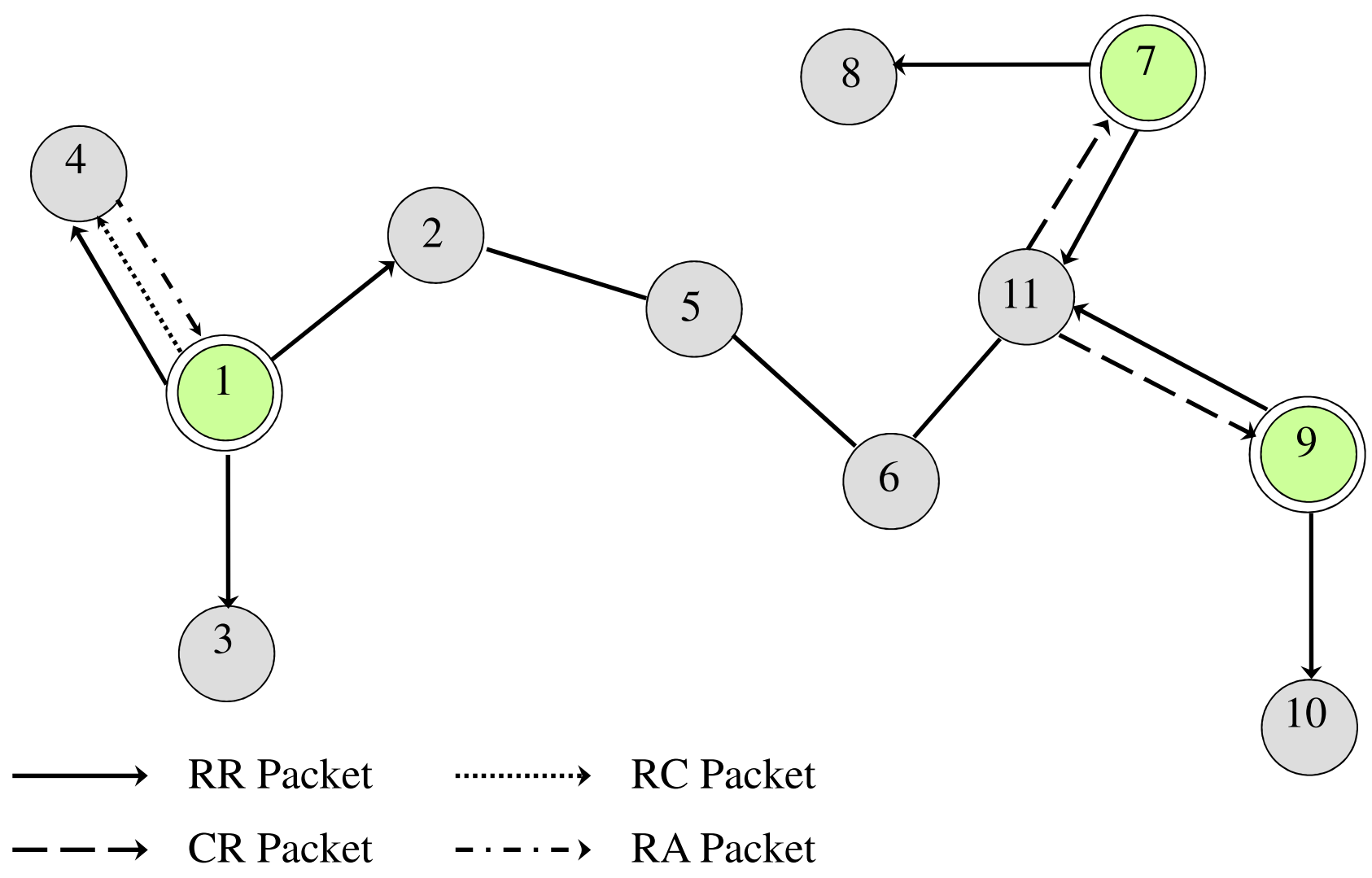


Figure 6.22. FPRP - Example.

# MACA/PR: MACA with Piggy-Backed Reservation

- MACA/PR is used to provide real time traffic support
- The main components: a MAC protocol (MACAW + non persistent CSMA), a reservation protocol, and a QoS routing protocol
- Each node maintains a reservation table (RT) that records all the reserved transmit and receive slots/windows of all nodes
- Non-real time packet: wait for a free slot in the RT + random time → RTS → CTS → DATA → ACK

# MACA/PR: MACA with Piggy-Backed Reservation (cont.)

- Real time packet:
  - Transmit real time packets at certain regular intervals (say CYCLE)
  - RTS → CTS → DATA (carry reservation info for next data) → ACK → ... → DATA (carry reservation info) → ACK
    - Hear DATA and ACK: update their reservation table
  - The ACK packet serves to renew the reservation, in addition to recovering from the packet loss
    - Reservation fail: fail to receive ACK packets for a certain number of DATA packets

# MACA/PR: MACA with Piggy-Backed Reservation (cont.)

- For maintaining consistent information regarding free slots
  - Periodic exchange of reservation tables
- Best effort and real time packet transmissions can be interleaved at nodes
- When a new node joins: receive reservation tables from each of its neighbors and learns about the reservations made in the network
- QoS Routing protocol: DSDV (destination sequenced distance vector)
- MACA/PR does not require global synchronization among nodes
- Drawback: possibility of many fragmented free slots not being used at all

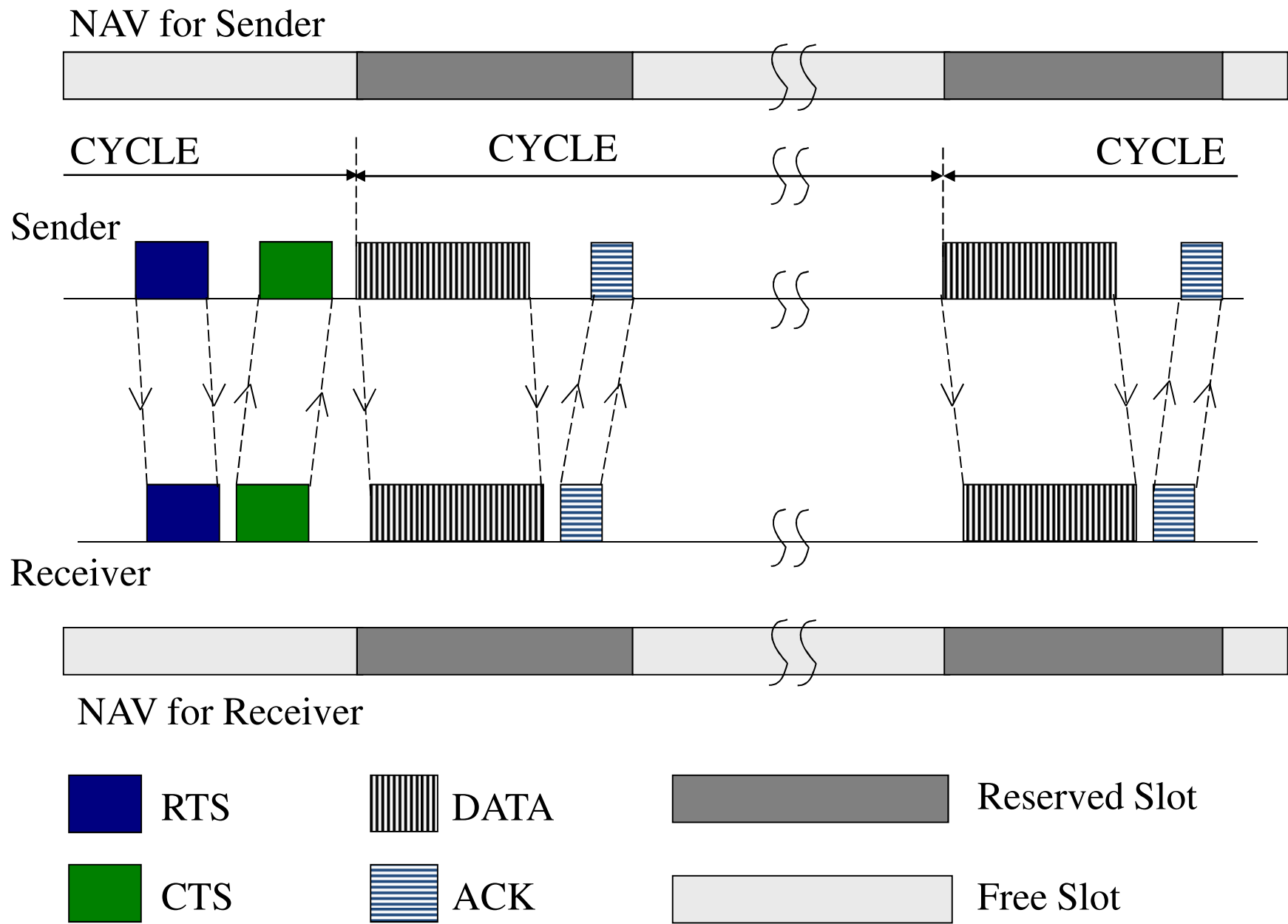


Figure 6.23. Packet transmission in MACA / PR.

# RTMAC: Real Time Medium Access Control Protocol

- The two components: MAC protocol and QoS routing protocol
- QoS routing: for end to end reservation + release of bandwidth
- MAC: medium access for best effort + reservation for real time
- Control packets
  - Real time : ResvRTS, ResvCTS, and ResvACK, half of DIFS
  - Best effort: RTS, CTS, and ACK
- The duration of each resv-slot is twice the maximum propagation delay
  - Transmit real time packets first reserves a set of resv-slots
  - The set of resv-slots for a connection is called a connection-slot
- The superframe for each node may not strictly align with the other nodes (use relative time for all reservation)



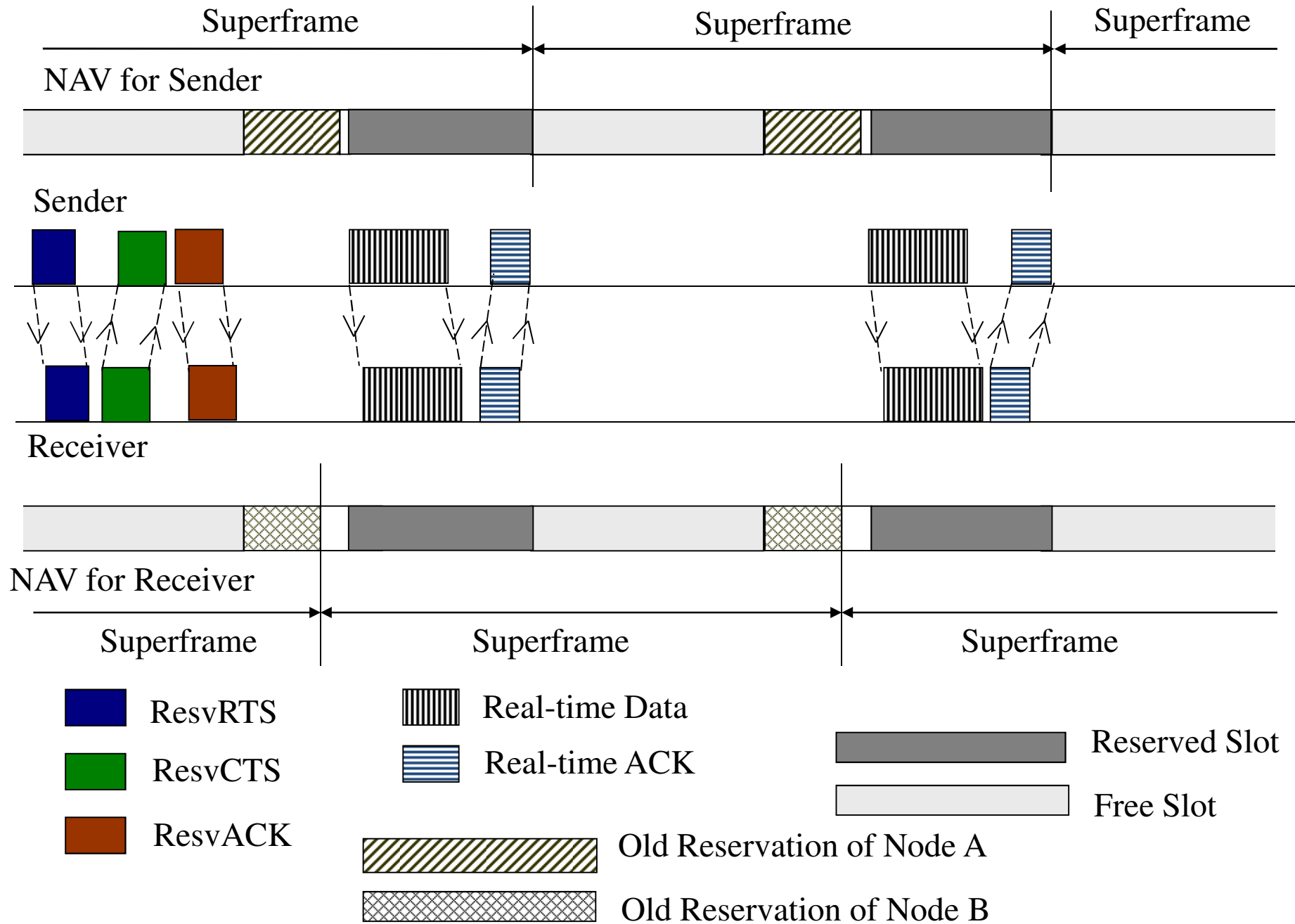
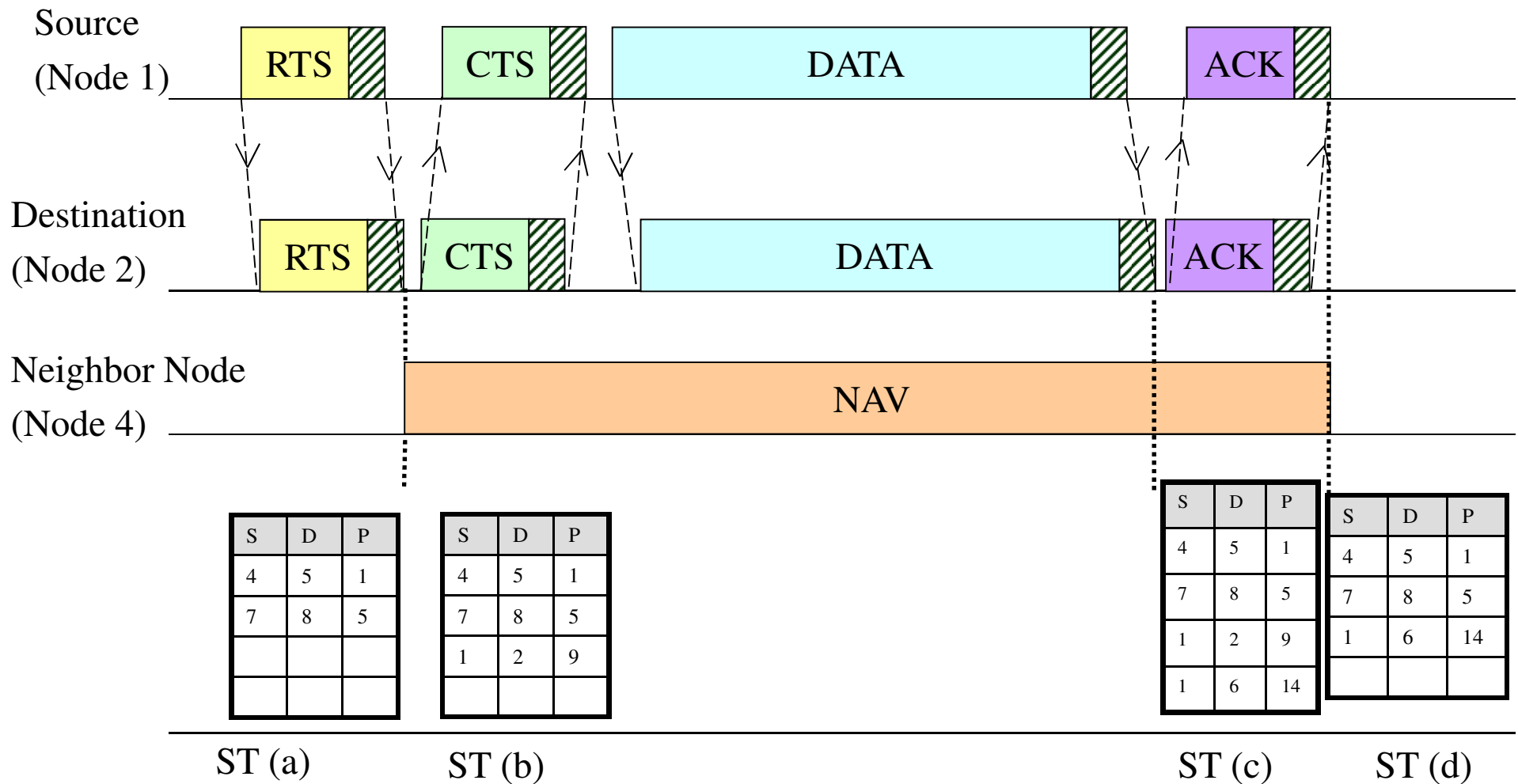


Figure 6.24. Reservation mechanism in RTMAC.

# Contention-Based MAC Protocols with Scheduling Mechanisms

# DPS: Distributed Priority Scheduling and MAC in Ad Hoc Networks

- Provide differentiated QoS levels to different wireless applications in ad hoc networks
- Achievable by QoS-sensitive MAC and network layer scheduling
- Distributed scheduling problem with local information
- Basic mechanisms:
  - Piggyback information
  - Head-of-line (HoL) packet as the packet with the highest priority (lowest index)
  - RTS, CTS : carry current packet info
  - DATA, ACK: carry next head-of-line info



Scheduling Table Updates at Neighbor Node 4

S – Source Id      D – Destination Id      P – Priority Index

 Piggy-backed priority information

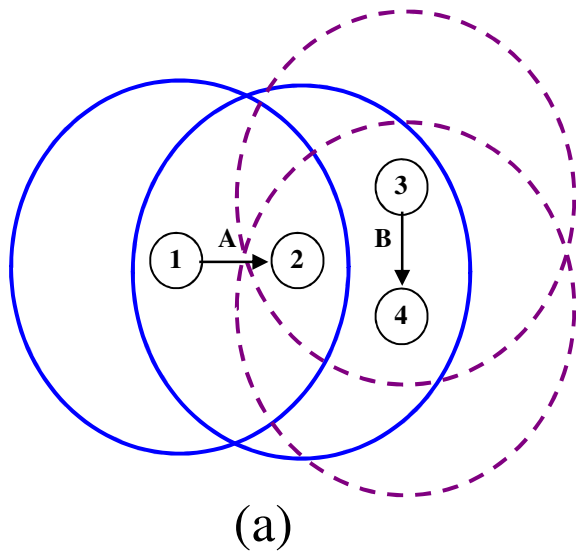
Figure 6.25. Piggy-backing and scheduling table update mechanism in DPS. 60

# Distributed Wireless Ordering Protocol (DWOP)

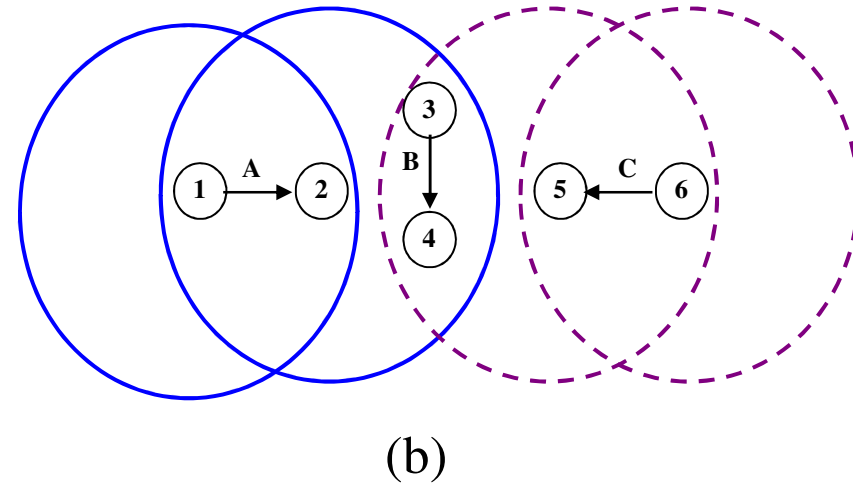
- DWOP based on the DSP, ensure that packet access the medium according to the order specified by an ideal reference schedule such as FIFO
- Each node builds up a scheduling table (ST) ordered according to the overheard arrival times
- A node is made eligible to contend for the channel only if its locally queued packet has a smaller arrival time compared to all other arrival times in its ST
- Scheduling problems: Information asymmetry and Perceived collisions

# Distributed Wireless Ordering Protocol (DWOP)

- Information asymmetry: a transmitting node might not be aware of the arrival times of packets queued at another node which is not within its transmission range
  - Solution: a receiver find that the sender is transmitting out of order, an out-of-order notification is piggy-backed by the receiver on the control packet (CTS/ACK)
- Perceived collisions: the ACK packet collides at the node, the corresponding entry in the ST will never be removed
  - Solution: when a node observes that its rank remains fixed while packets whose PR are below the priority of its packet are being transmitted, it deletes the oldest entry from its ST



— Coverage region of flow A  
 - - - Coverage region of flow B



— Coverage region of flow A  
 - - - Coverage region of flow C

Figure 6.26 (a) Information asymmetry.

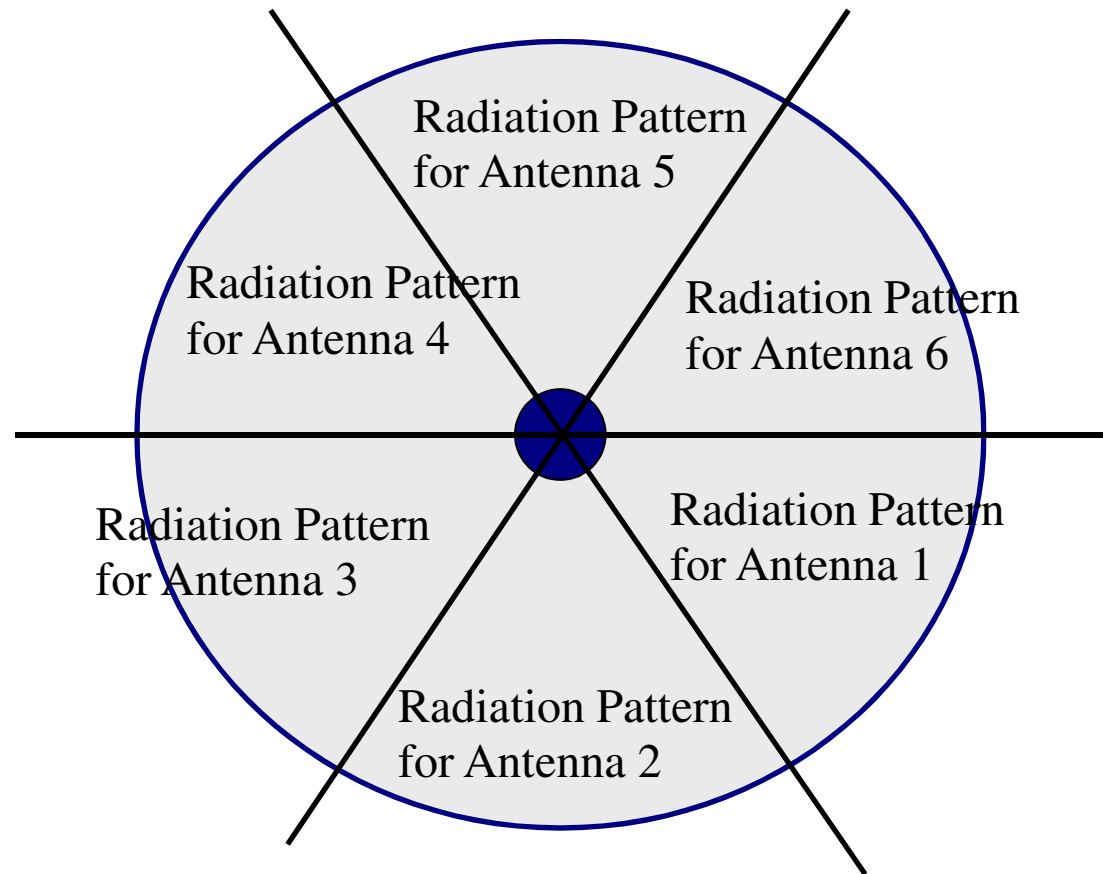
(b) Perceived collisions.

# MAC Protocols with Directional Antennas



# MAC Protocol Using Directional Antennas

- Advantages
  - Reduced signal interference, increase system throughput, and improved channel reuse
- Assumptions
  - Only one radio transceiver can transmit and receive only one packet at any given time
  - $M$  directional antennas, each antennas having a conical radiation pattern, spanning an angle of  $2\pi/M$  radians (See Figure 6.28)
  - Adjacent antennas never overlap
- If a node transmits when all its antennas are active, then the transmission's radiation pattern is similar to that of an omnidirectional antennas
- Packet transmission--See Figure 6.29



Node with 6 antennas ( $M = 6$ )

Figure 6.28. Radiation patterns of directional antennas.

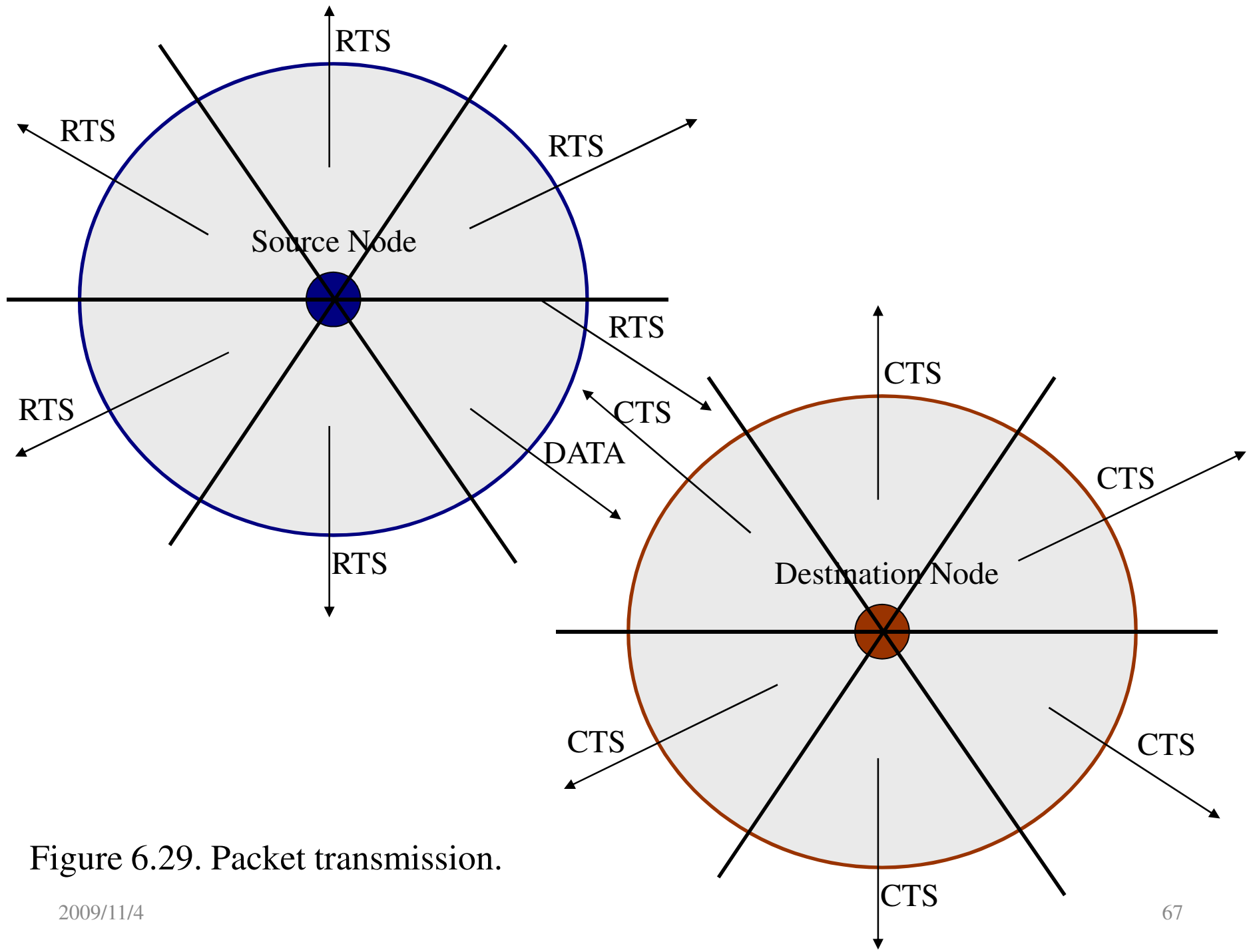


Figure 6.29. Packet transmission.

# DBTMA: Directional Busy Tone-Based MAC Protocol

- Adapt the DBTMA protocol for use with directional antennas.
- Directional Antenna
  - $N$  antenna elements, a sector =  $360/N$
  - Unicast: only a single antenna element
  - Broadcast: all the antenna elements
- Protocol: a) sender transmits RTS in all directions, b) receiver sends back CTS to the sender with the direction of maximum power and turns on the  $BT_r$  in the direction to the sender, c) sender turns on the  $BT_t$  in the direction of receiver and transmits data packet (See Figure 6.30 b)
- This protocol is not guaranteed to be collision free (see Fig. 6.31 b)

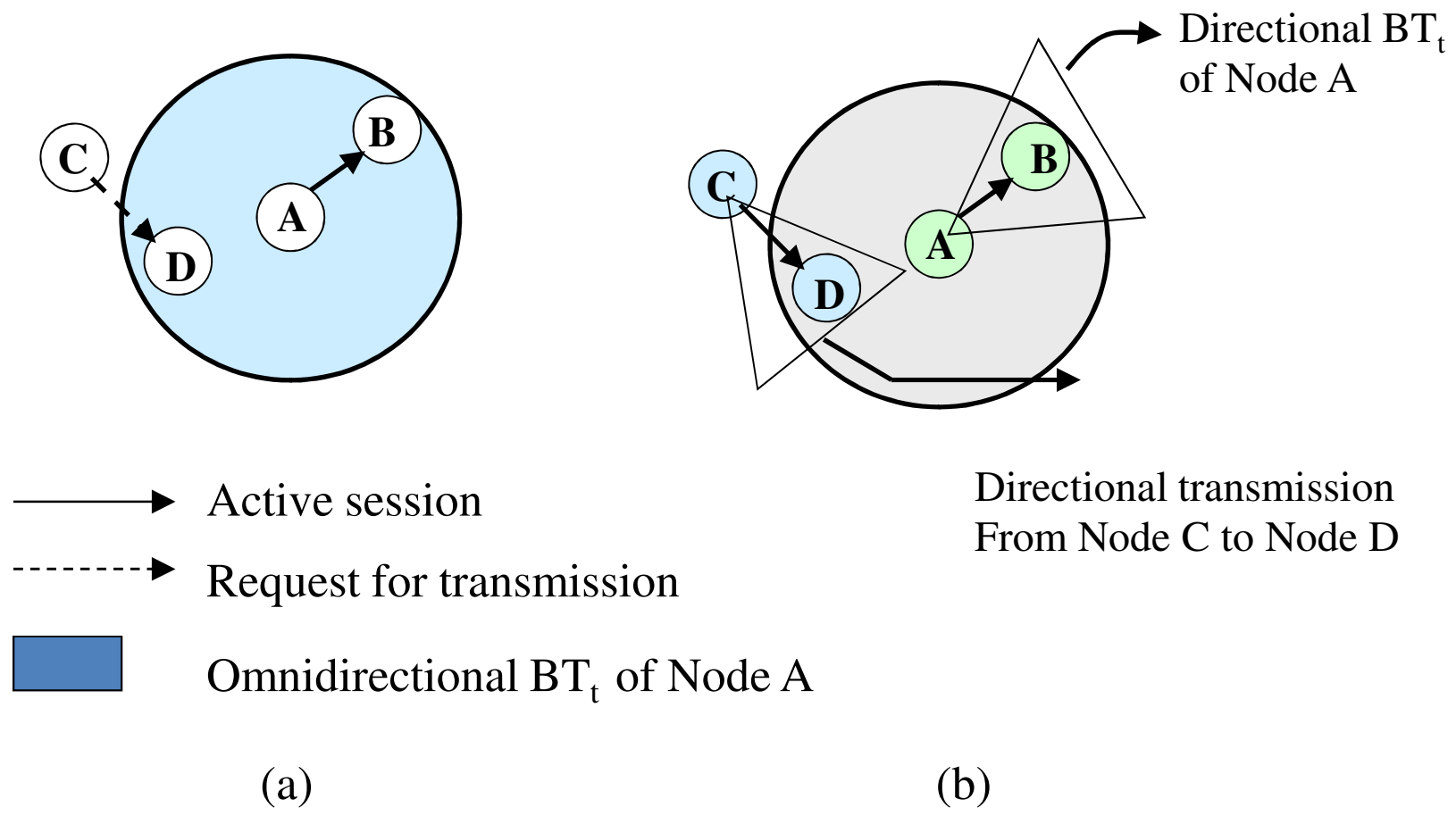


Figure 6.30. Directional DBTMA: Example 1.

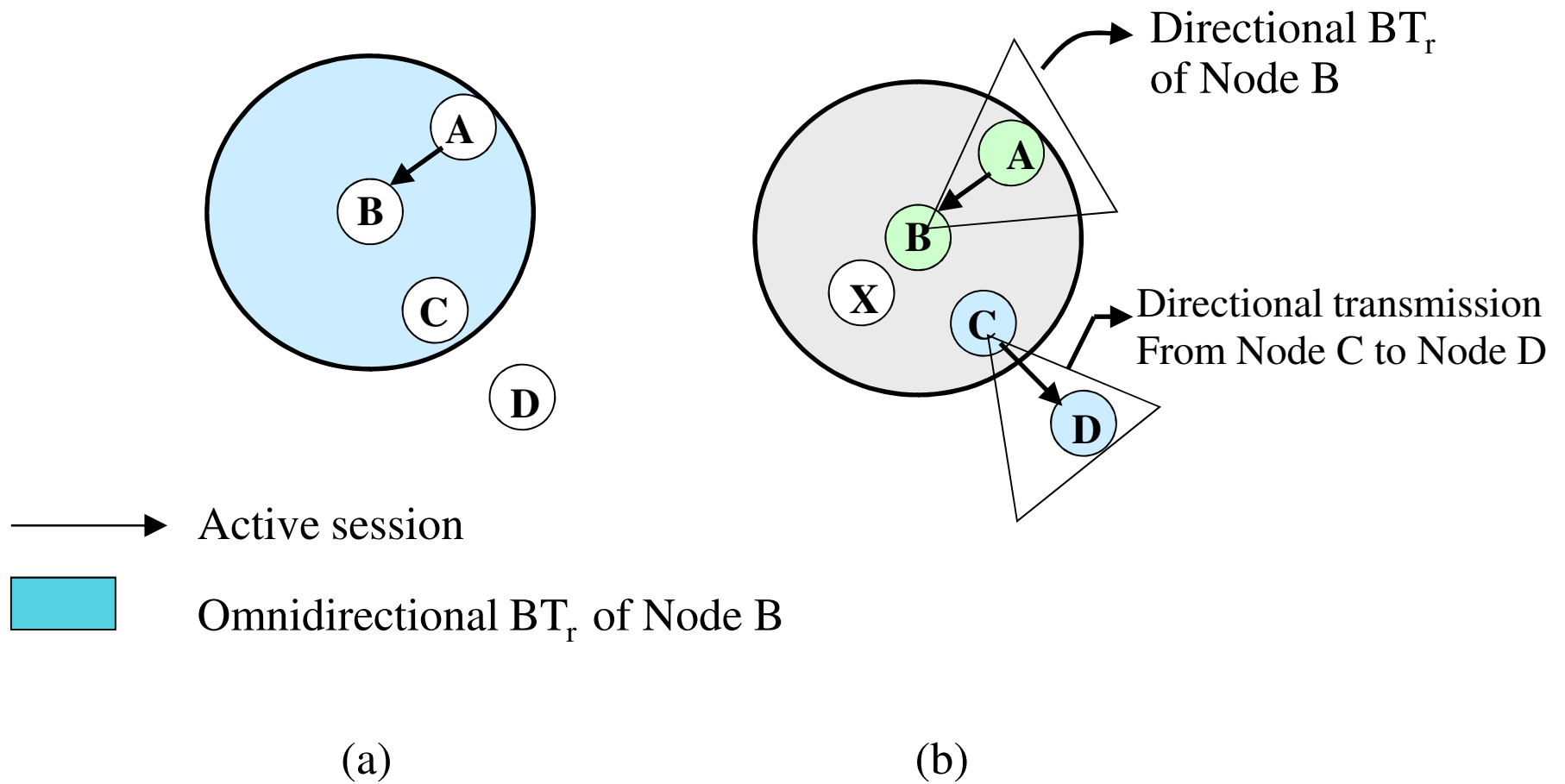
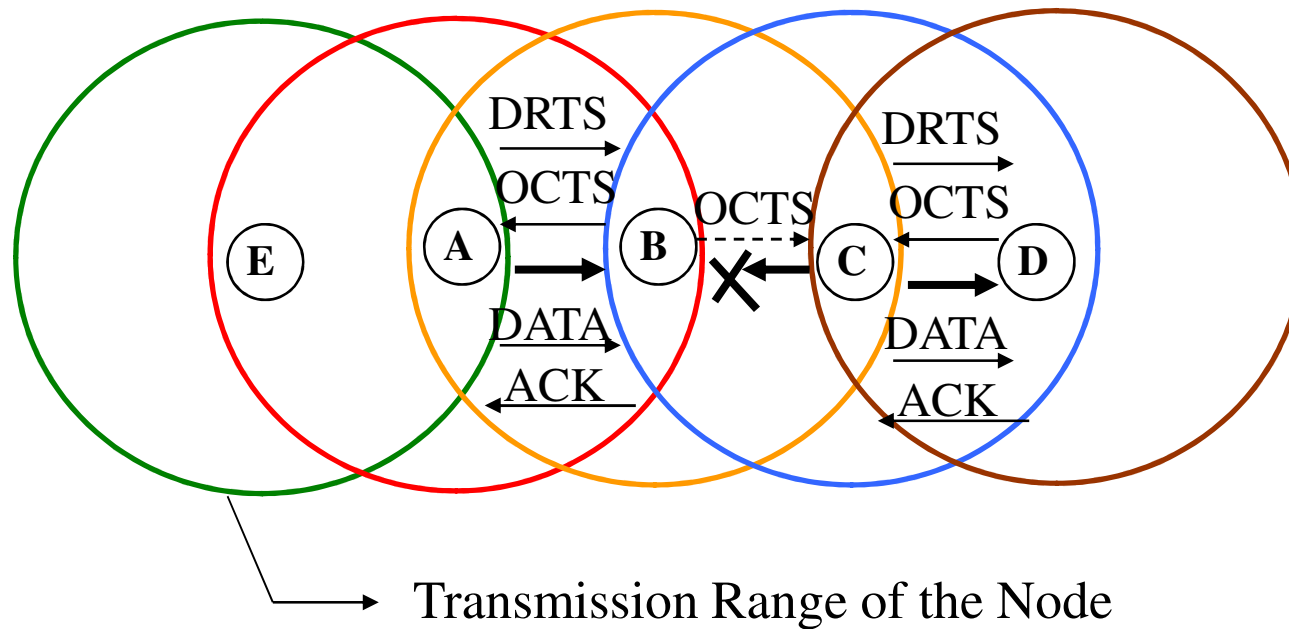


Figure 6.31. Directional DBTMA: Example 2.

# Directional MAC Protocols for Ad Hoc Wireless Networks

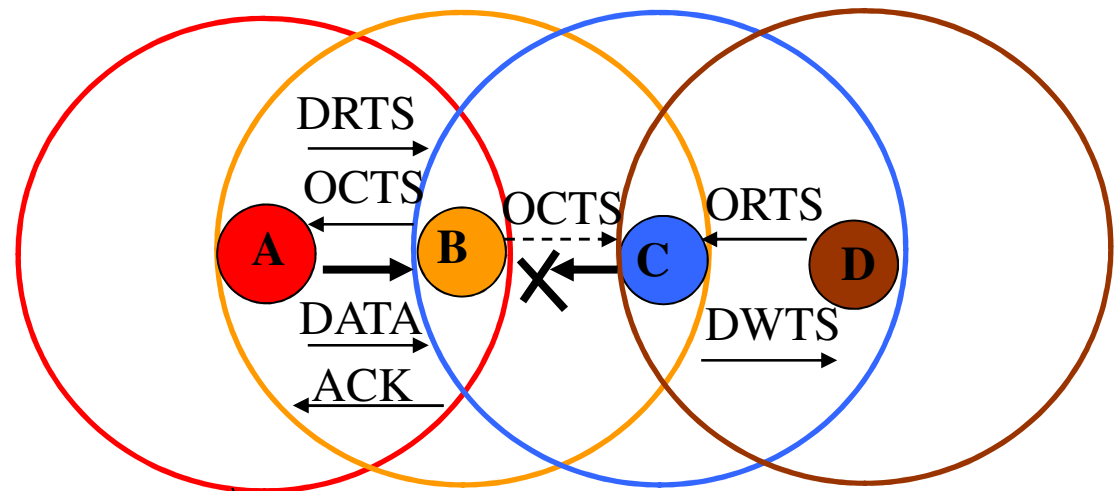
- D-MAC: assume each node knows about the location of neighbors
- In the first directional MAC scheme (DMAC-1)
  - Directional RTS (DRTS) → omni-directional CTS (OCTS) → Directional DATA (DDATA) → Directional ACK(DACK)
  - May increase the probability of control packet collisions
  - See Figure 6.32 (if node E send a packet to node A, it will collide the OCTS or DACK)
- In the second directional MAC scheme (DMAC-2)
  - Both the directional RTS (DRTS) and omni-directional RTS (ORTS) transmissions are used
    - Reduced control packet collisions
- Rules for using DRTS and ORTS:
  - ORTS: none of the directional antennas are blocked
  - DRTS : otherwise
  - Another packet called directional wait-to-send (DWTS) is used in this scheme (See Figure 6.33)



- Control/Data Packet
- Data session
- ✕ Non-permissible session

Figure 6.32. Operation of DMAC protocol.





Transmission Range of the Node

→ Control/Data Packet

→ Data session

→ X Non-Permissible Session

Figure 6.33. Operation of DMAC protocol.

# Other MAC Protocols

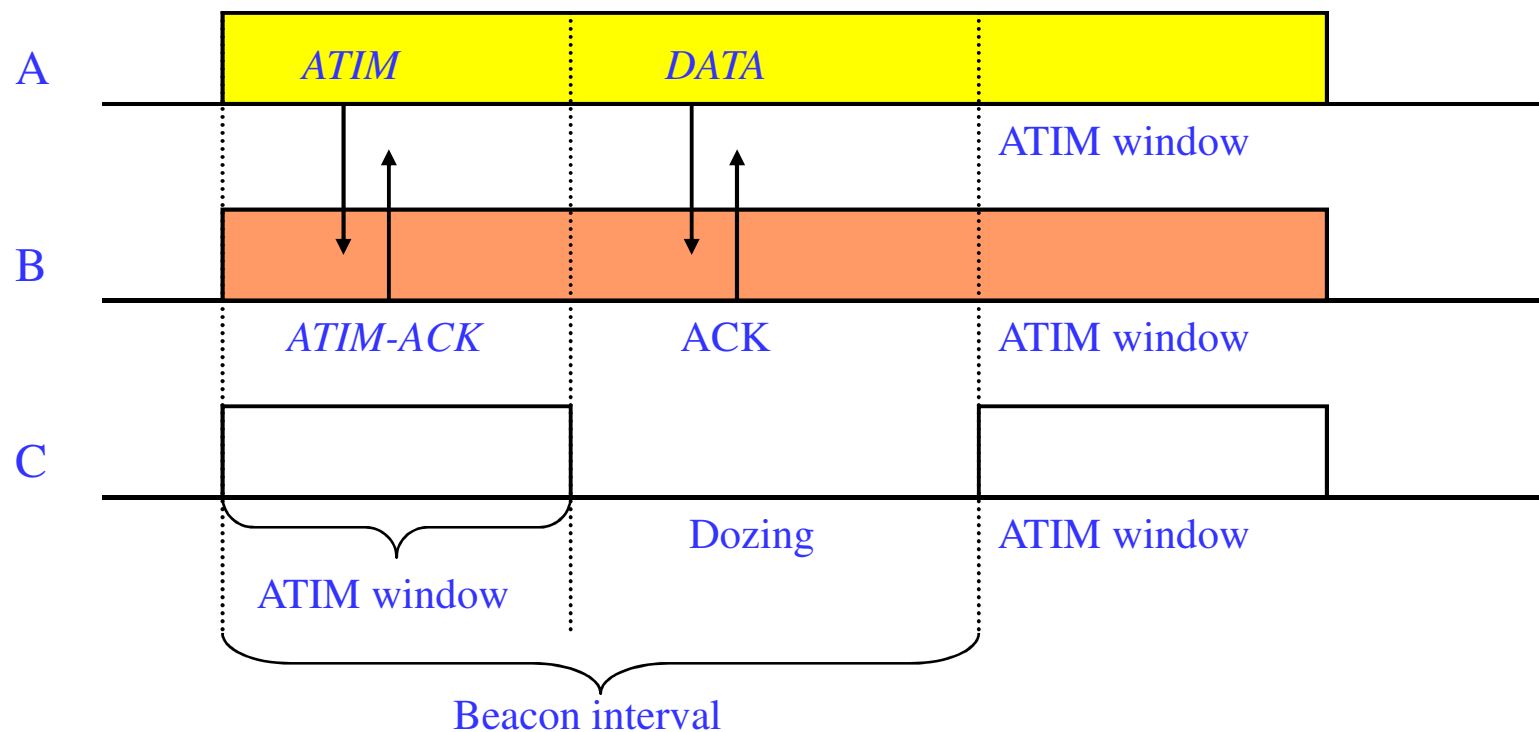
# MMAC: Multi-Channel MAC Protocol

- Assumptions:
  - No dedicated control channel
  - $N$  channels for data transmission
  - Each node maintains a data structure called PreferableChannelList (PCL)
- Three types for channels:
  - High preference channel (HIGH): the channel is selected by the current node and is used by the node
  - Medium preference channel (MID): a channel which is free and is not being currently used
  - Low preference channel (LOW): such a channel is already being used in the transmission range of the node by other neighboring nodes

# MMAC: Multi-Channel MAC Protocol (cont.)

- Time is divided into beacon intervals and every node is synchronized by periodic beacon transmissions
- Ad hoc traffic indication messages (ATIM) window is used to negotiate for channels for transmission
  - ATIM, ATIM-ACK, and ATIM-RES (ATIM-reservation) message
  - ATIM messages takes place on a particular channel (*default channel*)
- Operation of the MMAC protocol is illustrated in Figure 6.34
- The receiver plays a dominant role in channel selection

# ATIM Window



Power saving mechanism for DCF: Node A announces a buffered frame for B using an ATIM frame. Node B replies by sending an ATIM-ACK, and both A and B stay awake during the entire beacon interval. The actual data transmission from A to B is completed during the beacon interval. Since C does not have any frame to send or receive, it dozes after the ATIM window.

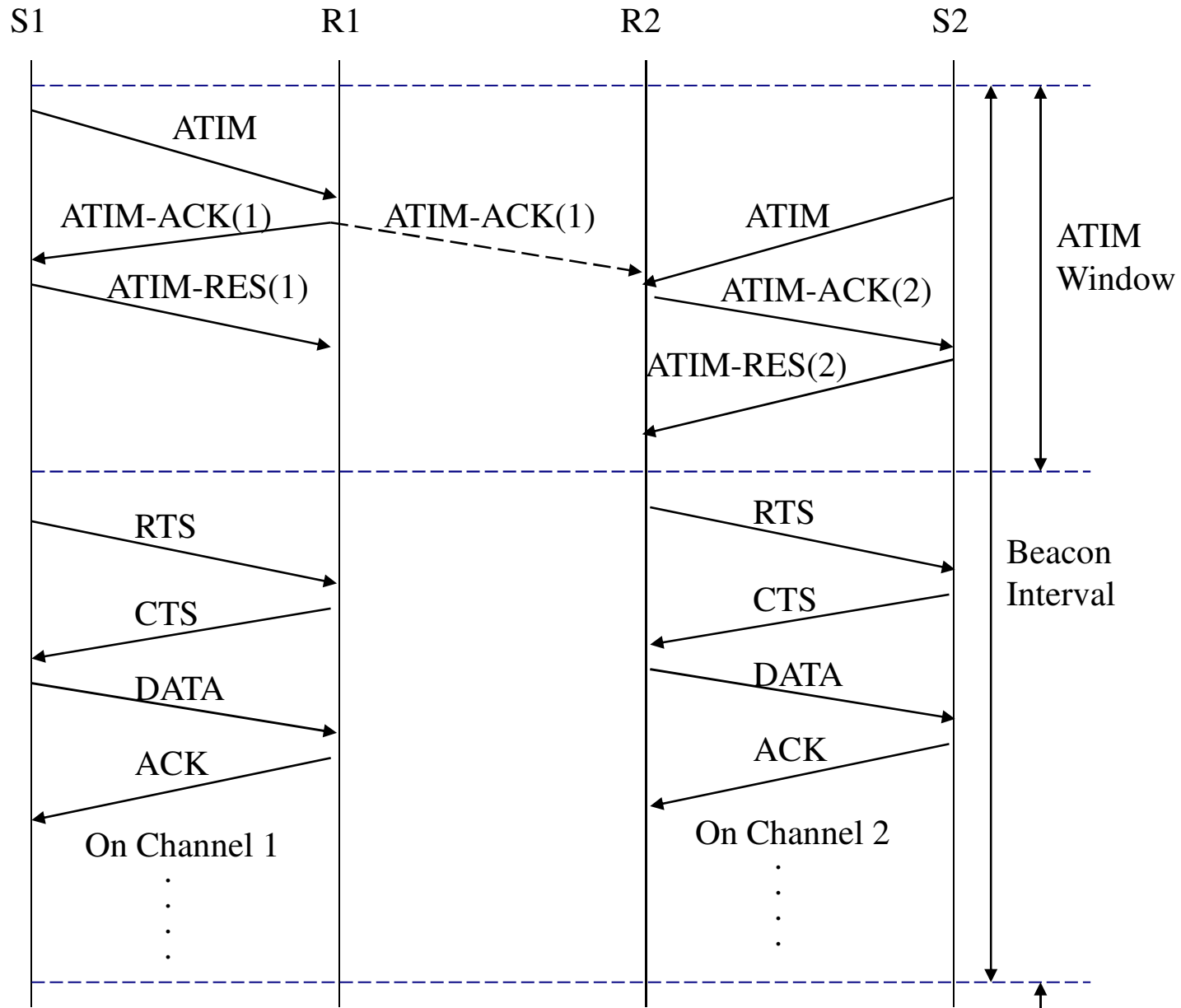


Figure 6.34. Operation of MMAC protocol.

Start of Next  
ATIM Window

# MMAC: Multi-Channel MAC Protocol (cont.)

- Channel selection mechanism:
  - If a HIGH state channel exists in node  $R$ 's PCL then that channel is selected
  - Else if there exists a HIGH state channel in the PCL of node  $S$  then this channel is selected
  - Else if there exists a common MID state channel in the PCLs of both node  $S$  and node  $R$  then that channel is selected
  - Else if there exists a MID state at only one of the two nodes then that channel is selected
  - if all channels in both PCLs are in LOW state the channel with the least count is selected

# MCSMA: Multi-Channel CSMA MAC Protocol

- Select an idle channel randomly and employ the notion of soft channel reservation
- Assumptions
  - $N$  channel: bandwidth =  $W/N$ ,  $W$  is the total bandwidth for communication
- An idle node (which is not transmitting packets) continuously monitors all the  $N$  channels
  - Idle state: total received signal strength (TRSS) < sensing threshold (ST)
  - Maintain a free-channels list
- Channel selection protocol:
  - if free-channels list is empty then wait for long inter-frame space time (LIFS) + back-off period
  - if the channel remains idle start transmitting on this channel
  - if free-channels list is non-empty then first checks whether the channel it used for its most recent successful transmission in the list
  - then use this channel for its new transmission else in the free-channels is randomly chosen



# MCSMA: Multi-Channel CSMA MAC Protocol (cont.)

- Before the actual packet transmission
  - if TRSS of the chosen channel  $< ST$  for at least LIFS period initiate packet transmission
  - otherwise initiate back-off delay after the LIFS time period
  - During the back-off period, if (TRSS of the chosen channel  $> ST$ ) back-off is immediately canceled
  - A new back-off delay is scheduled when the TRSS again goes below  $ST$
- After successfully transmitting a packet, the sender node notes the ID of the channel used and this channel would be given preference for its next transmission
- When the number of channel is sufficiently large, each node tends to reserve a channel for itself

# PCM: Power Control MAC Protocol for Ad Hoc Networks

- The PCM allows nodes to vary their transmission power levels on a per-packet basis
- BASIC scheme
  - RTS and CTS are transmitted with maximum power  $p_{max}$
  - The RTS is received at the receiver with signal level  $p_r$
  - the receiver calculate the desired power level  $p_{desired}$  based on the received power level  $p_r$ , the transmitted power level  $p_{max}$ , and the noise level at receiver
- In the second method, when the source receives the CTS (in maximum power) packet, it calculates  $p_{desired}$  as follows:
$$p_{desired} = (p_{max} / p_r) \times Rx_{thresh} \times c$$
, where  $Rx_{thresh}$  is the minimum necessary received signal strength and  $c$  is the constant
  - Drawbacks: May the probability of collision (see Figure 6.35)

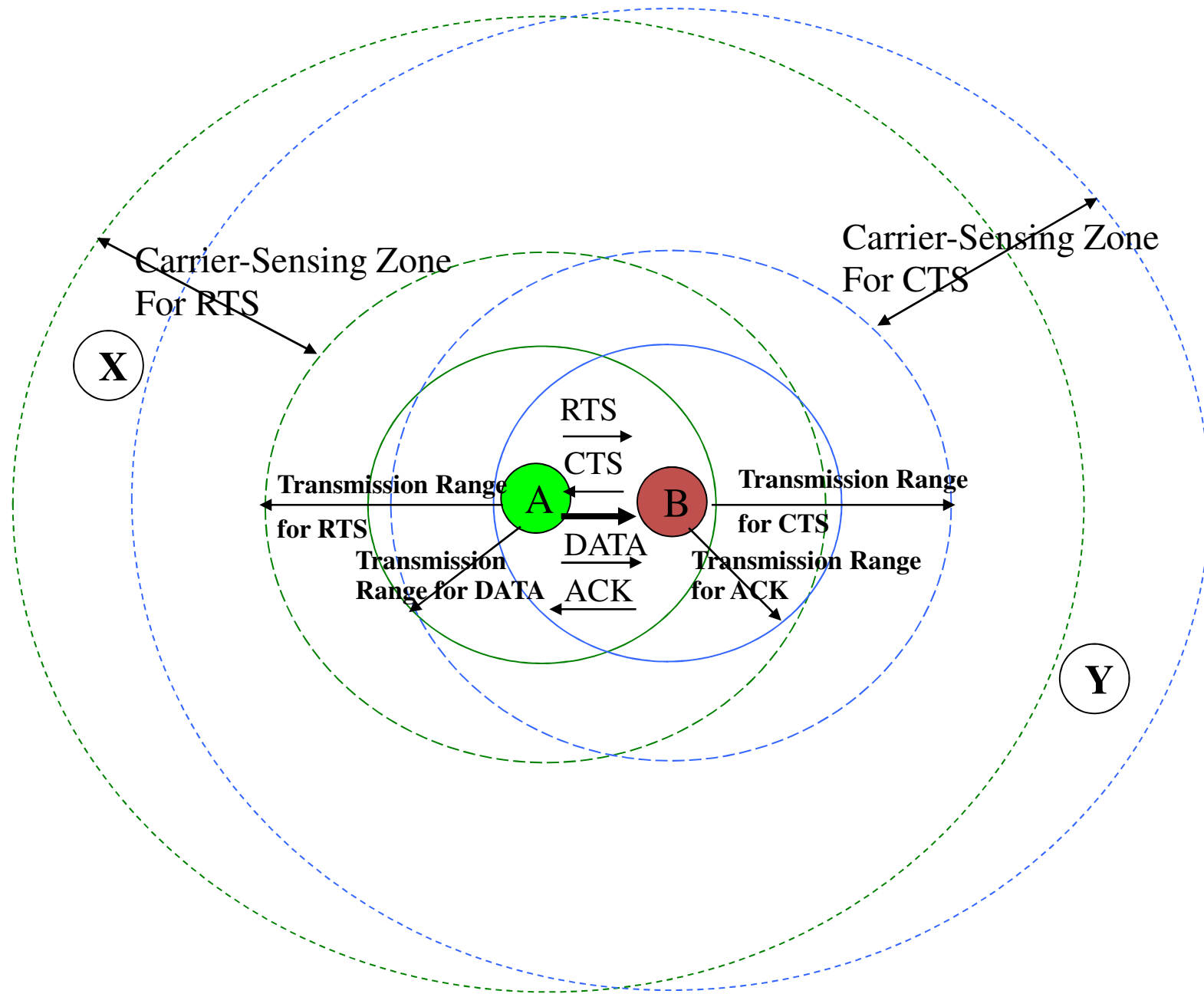


Figure 6.35. Packet transmission in BASIC scheme.

# PCM: Power Control MAC Protocol for Ad Hoc Networks

- Solution:
  - RTS and CTS are transmitted with maximum power  $p_{max}$
  - Carrier-sensing zone: the received signal is not high enough to decode it correctly
  - Transmit the DATA packet at maximum power level  $p_{max}$  periodically
    - The duration of each such transmission must larger than the time required for physical carrier sensing (see Figure 6.36)

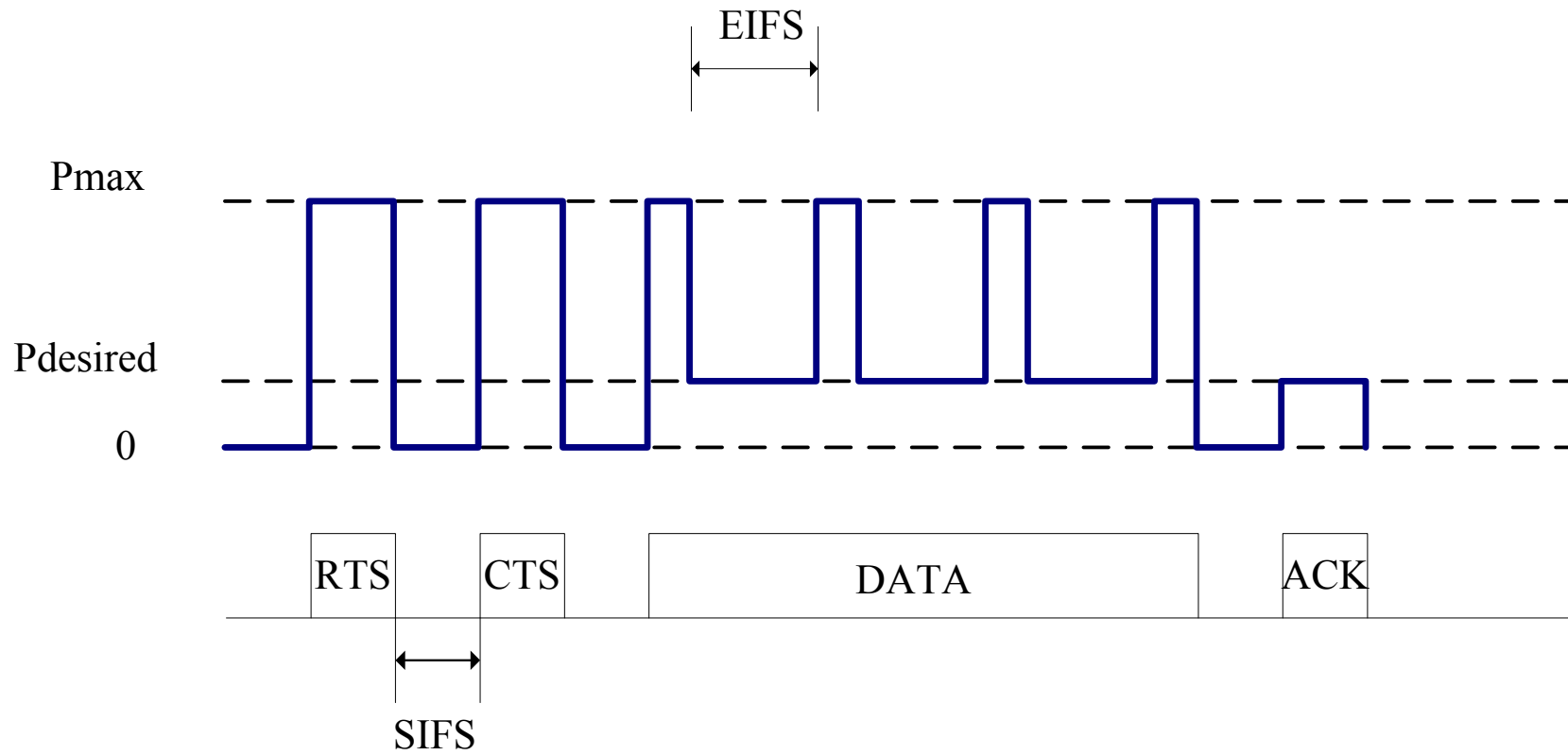


Figure 6.36 . Transmission power pattern in PCP.

# RBAR: Receiver-Based Autorate Protocol

- Rate Adaptation Mechanism
  - run at the receiver instead of being located at the sender
  - consist of channel quality estimation and rate selection
- Rate selection is done during RTS-CTS packet exchange
- The RTS and CTS packets carry the chosen modulation rate and the size of the data packet, instead of the duration of the reservation (see Figure 6.37)
- The rate chosen by the sender and receiver are different
  - $D_{RTS}$  calculated by the neighbor nodes of the sender would not be valid if the rates chosen by the sender and receiver are different
  - Overcome problem: a special MAC header containing a reservation subheader (RSH) which contains control information for determining the transmission duration

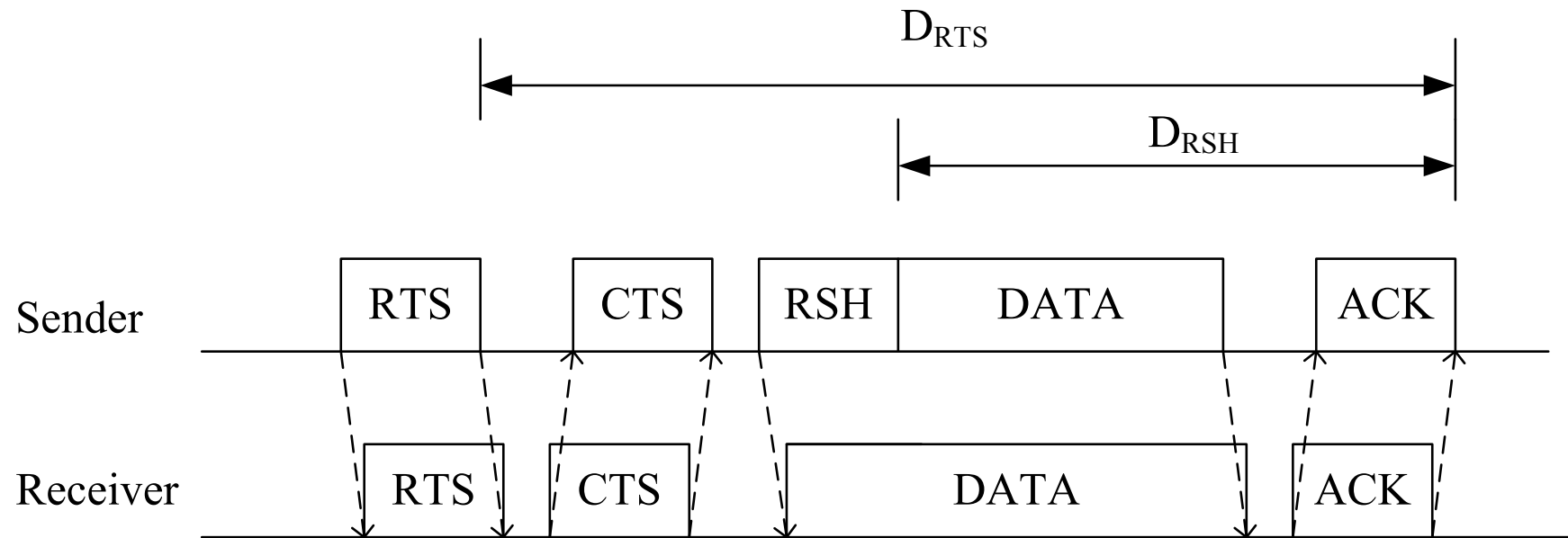


Figure 6.37. Packet transmission in RBAR

# RBAR: Receiver-Based Auto-rate Protocol (cont.)

- Channel quality estimation
  - The receiver uses a sample of the instantaneous received signal strength at the end of RTS reception
- Rate selection algorithm
  - A simple threshold based technique is used e.g. signal to noise ratio (SNR)
- It is important that the best available channel quality estimates are used for rate selection



# ICSMMA: Interleaved Carrier-Sense Multiple Access Protocol

- Efficiently overcomes the exposed terminal problem (see Figure 6.38)
  - Node *C* is called a send-exposed node, and node *E* is called a receiver-exposed node
- The total available bandwidth is split into two equal channels (say, channel 1 and channel 2)
- The handshaking process is interleaved between the two channels
  - Sender uses a channel (channel 1 ) to send RTS and DATA while receiver uses another channel (channel 2) to send CTS and ACK
- A node hear RTS in a particular channel and do not hear CTS on the other channel, it can send RTS in the same channel
- A node hear CTS in a particular channel and do not hear RTS on the other channel, it can send CTS in the same channel

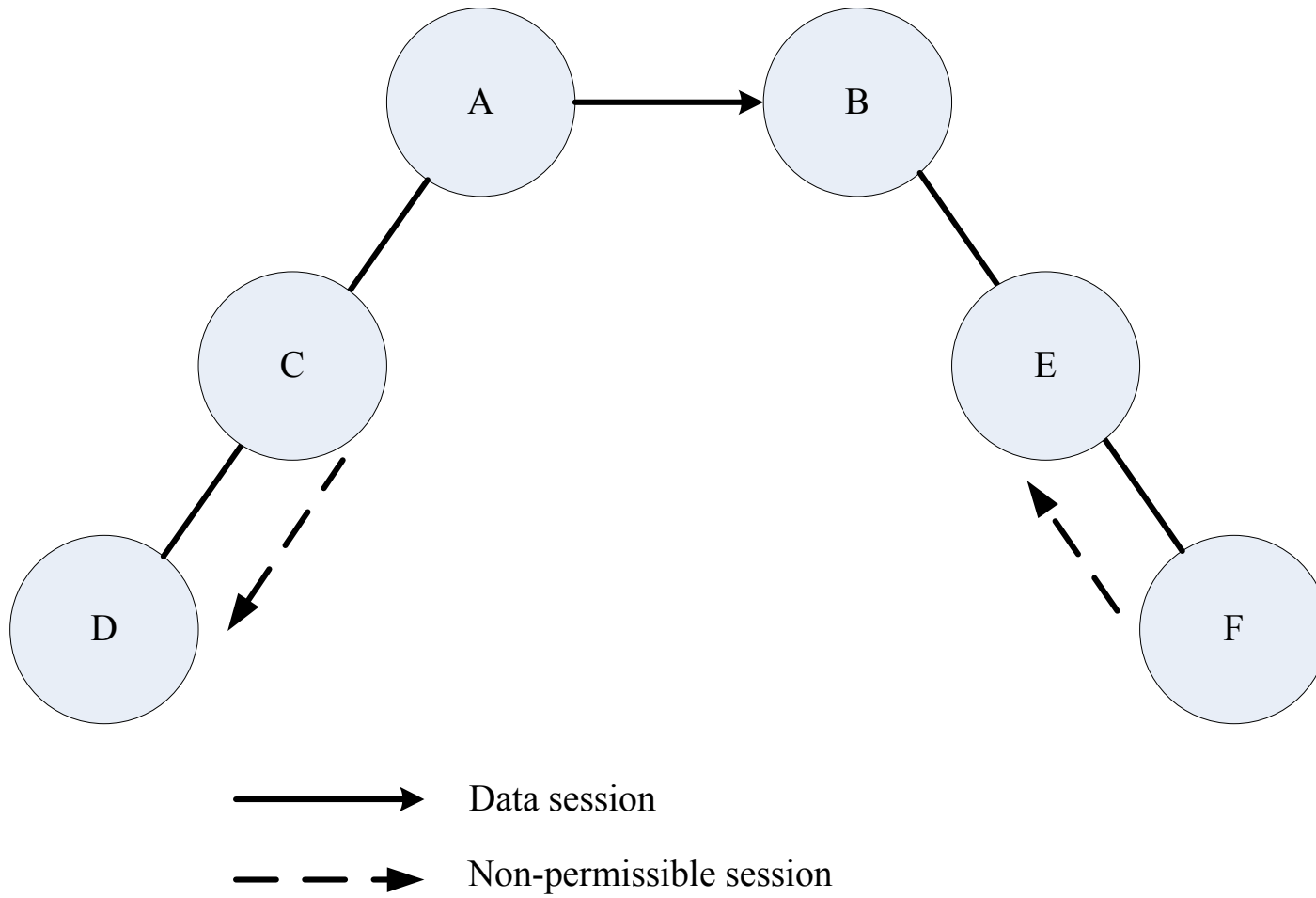


Figure 6.38. Exposed terminal problem.

# ICSMMA: Interleaved Carrier-Sense Multiple Access Protocol (cont.)

- Each node maintains a structure called extended network allocation vector (E-NAV)
  - Two linked lists of blocks (*SEList* and *REList*):
  - List looks like  $s_1, f_1; s_2, f_2; \dots; s_k, f_k$  where  $s_i$  denotes start time of the  $i$ -th block list and  $f_i$  denotes finish time of the  $i$ -th block
  - *SEList* : the node would be sender-exposed in the future such that  $s_j < t < f_j$
  - *REList* : the node would be receiver-exposed in the future such that  $s_j < t < f_j$
  - Both lists are updated when RTS and CTS packets are received by the node
- See Figure 6.39

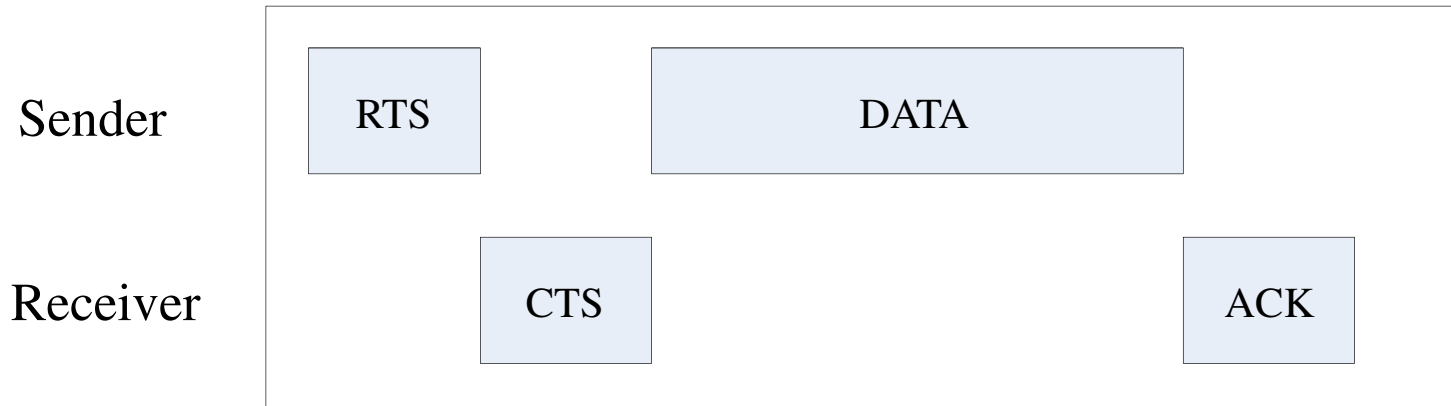


Figure 6.39. (a) Packet transmissions in 802.11 DCF

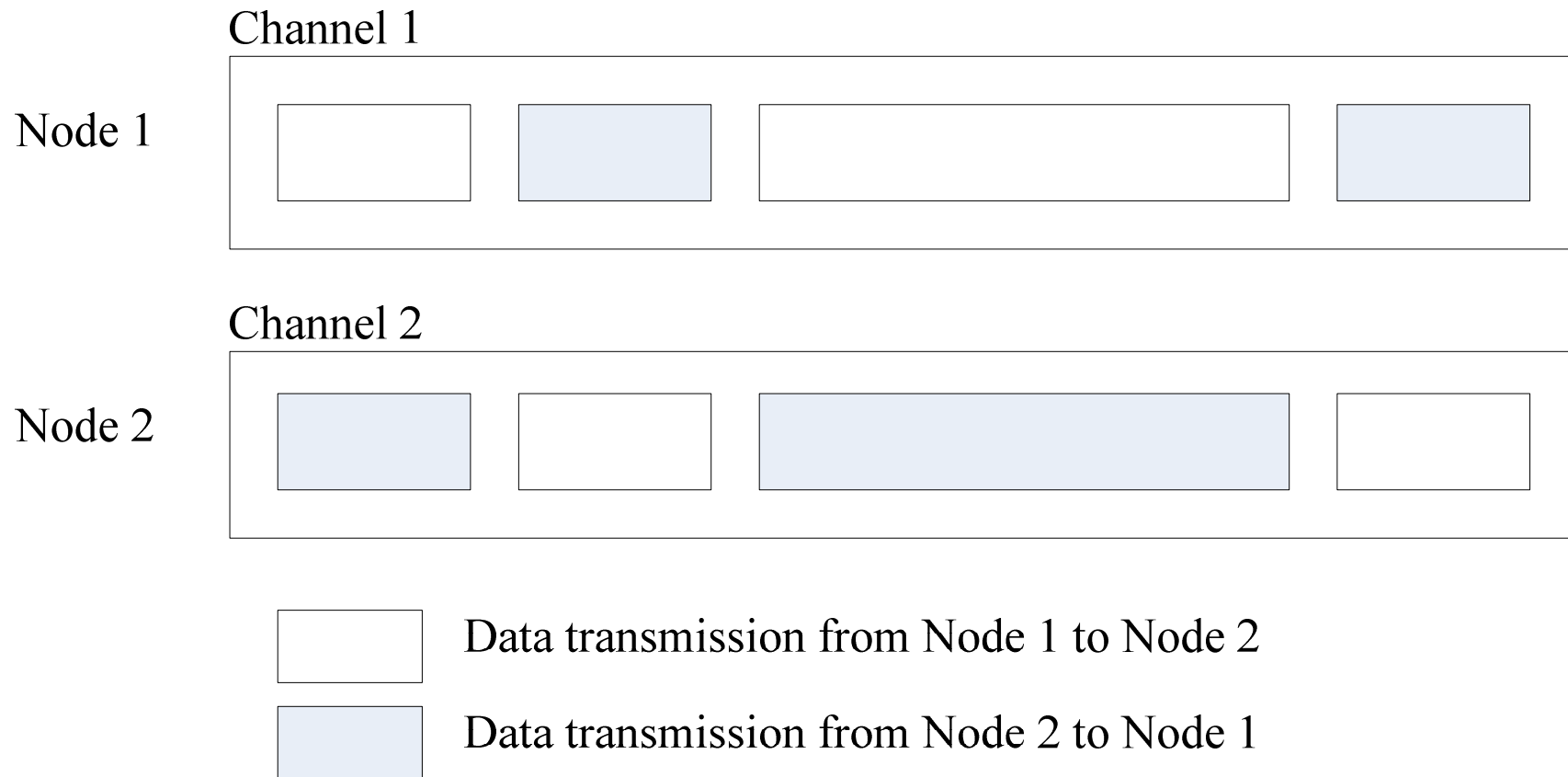


Figure 6.39. (b) Packet transmissions in ICSMA.

# Summary

- We have discussed the characteristics and operating principles of several MAC schemes
- Several International standards exists for MANETs, such as IEEE 802.11a, b, and g
- New Standards are still be developed such as UWB, IEEE 802.16 (WiMax)
- Future directions and current research:
  - Hidden/exposed terminal problem
  - Interference limited model
  - Energy conservation
  - Single channel v.s. Multiple channels

# Summary (cont.)

- Multi-hop networks
- Fairness among competing nodes
- Directional antennas
- QoS issues

# Home Work

- 2, 6, 8, 13, 17