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 Share Broadcast Channel

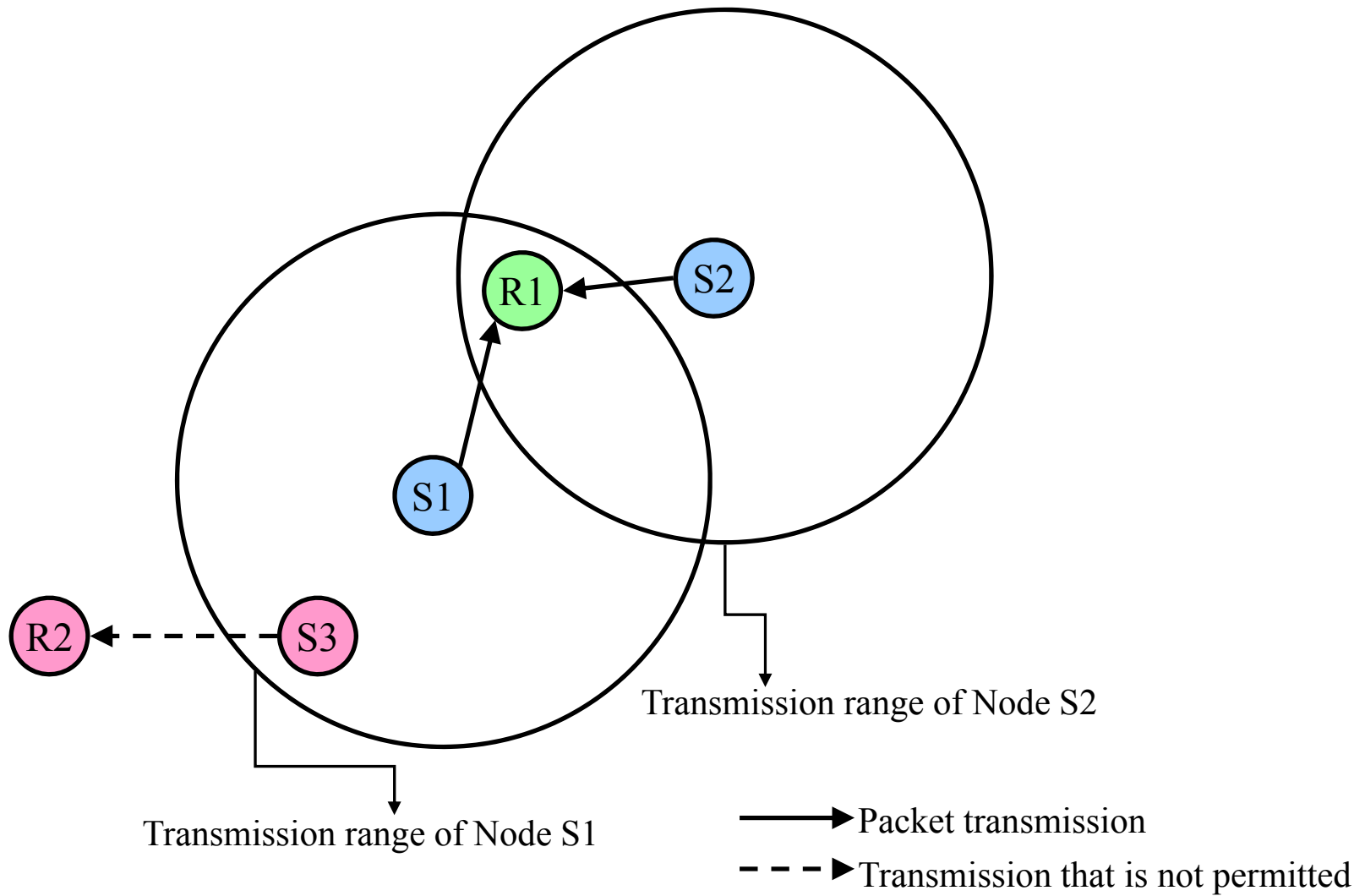- Distributed Nature/Lack of Central Coordination

- Mobility of Nodes

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Figure 6.1 Hidden and exposed terminal problems

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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
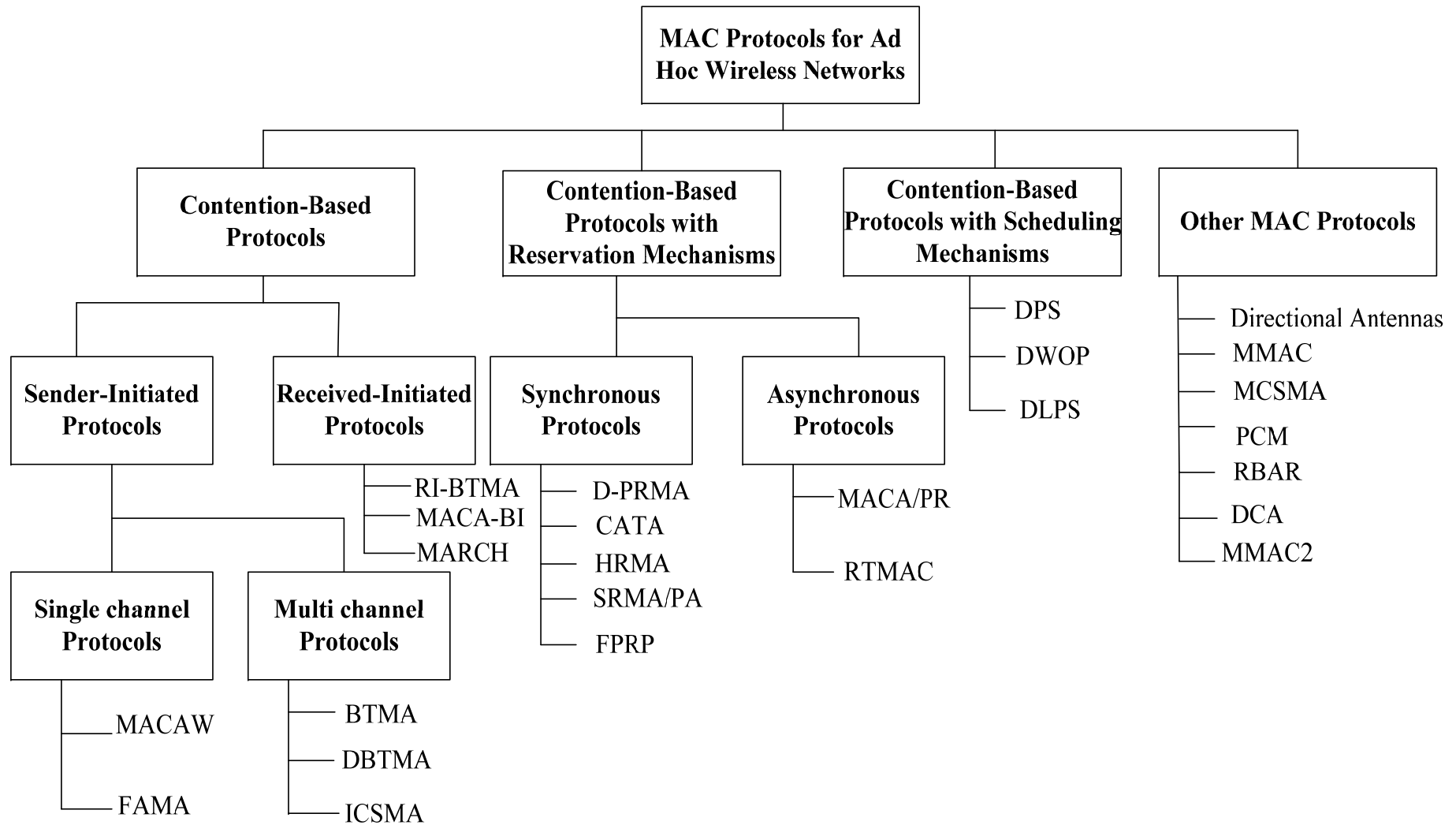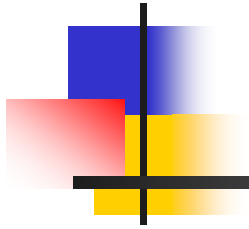 - Scheduling nodes for access to the channel

Figure 6.2: MAC protocols for ad hoc network

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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

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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
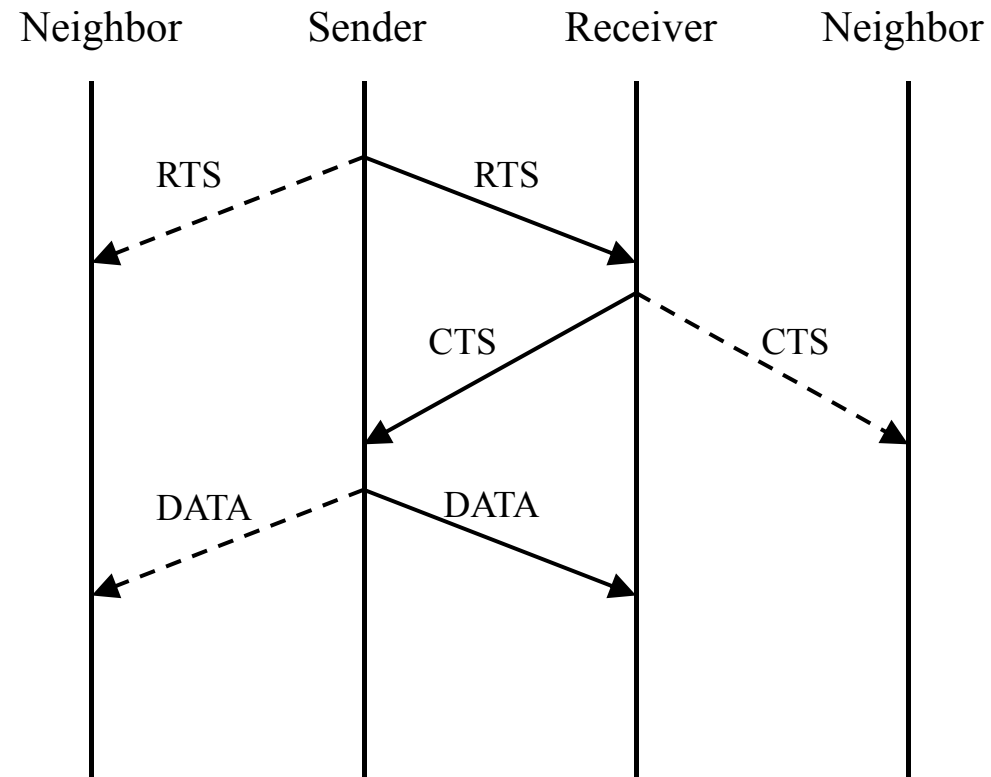
Figure 6.3 Packet transmission in MACA

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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 filed carrying the current back-off counter value of the transmitting node

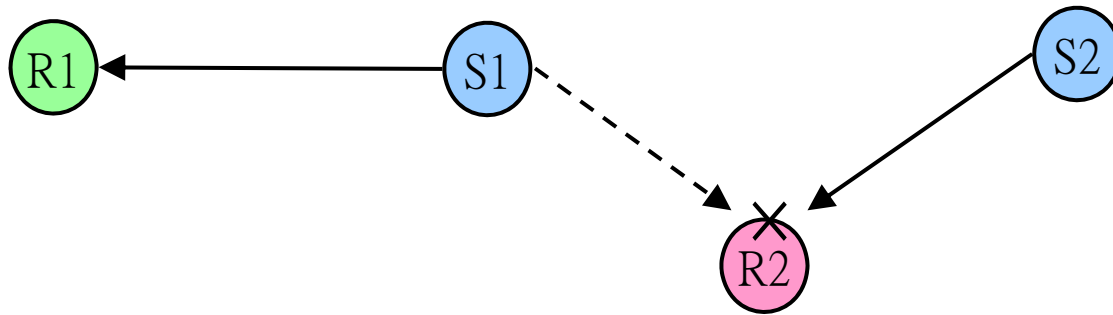 - A node receiving the packet copies this value into its own back-off counter

Figure 6.4 Example topology

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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
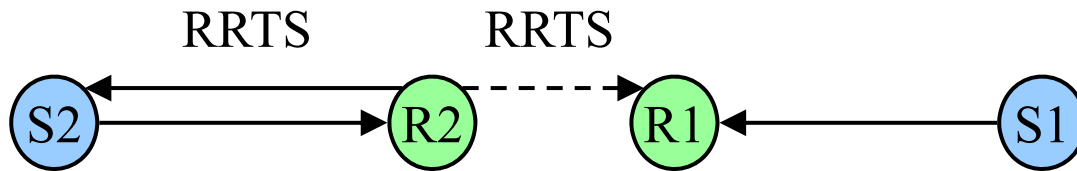
Figure 6.5 Example topology

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
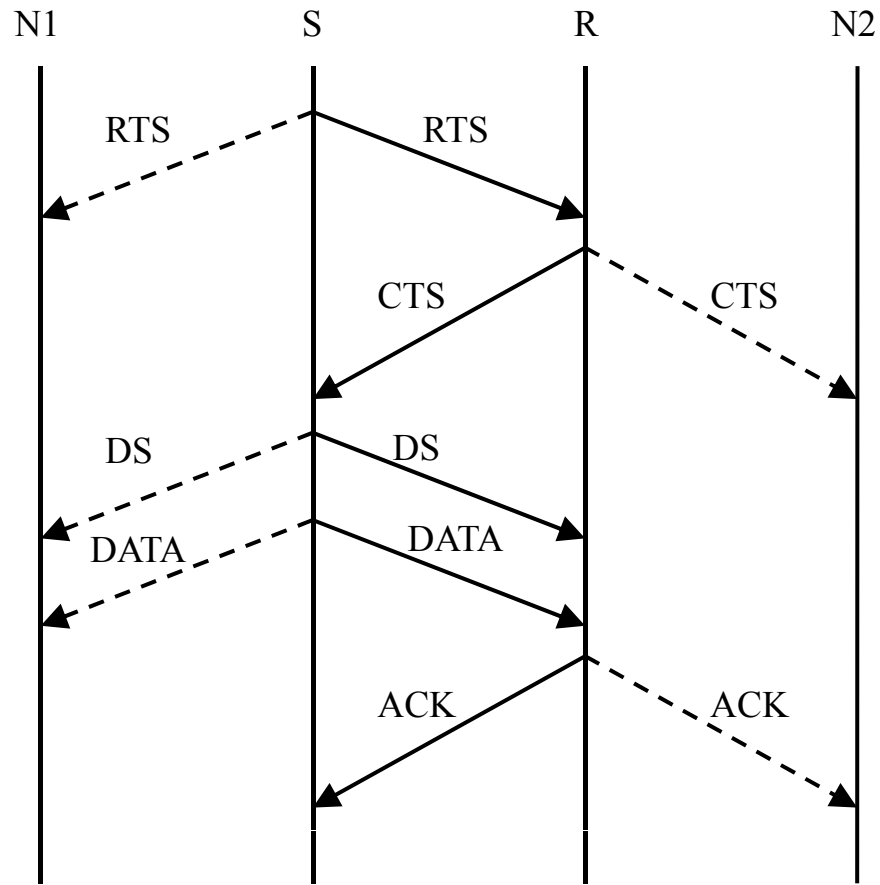 - RTS-CTS-DS-DATA-ACK

Figure 6.7 Packet exchange in MACAW.

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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)

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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 τ seconds after a packet is received

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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)
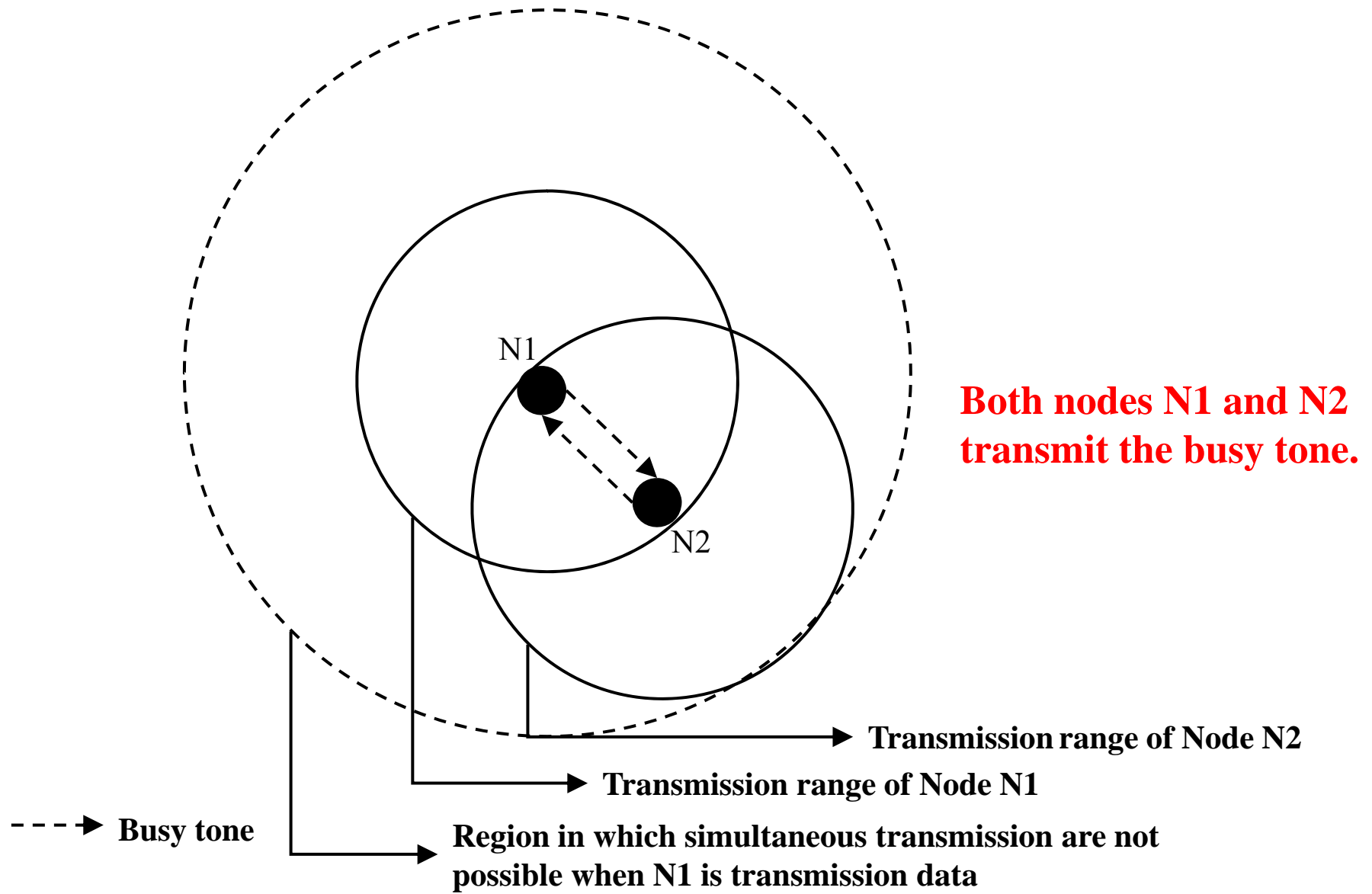
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Both nodes N1 and N2 transmit the busy tone.

N1

N2

- - -> **Busy tone**

Transmission range of Node N2

Transmission range of Node N1

Region in which simultaneous transmission are not possible when N1 is transmission data

Figure 6.8 Transmission in BTMA.

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DBTMA: Dual Busy Tone Multiple Access Protocol

- The transmission channel is divided into:
    - The data channel $\rightarrow$ data packet transmission
    - The control channel $\rightarrow$ 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 → transmit RTS packet
  - On receiving the RTS packets, checks whether the BT_t tone is active
    - No BT_t signal → Sending CTS packet and turn on the BT_r signal
  - Sender: receive CTS → turn on BT_t signal → start data → turn off BT_t signal
  - Receiver: receive data → turn off BT_r signal

- DBTMA has better network utilization than RTS/CTS based protocol (why?)

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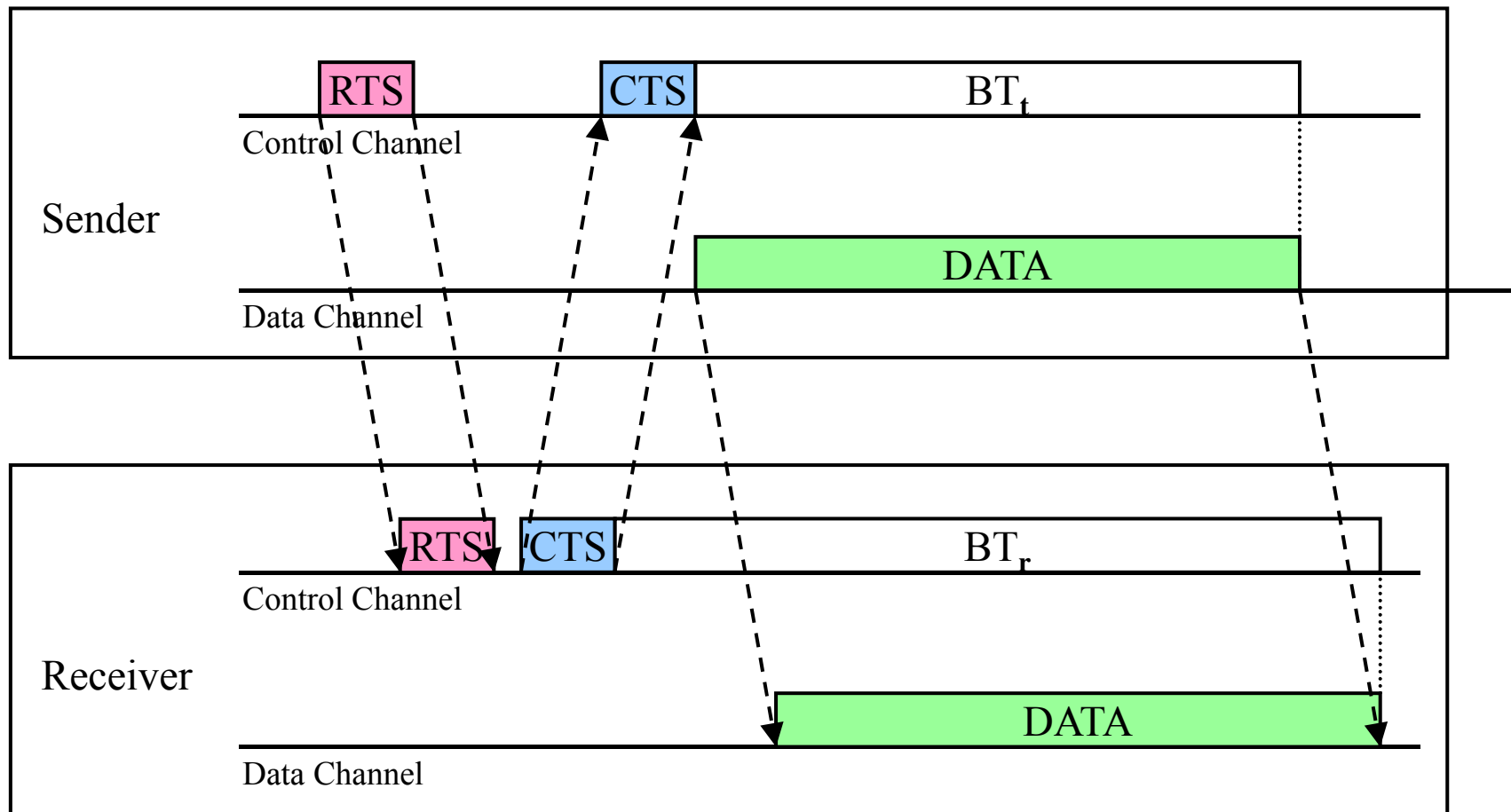
Figure 6.9 Packet transmission in DBTMA.

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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

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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 → packets that suffer collisions cannot be retransmitted

  - the controlled protocol

    - Backlogged mode → backlog buffer is non-empty

      - Backlog buffers: transmitting a backlogged packet in the next idle slot with a probability q (why?)

    - Non-backlogged mode → transmitting a non-backlogged packet in the next idle slot with a probability p (why?)
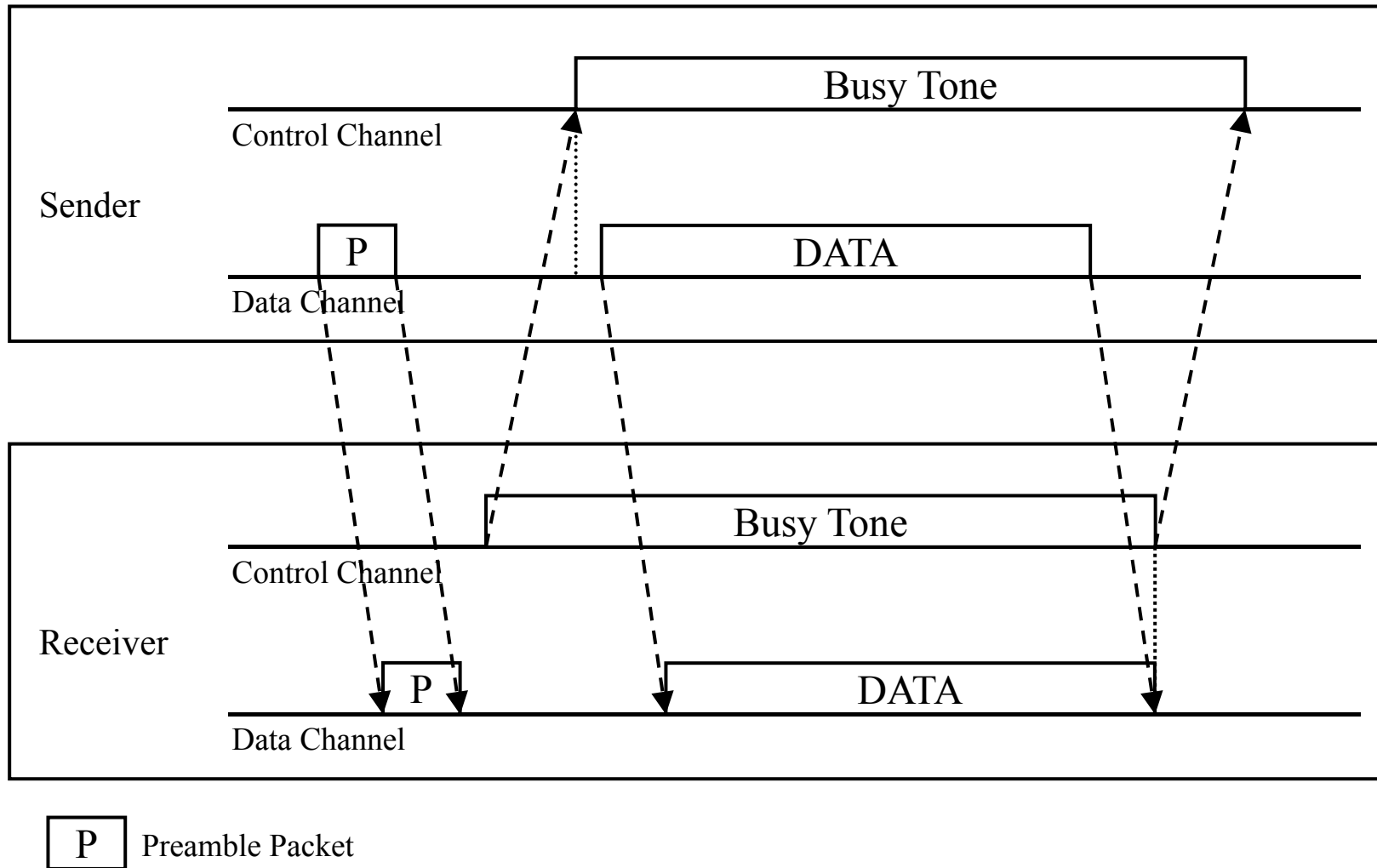
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Figure 6.10 Packet transmission in RI-BTMA.

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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
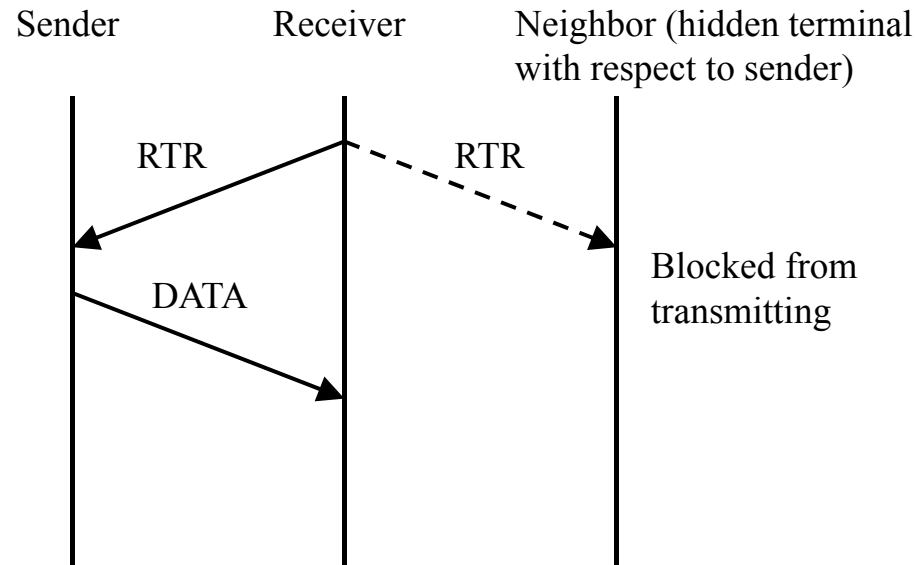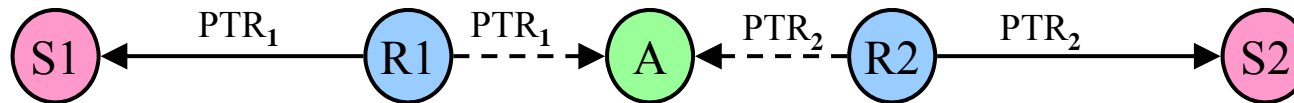   - RTR packets can collide with DATA packets (See Figure 6.12)

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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 $\rightarrow$ . . .
  - MARCH: RTS $\rightarrow$ CTS$_1$ $\rightarrow$ DATA $\rightarrow$ CTS$_2$ $\rightarrow$ DATA $\rightarrow$ … (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} = 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
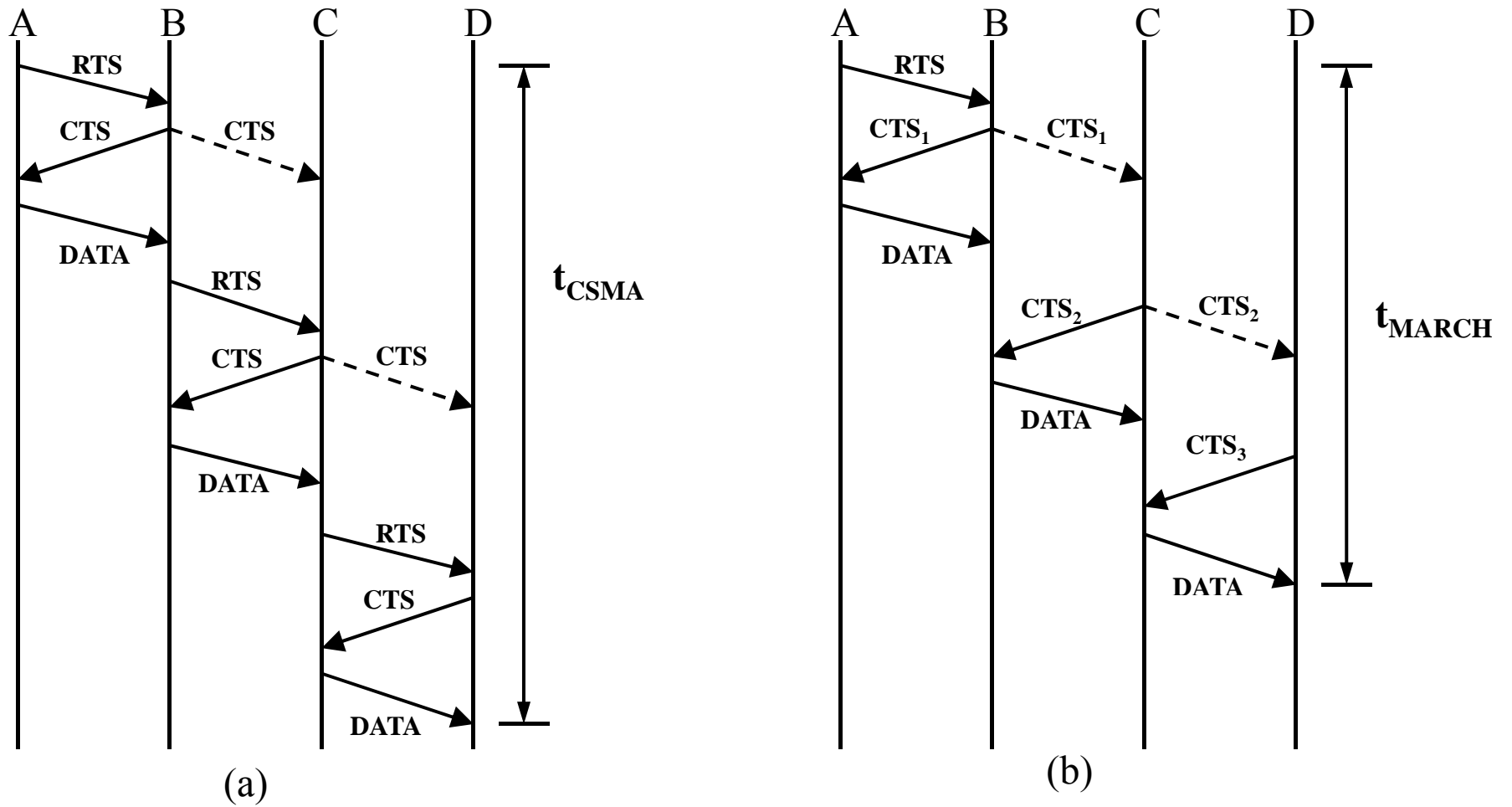
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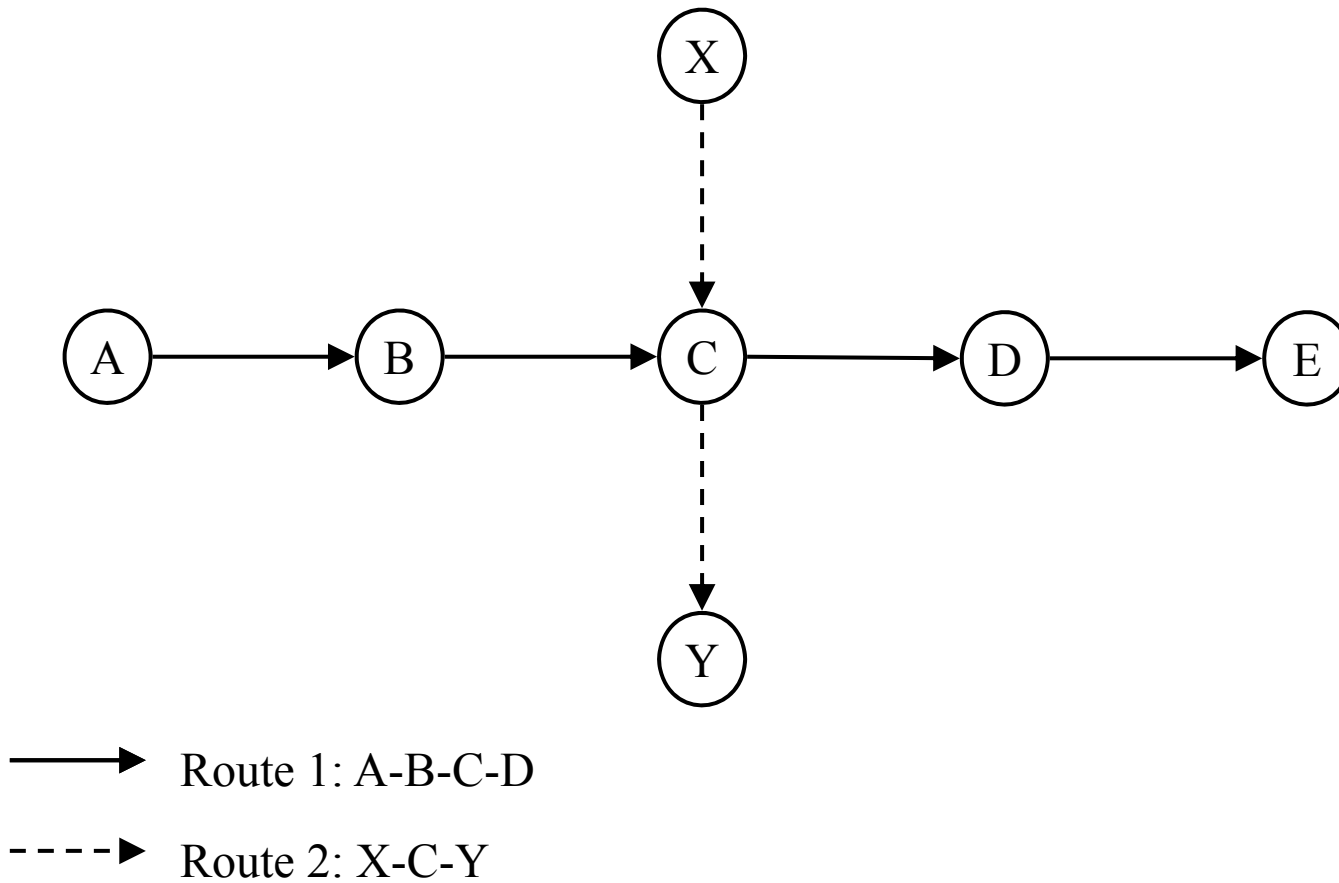Figure 6.13 Handshake mechanism in (a) MACA and (b) MARCH
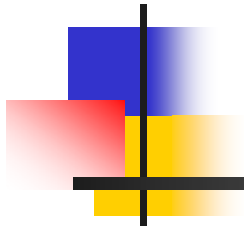
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Figure 6.14 Example Topology

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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
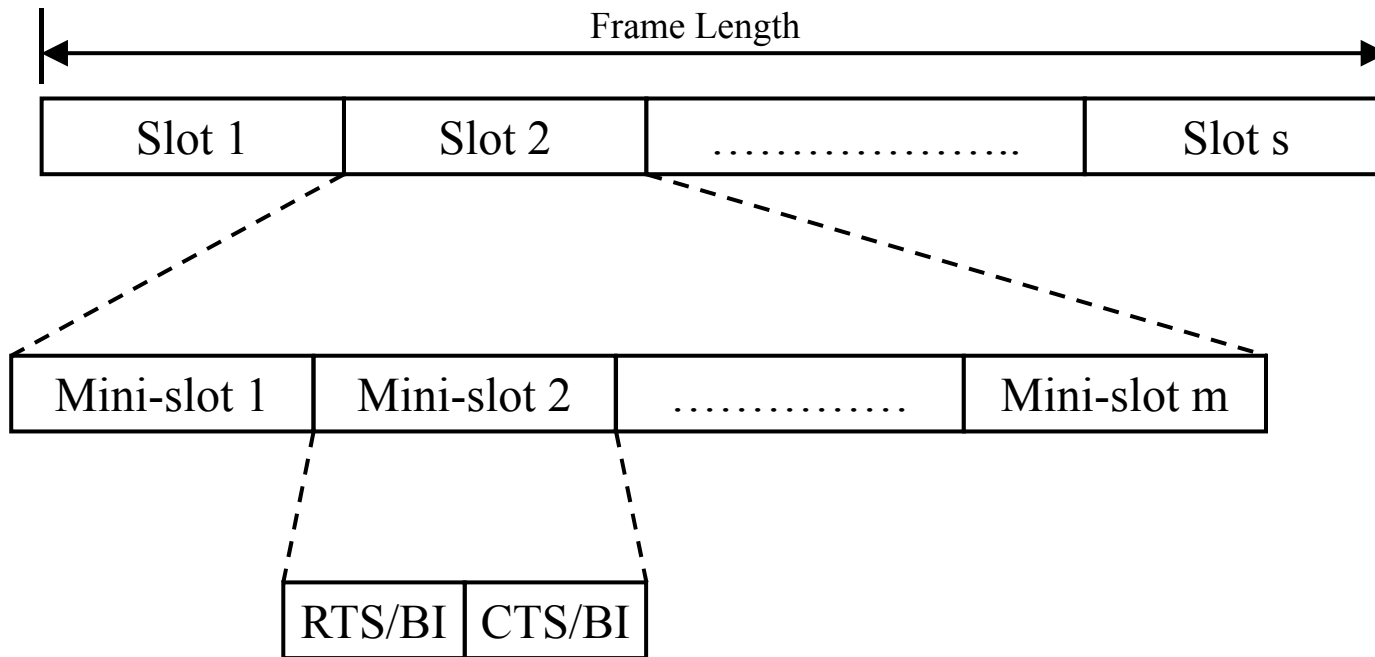
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Figure 6.15 Frame structure in D-PRMA

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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)

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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

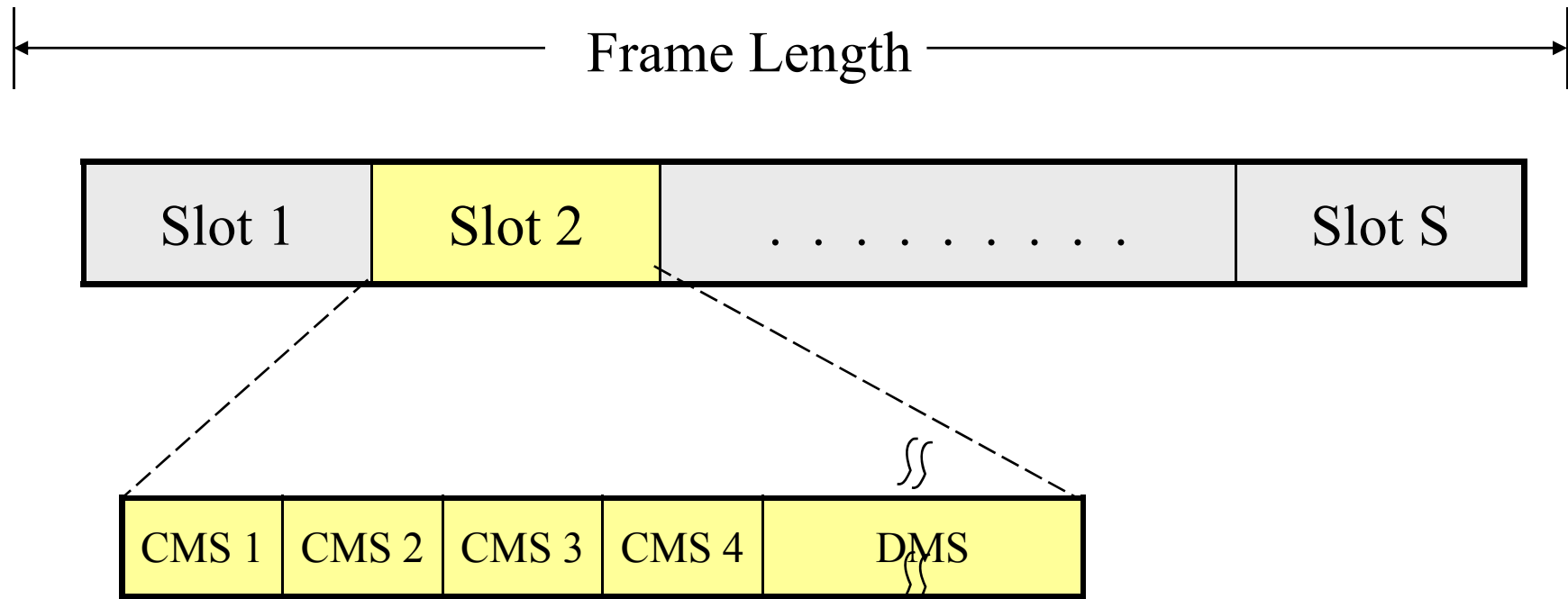- CATA works well with simple single-channel half-duplex radios

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 channel (See Figure 6.17)

- Assumptions
  - L: frequency channels
  - f_0: dedicated synchronized channel frequency
  - The remaining L - 1 frequencies are divided into $M = \left\lfloor \dfrac{(L-1)}{2} \right\rfloor$ frequency pairs denoted by
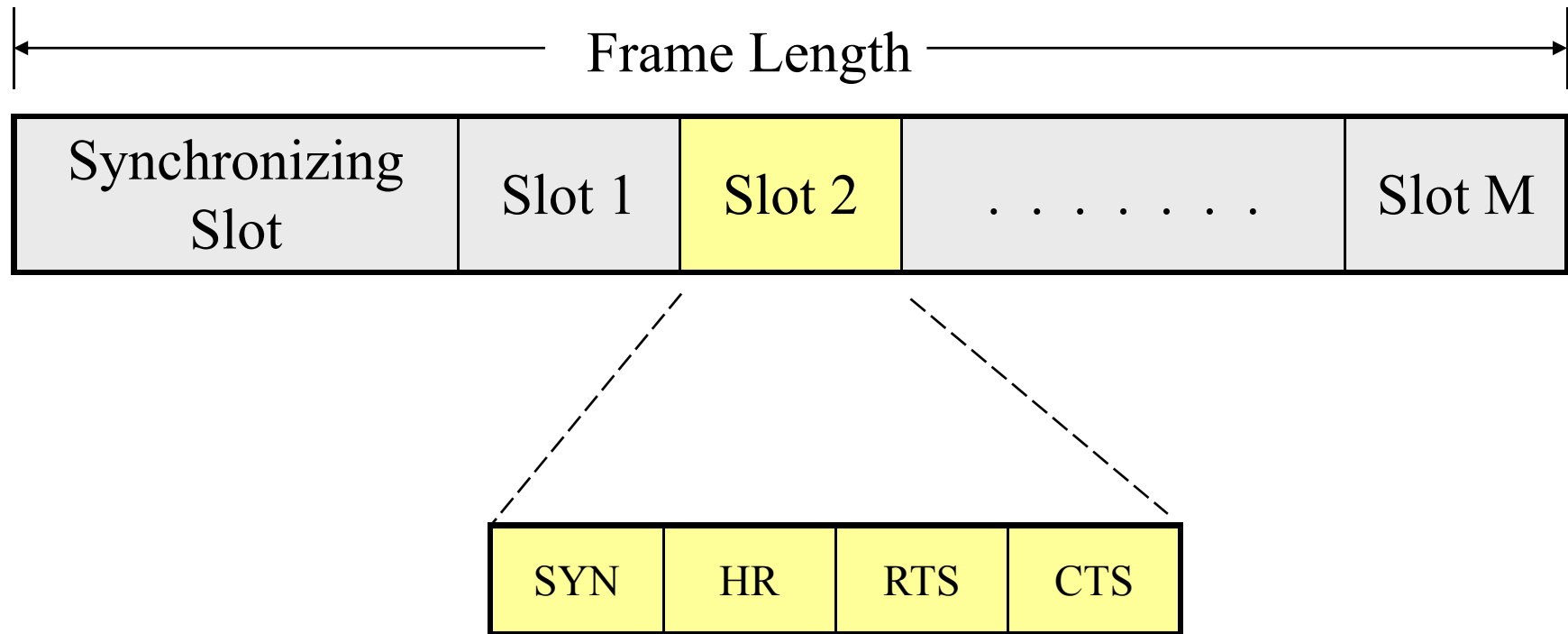
$$(f_i, f_i^*), i = 1, 2, 3, \ldots, M$$

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Figure 6.17. Frame format in HRMA .

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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 μ_s on the frequency f_0 (See Figure 6.18)

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

Figure 6.18. Merging of subnets.
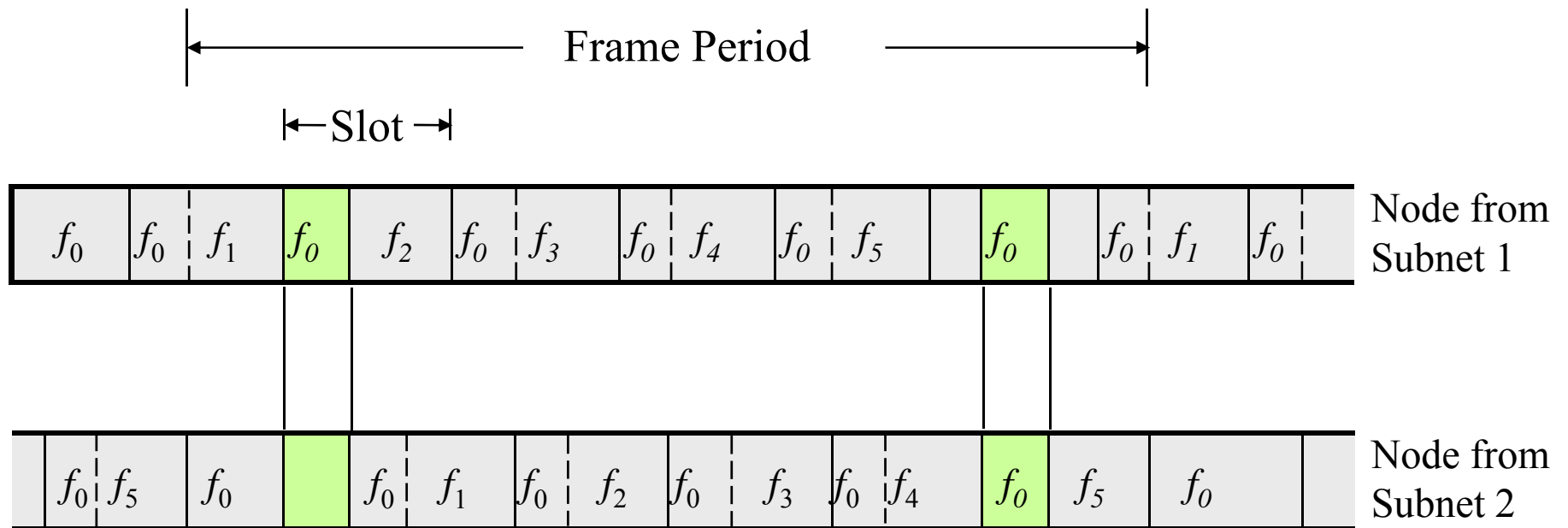
f_0 synchronizing frequency

$M = 5$

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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)

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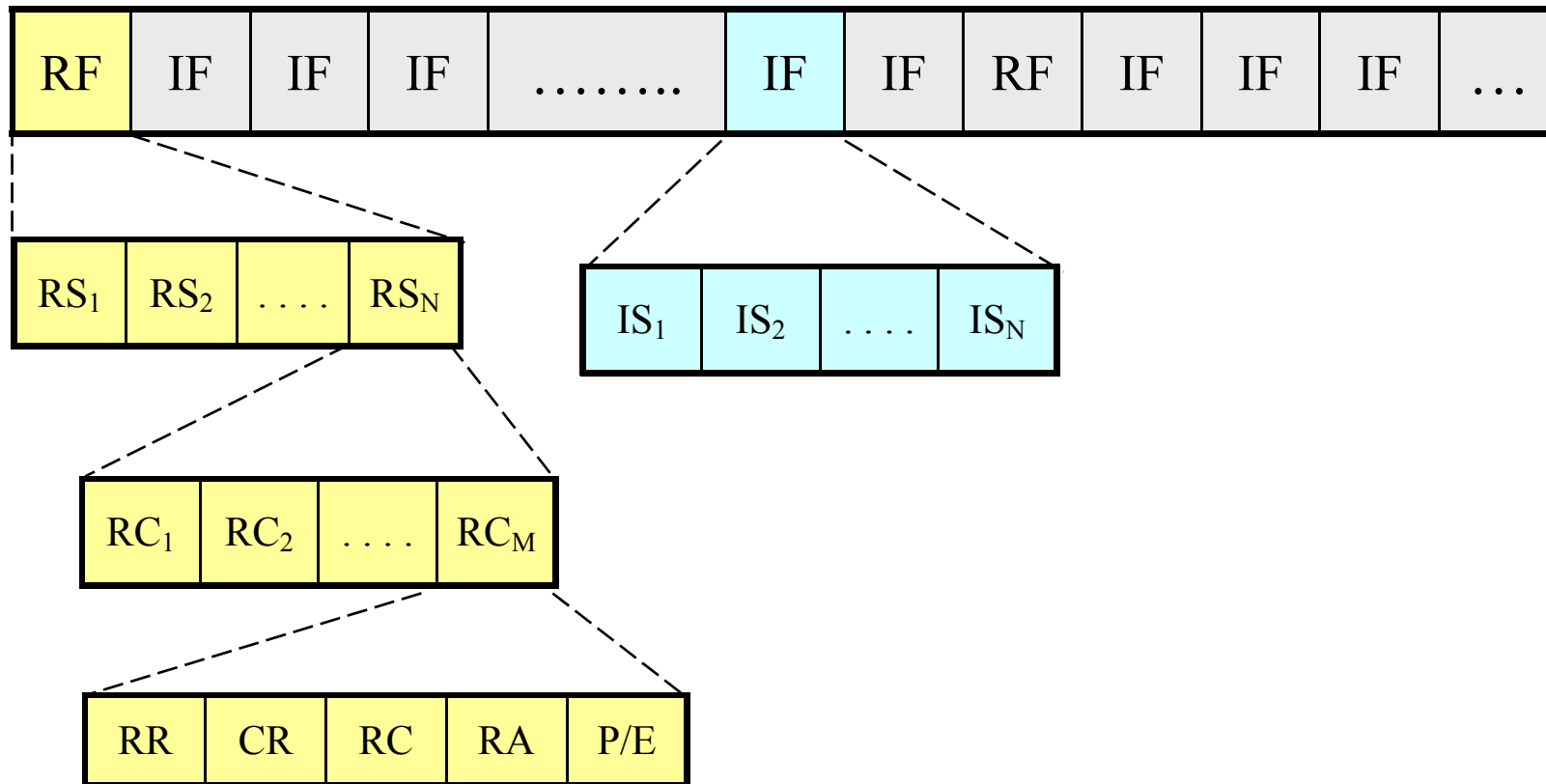
Figure 6.21. Frame structure in FPRP.

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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
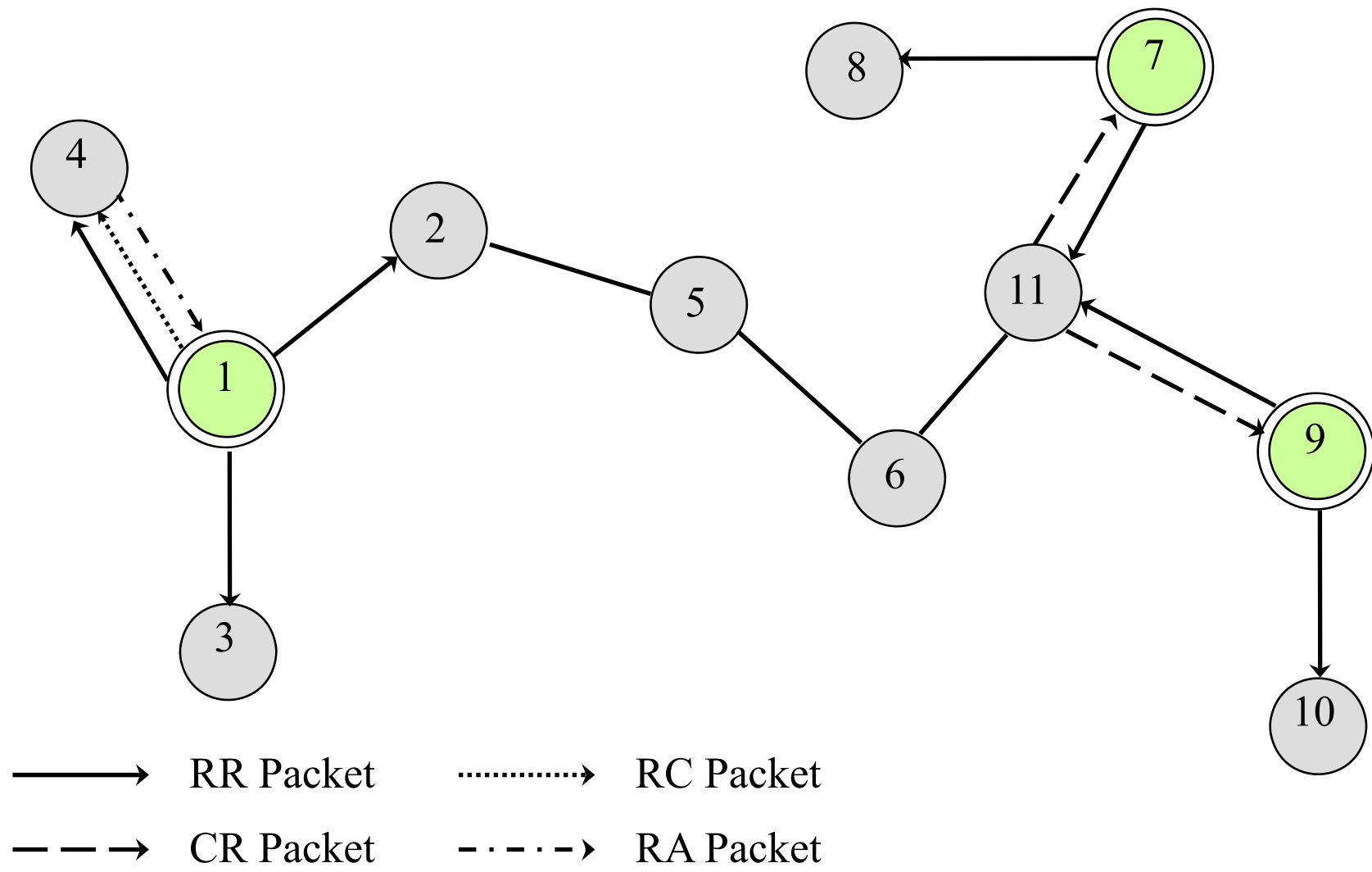- An example is shown in Figure 6.22

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Figure 6.22. FPRP - Example.

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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

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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
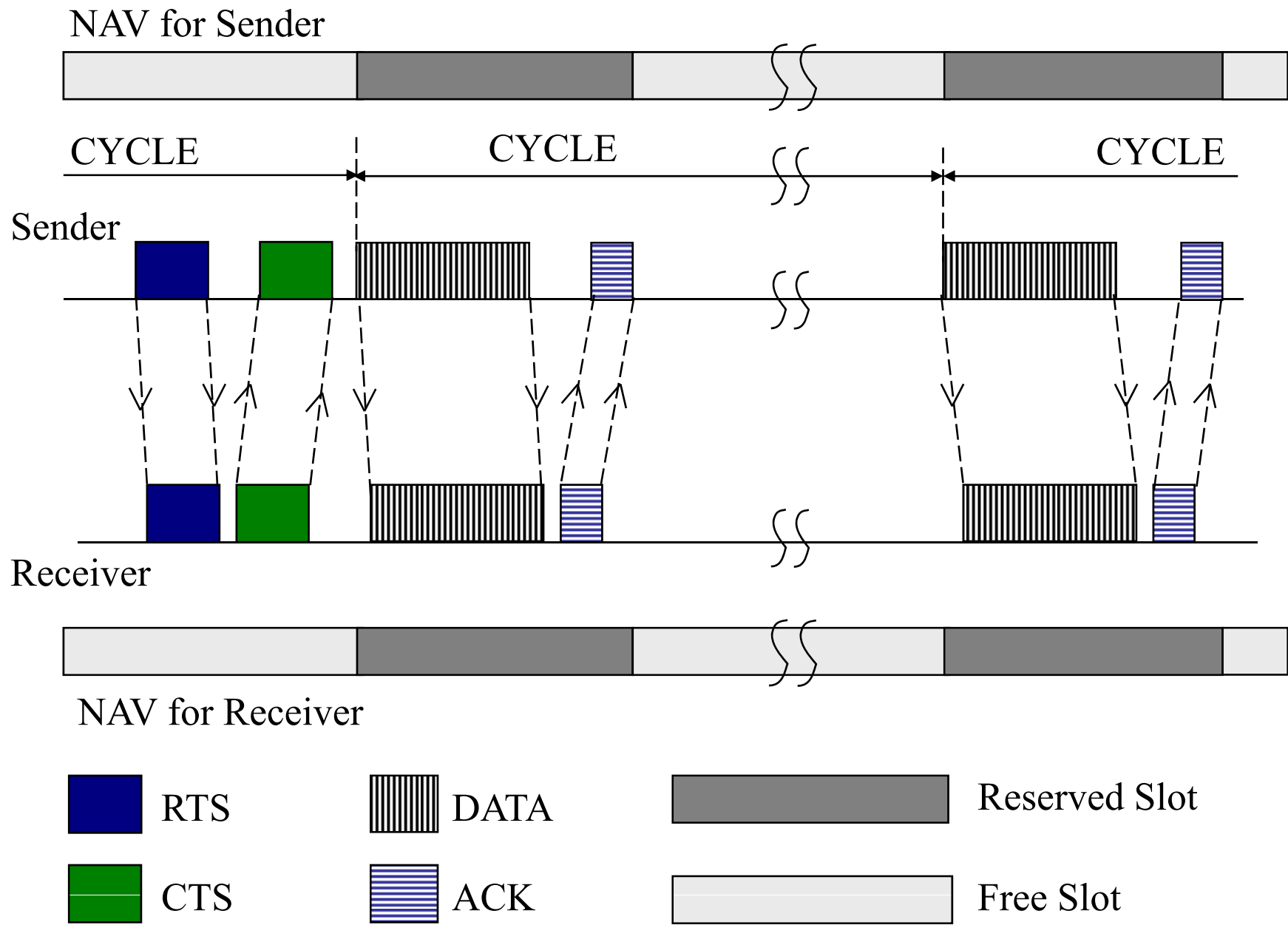- Drawback: possibility of many fragmented free slots not being used at all

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NAV for Sender

CYCLE CYCLE CYCLE

Sender

Receiver

NAV for Receiver

RTS DATA Reserved Slot

CTS ACK Free Slot

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)
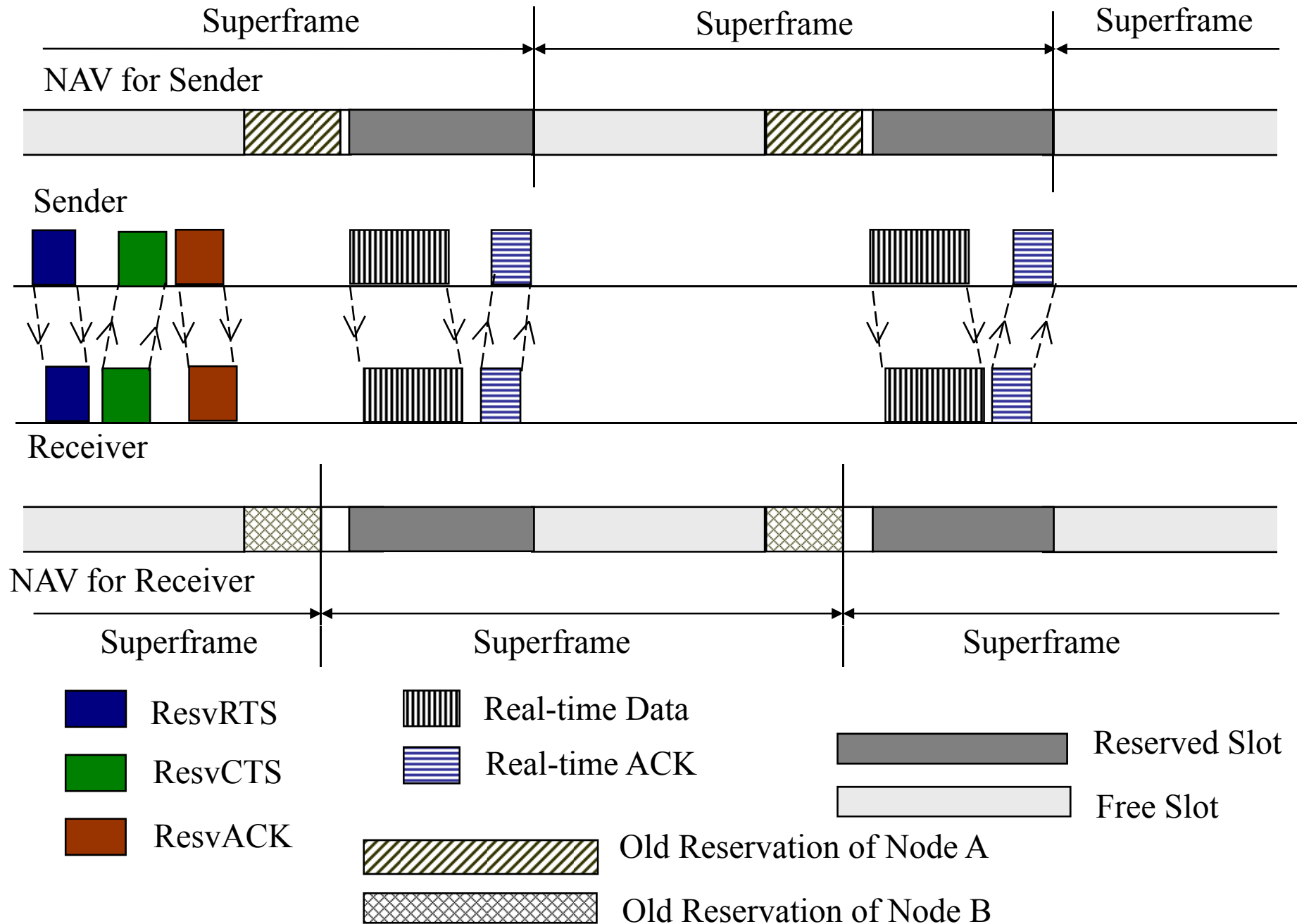
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Figure 6.24. Reservation mechanism in RTMAC.

Contention-Based MAC Protocols with Scheduling Mechanisms
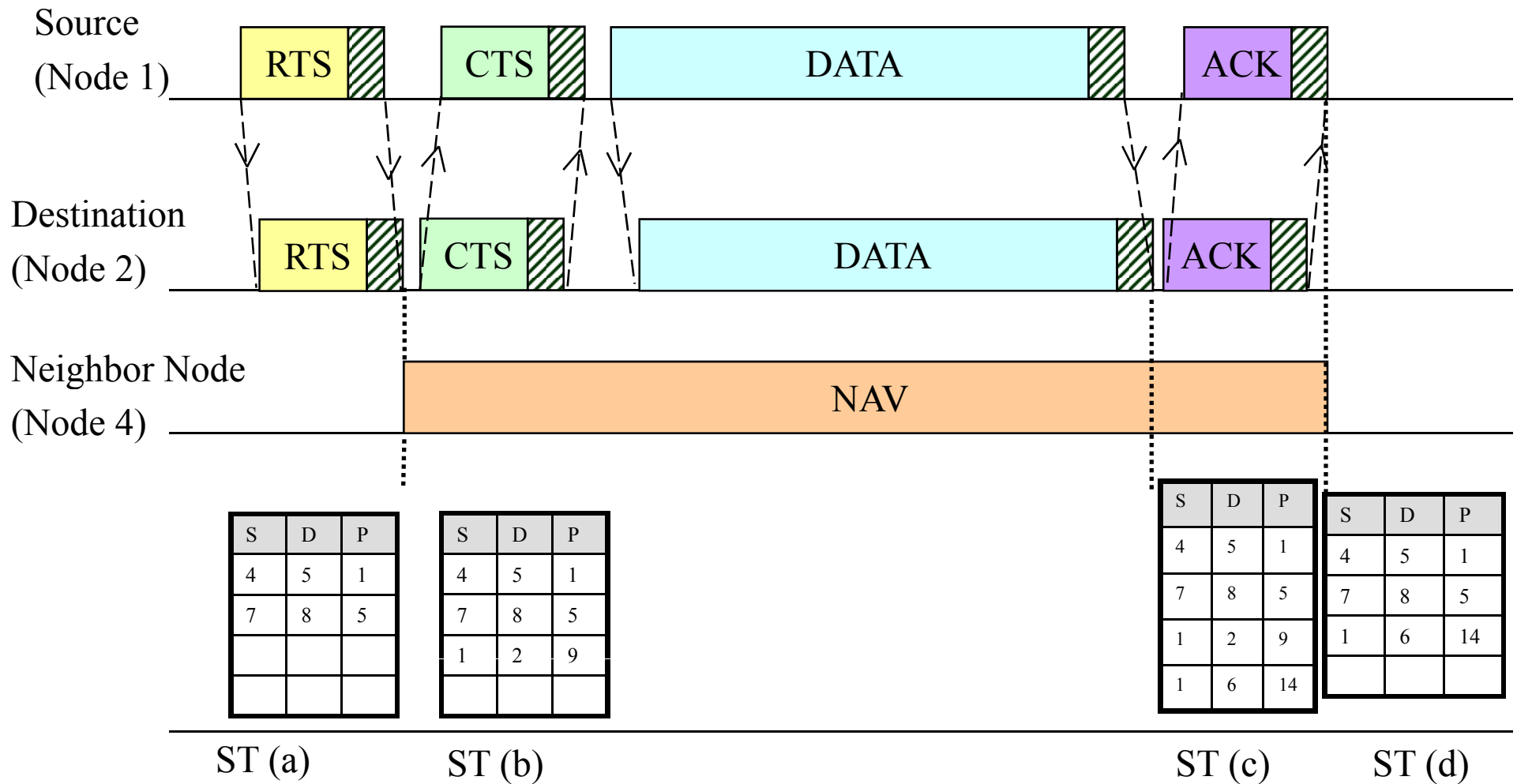
DPS: Distributed Priority Scheduling and MAC in Ad Hoc Networks

- 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
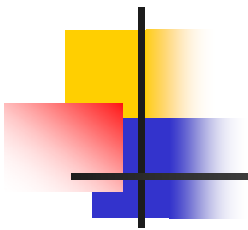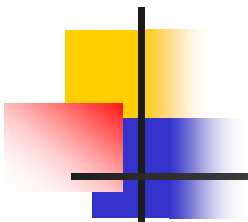 - DATA, ACK: carry next head-of-line info

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

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
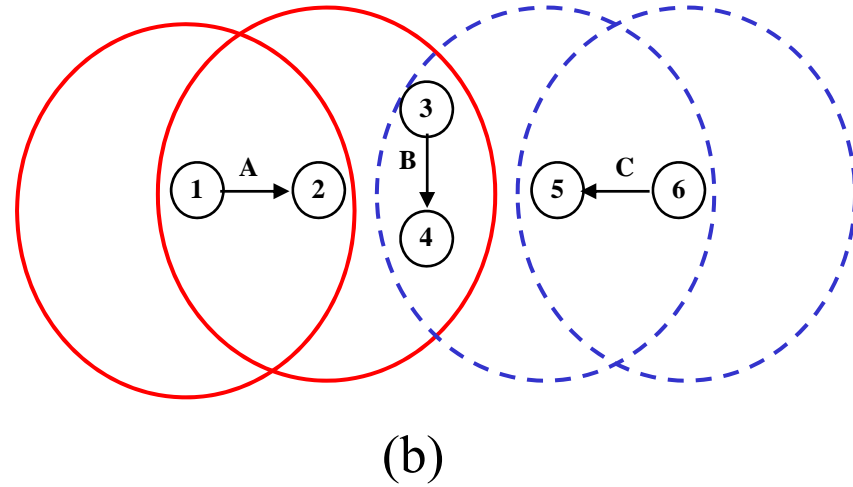
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Distributed Wireless Ordering Protocol (DWOP)

- 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

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(a)
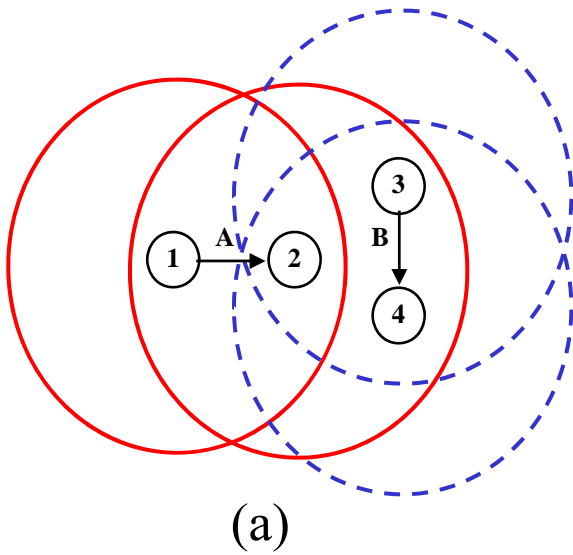
────── Coverage region of flow A

- - - - - Coverage region of flow B

────── Coverage region of flow A

- - - - - Coverage region of flow C

Figure 6.26 (a) Information asymmetry.　　(b) Perceived collisions.
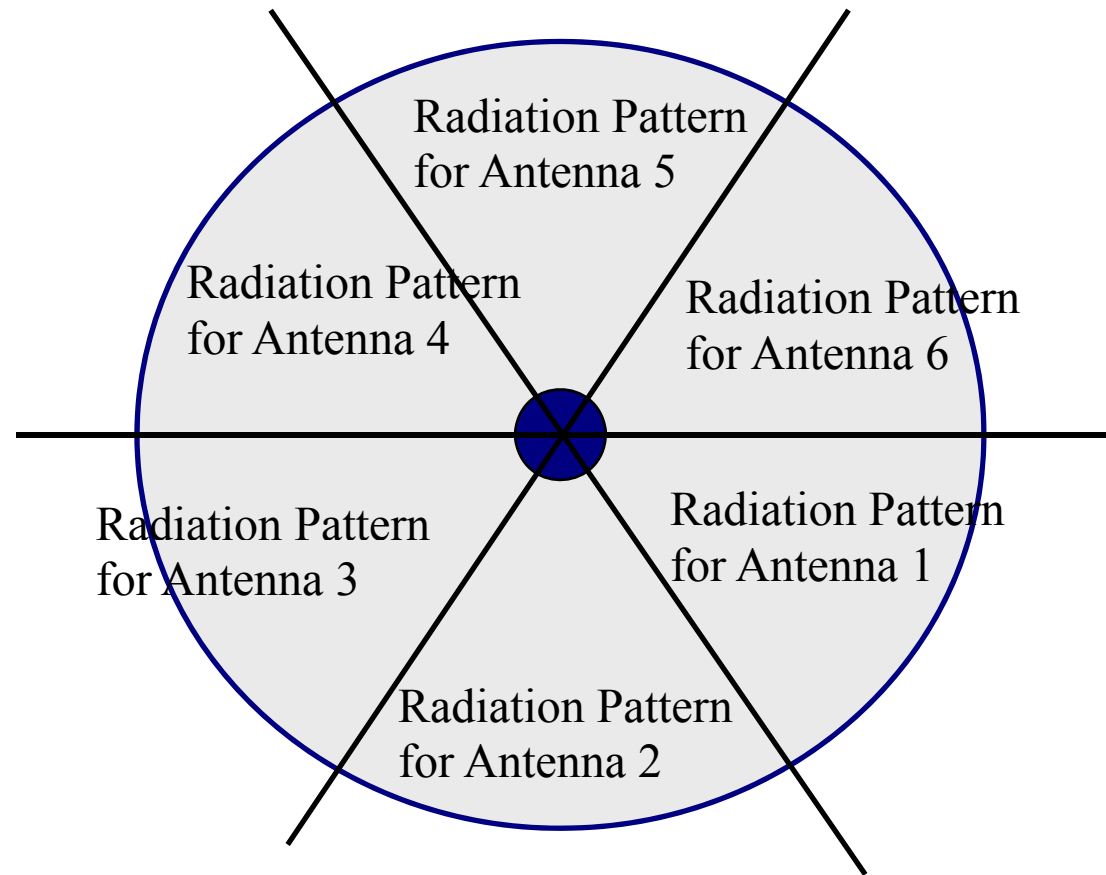
MAC Protocols with Directional Antennas
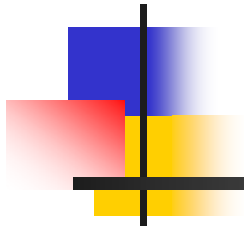
MAC Protocol Using Directional Antennas

- 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 omni-directional antennas
- Packet transmission--See Figure 6.29

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Radiation Pattern for Antenna 5

Radiation Pattern for Antenna 4

Radiation Pattern for Antenna 6

Radiation Pattern for Antenna 3

Radiation Pattern for Antenna 1

Radiation Pattern for Antenna 2

Node with 6 antennas ($M = 6$)

Figure 6.28. Radiation patterns of directional antennas.
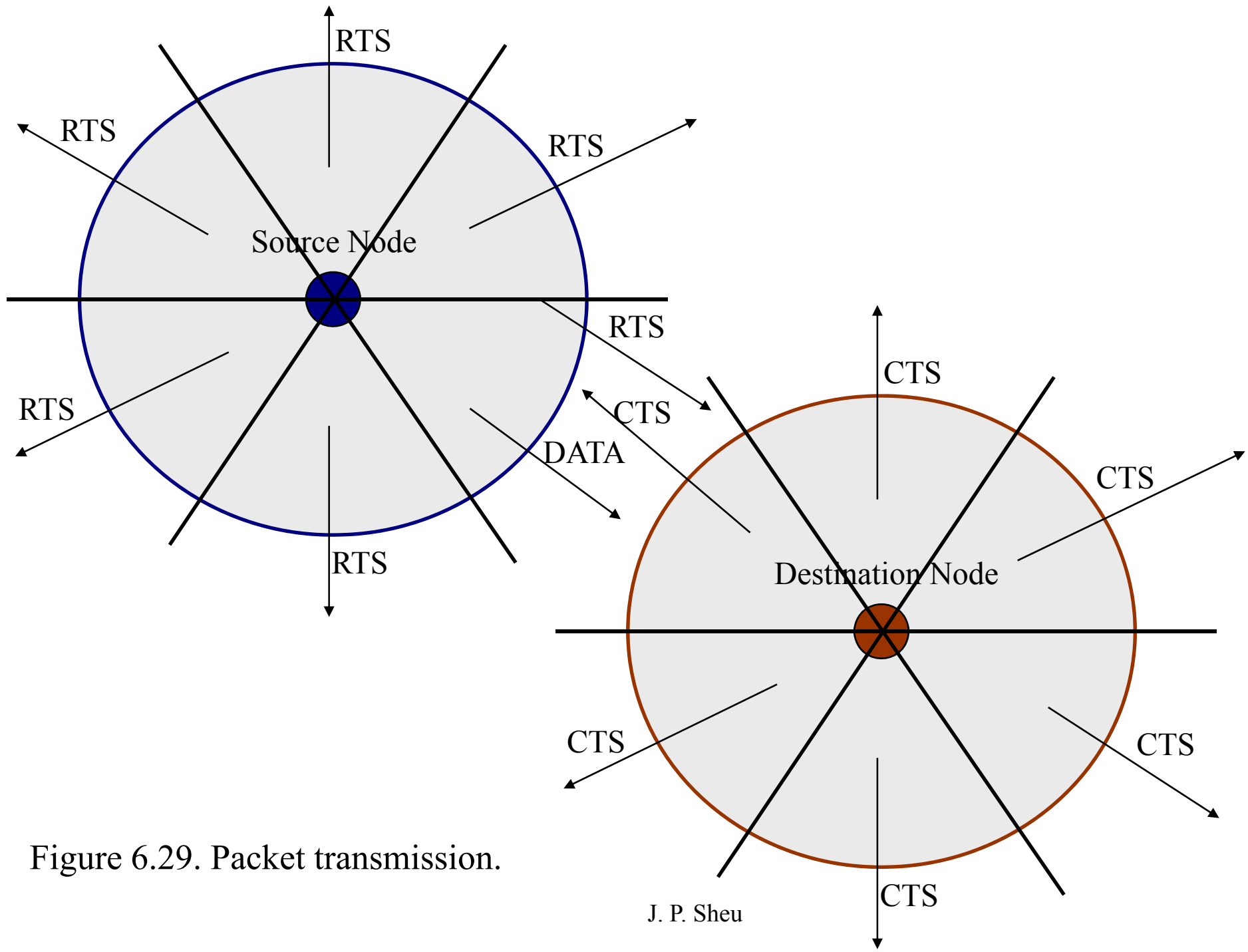
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Figure 6.29. Packet transmission.

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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)
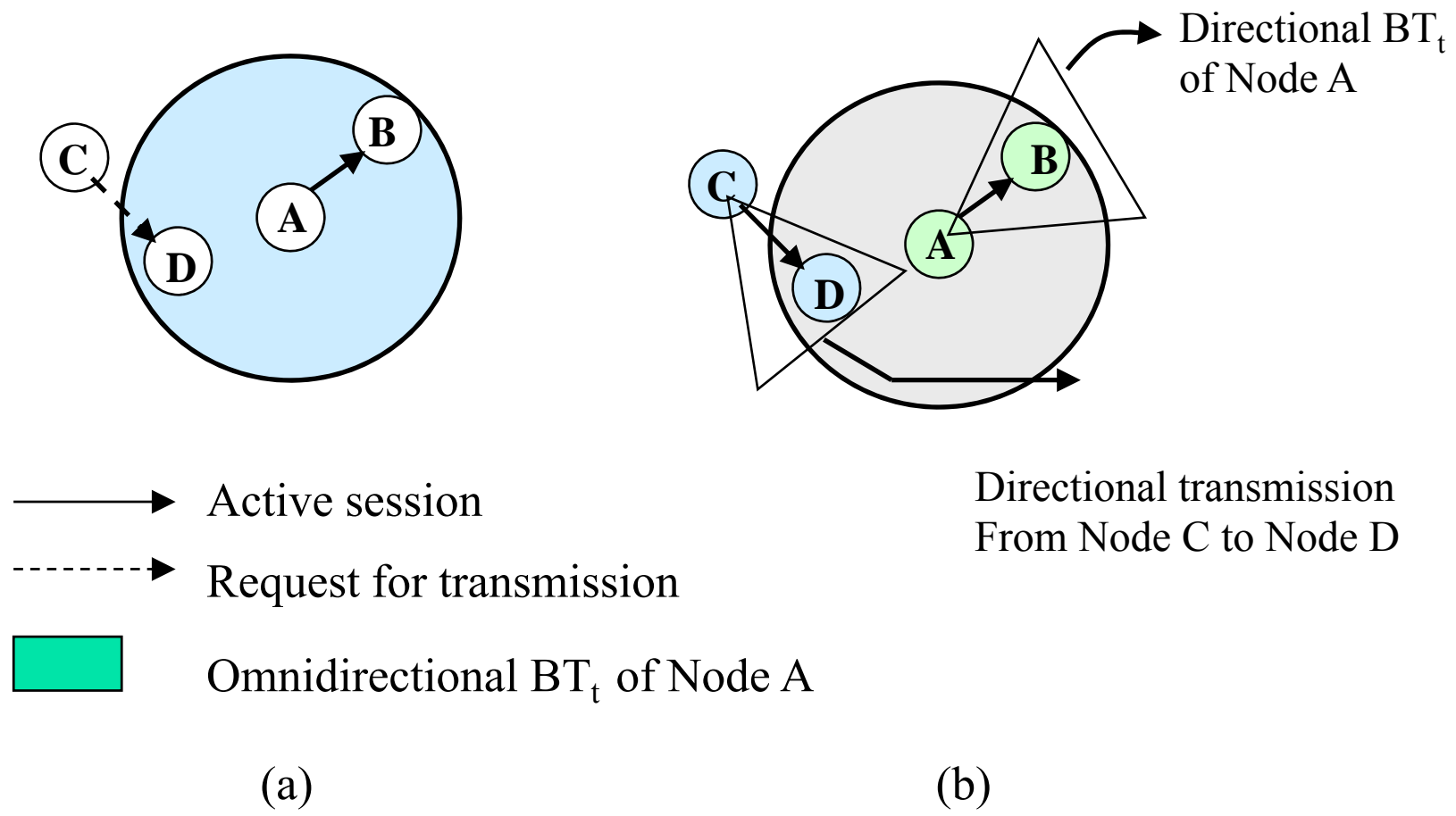- This protocol is not guaranteed to be collision free (see Fig. 6.31 b)

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Active session

Request for transmission

Omnidirectional BT_t of Node A

Directional BT_t of Node A

Directional transmission From Node C to Node D

(a)

(b)

Figure 6.30. Directional DBTMA: Example 1.

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Directional BT$_r$
of Node B

Directional transmission
From Node C to Node D

Active session

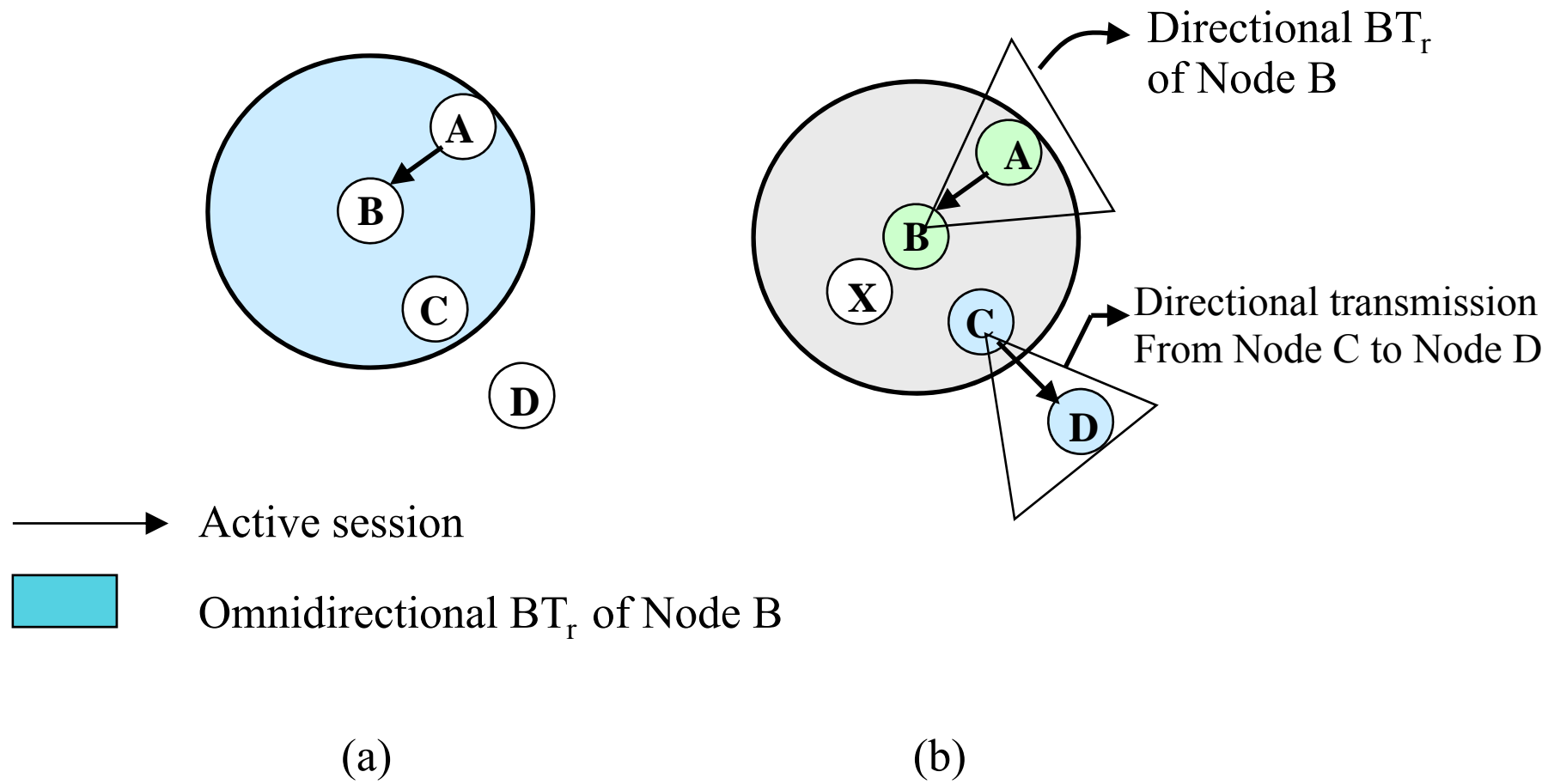Omnidirectional BT$_r$ of Node B

(a)   (b)

Figure 6.31. Directional DBTMA: Example 2.

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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)

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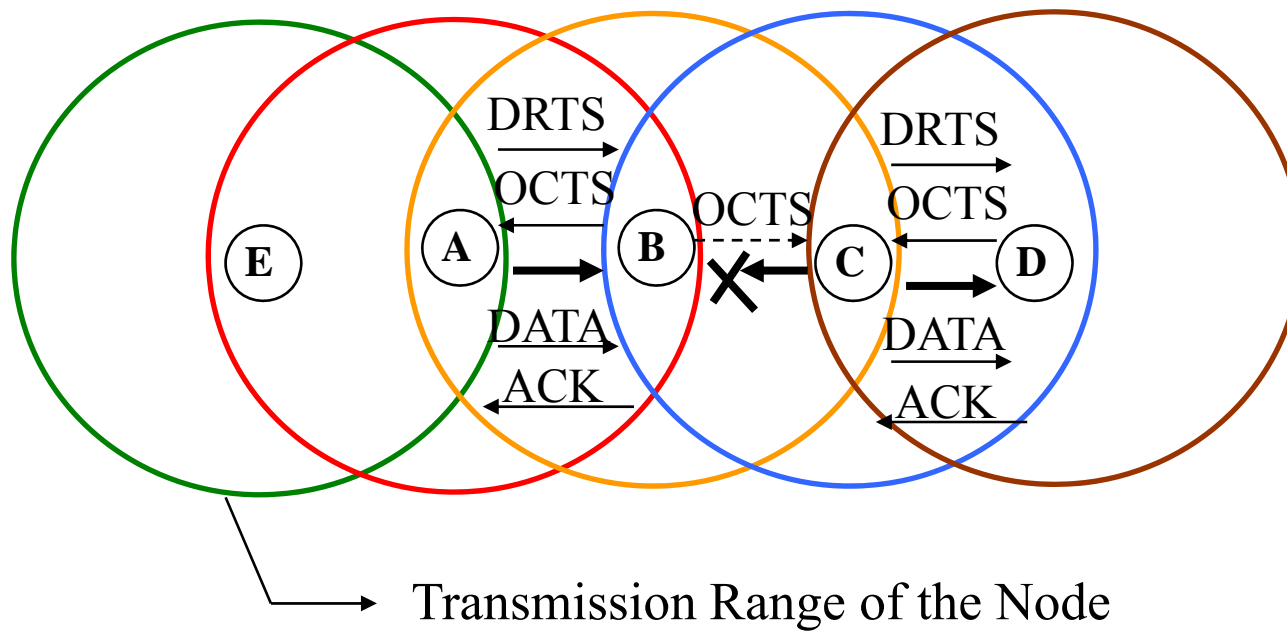
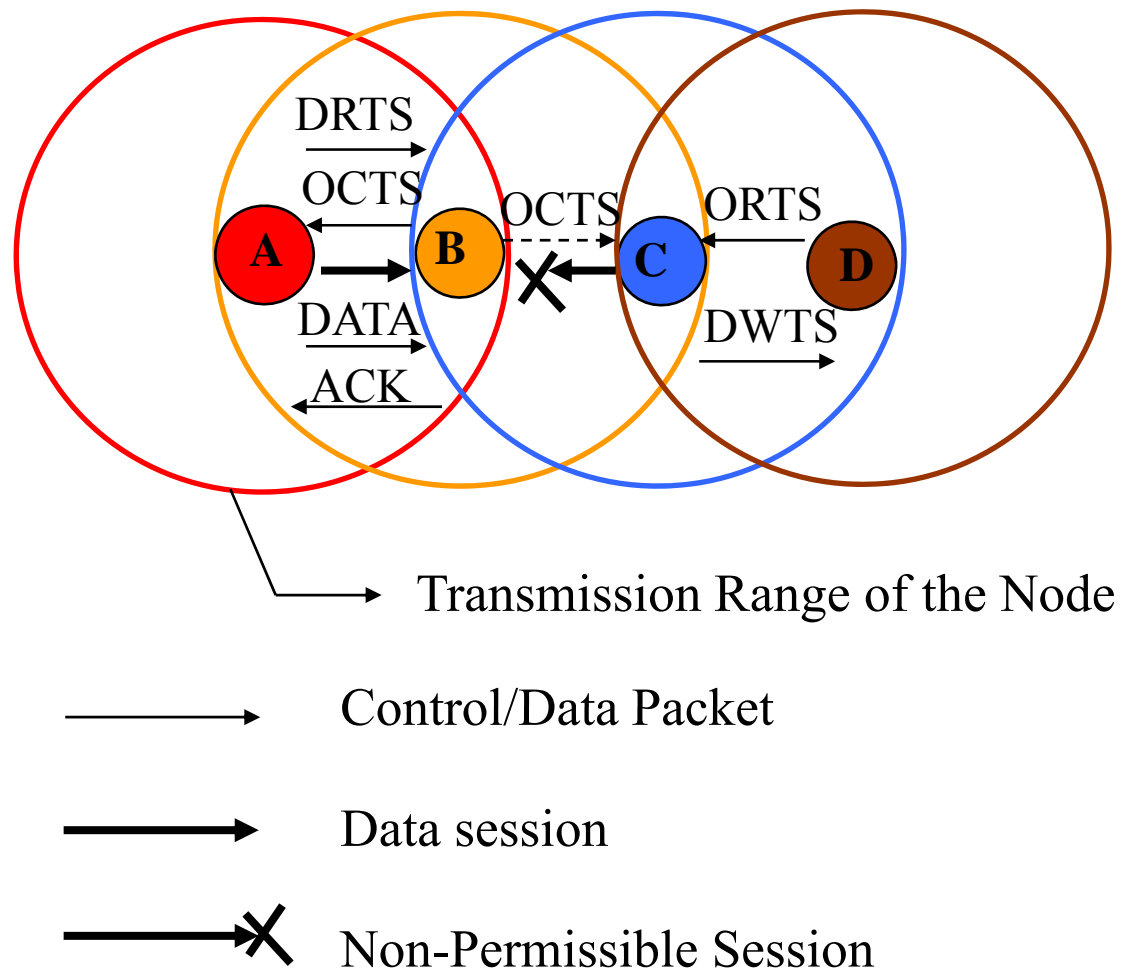Figure 6.32. Operation of DMAC protocol.

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Figure 6.33. Operation of DMAC protocol.

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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

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ATIM Window
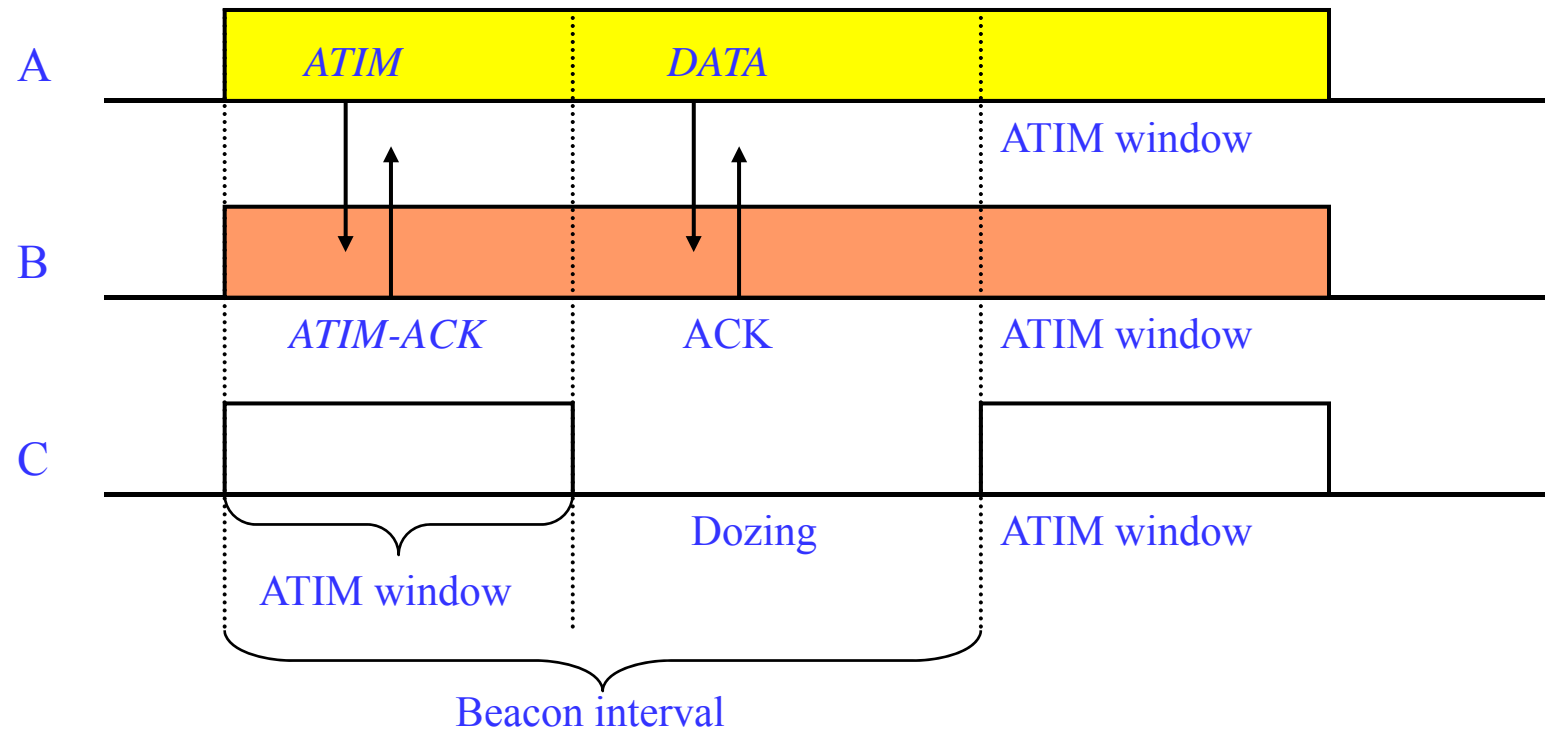
Power saving mechanism for DCF: Node A announces a buffered frame for B using an ATIM frame. Node B replies by sending an ATIM-ACK, and both A and B stay awake during the entire beacon interval. The actual data transmission from A to B is completed during the beacon interval. Since C does not have any frame to send or receive, it dozes after the ATIM window.
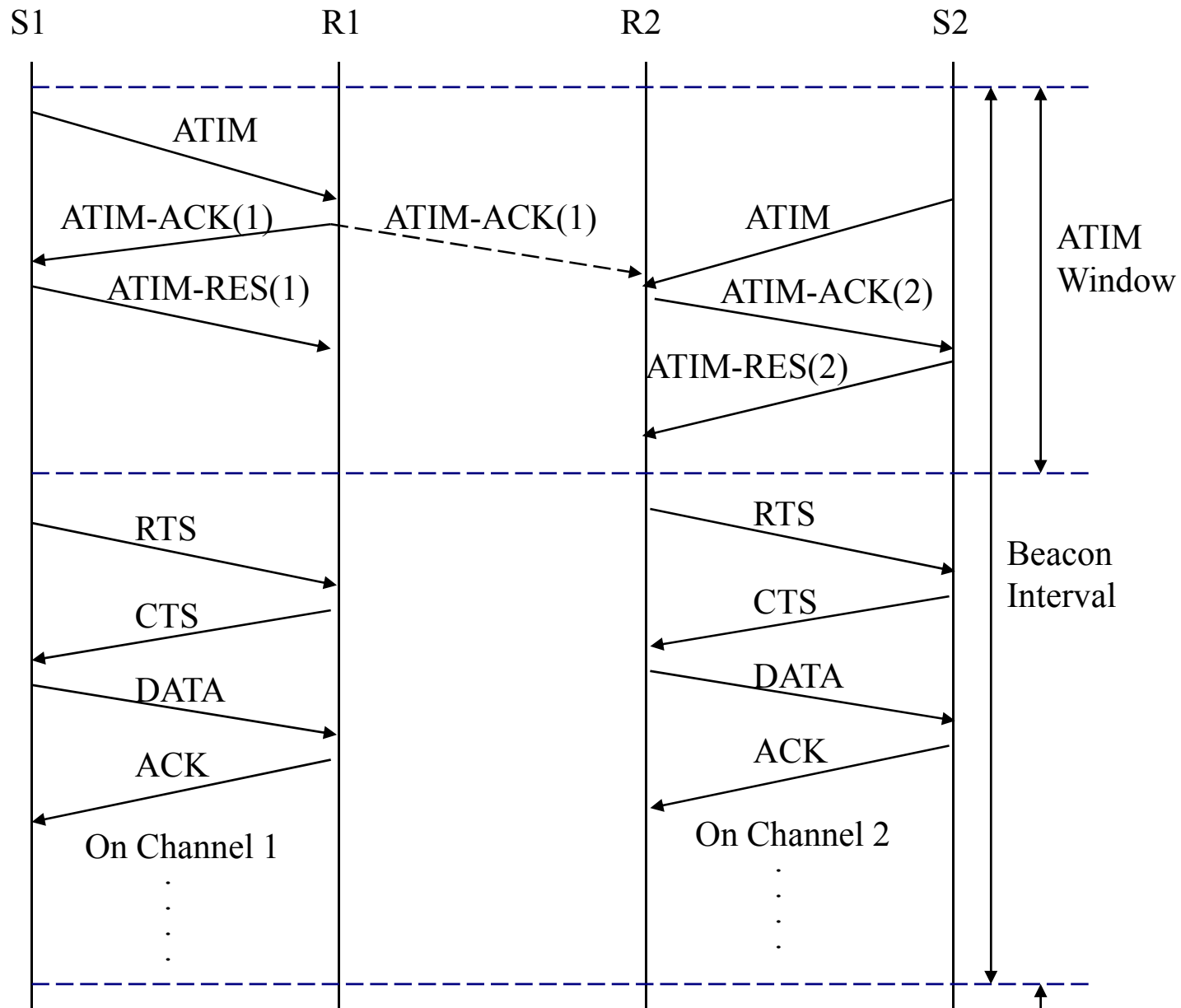
Figure 6.34. Operation of MMAC protocol.

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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

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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

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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:

  $p_{desired} = (p_{max}/p_r)$ x Rx_{thresh} x 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)
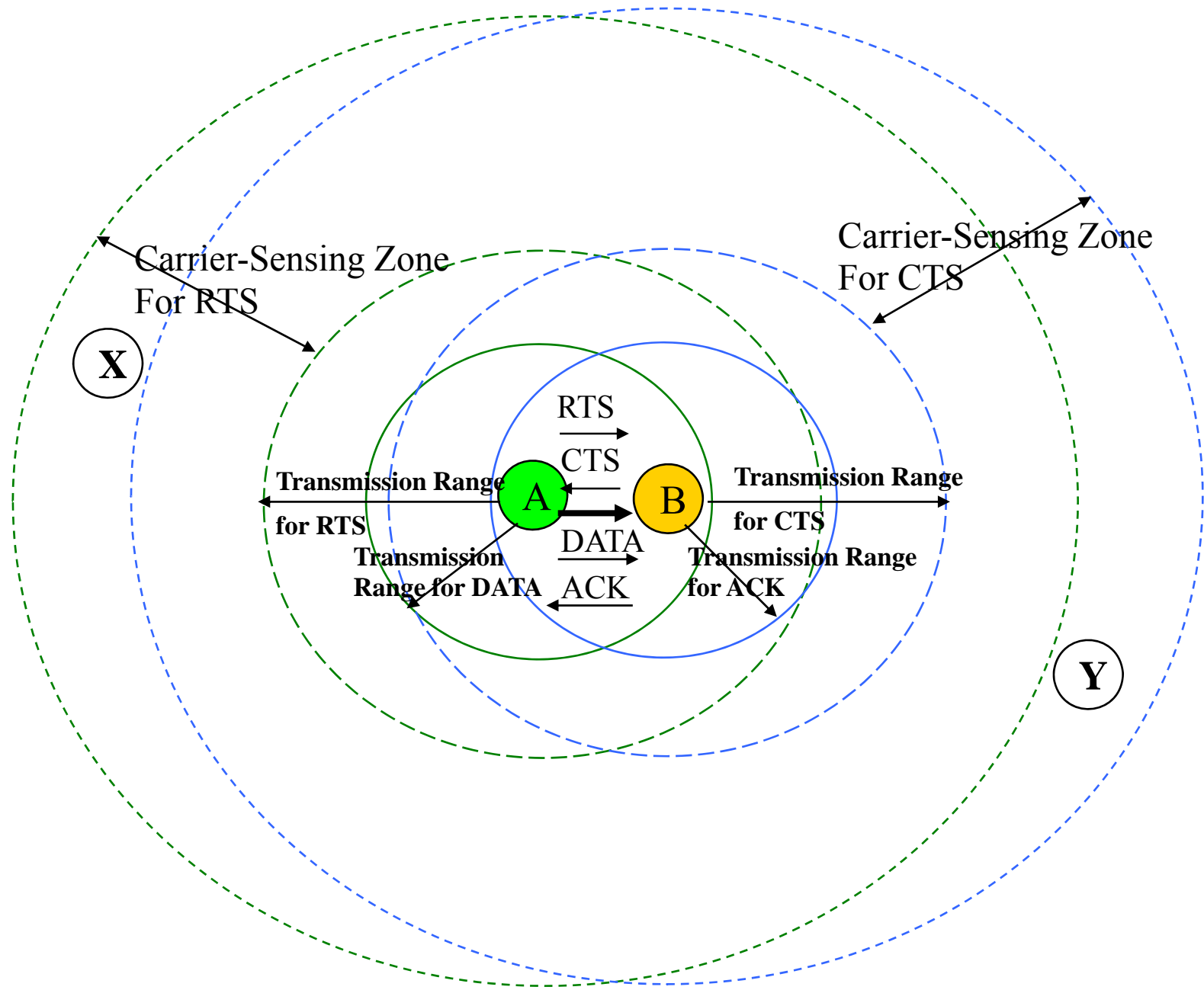
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Figure 6.35. Packet transmission in BASIC scheme.

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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)
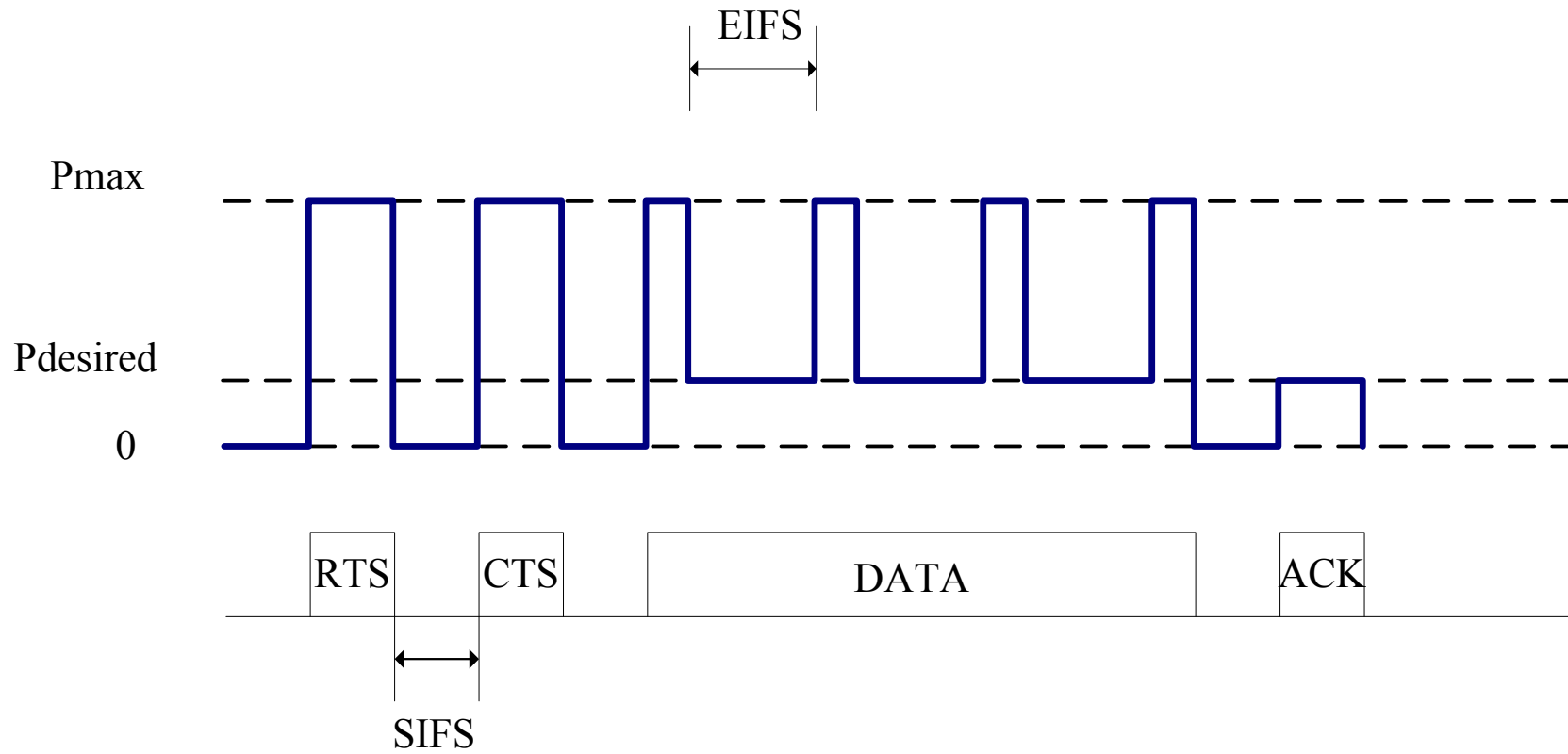
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Figure 6.36 . Transmission power pattern in PCM.

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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
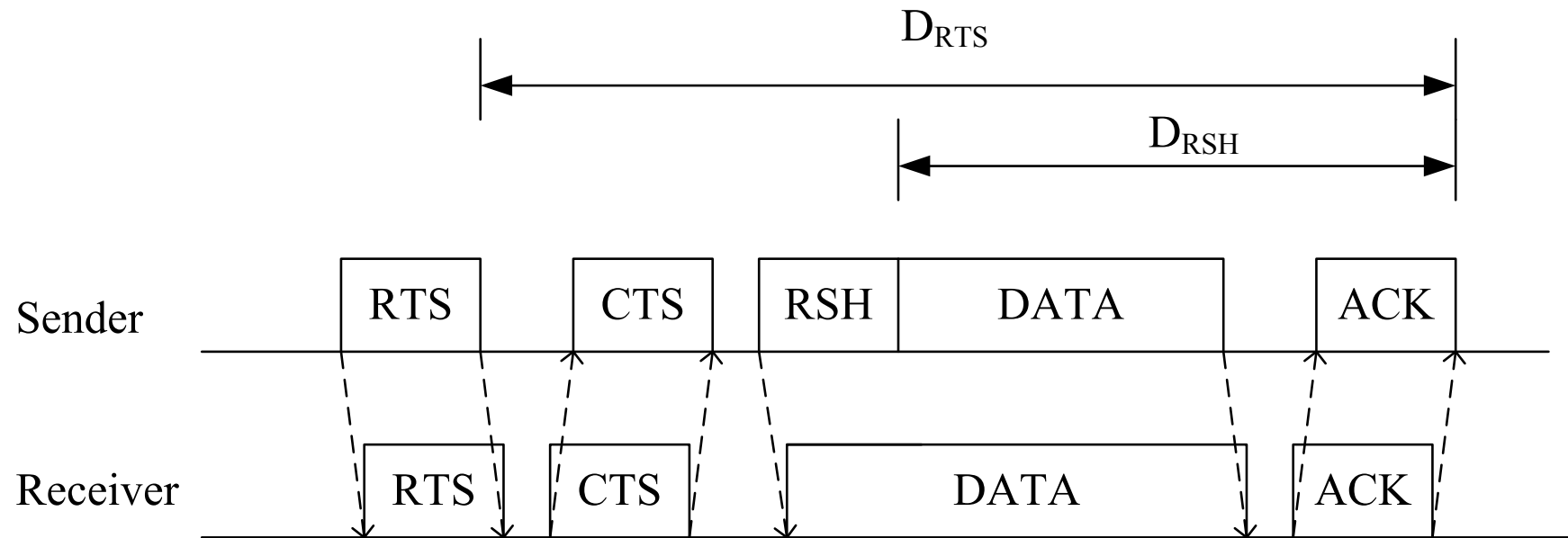
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Figure 6.37. Packet transmission in RBAR

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

ICSMA: 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
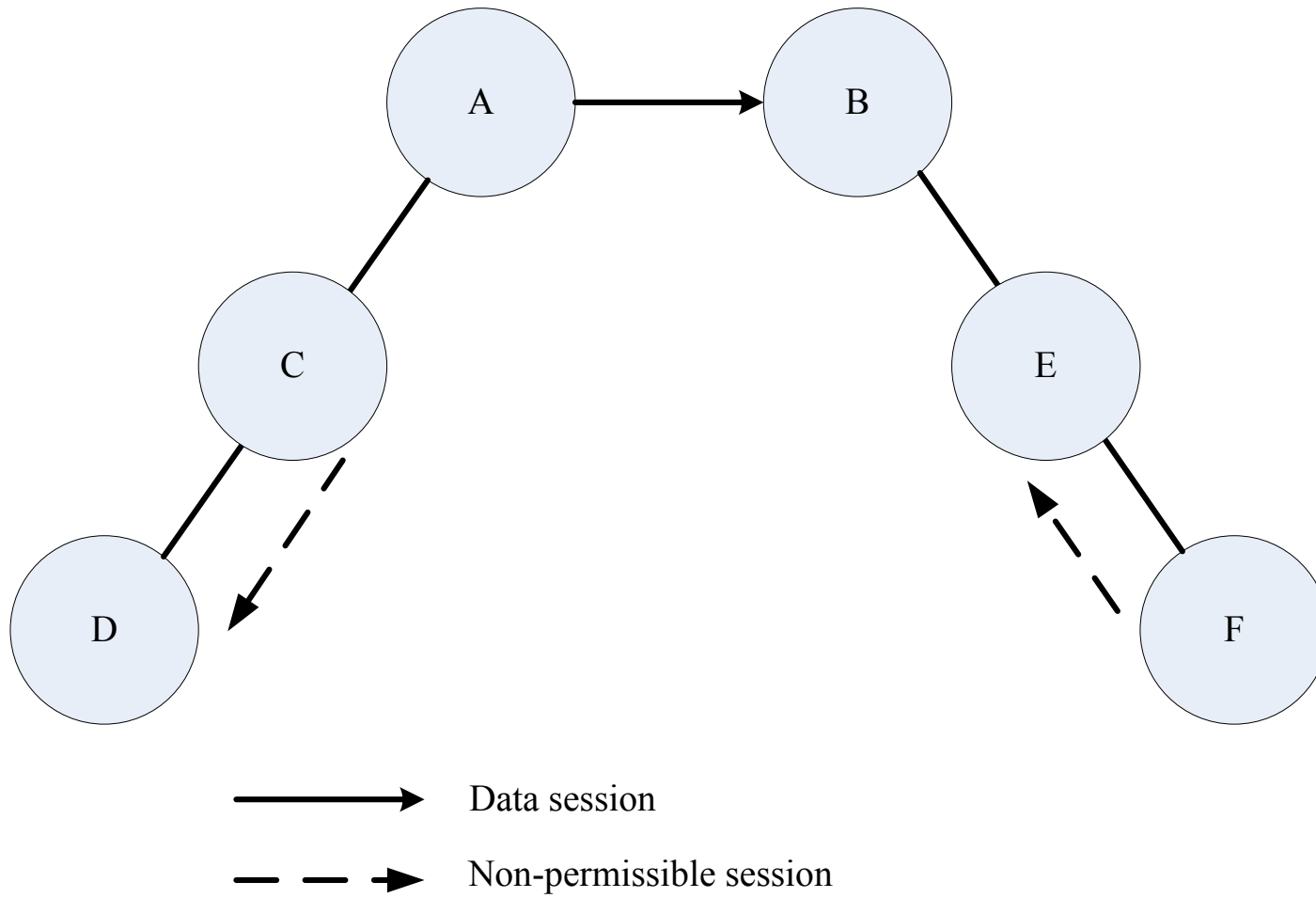
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Figure 6.38. Exposed terminal problem.

ICSMA: 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 $s_1, f_1; s_2, f_2; \ldots; s_k, f_k$, 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
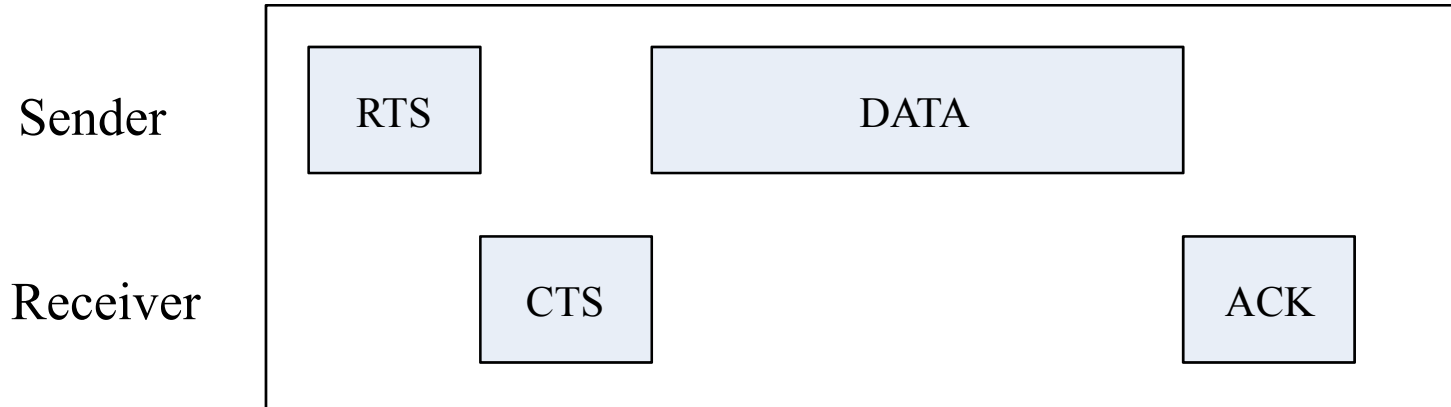- See Figure 6.39

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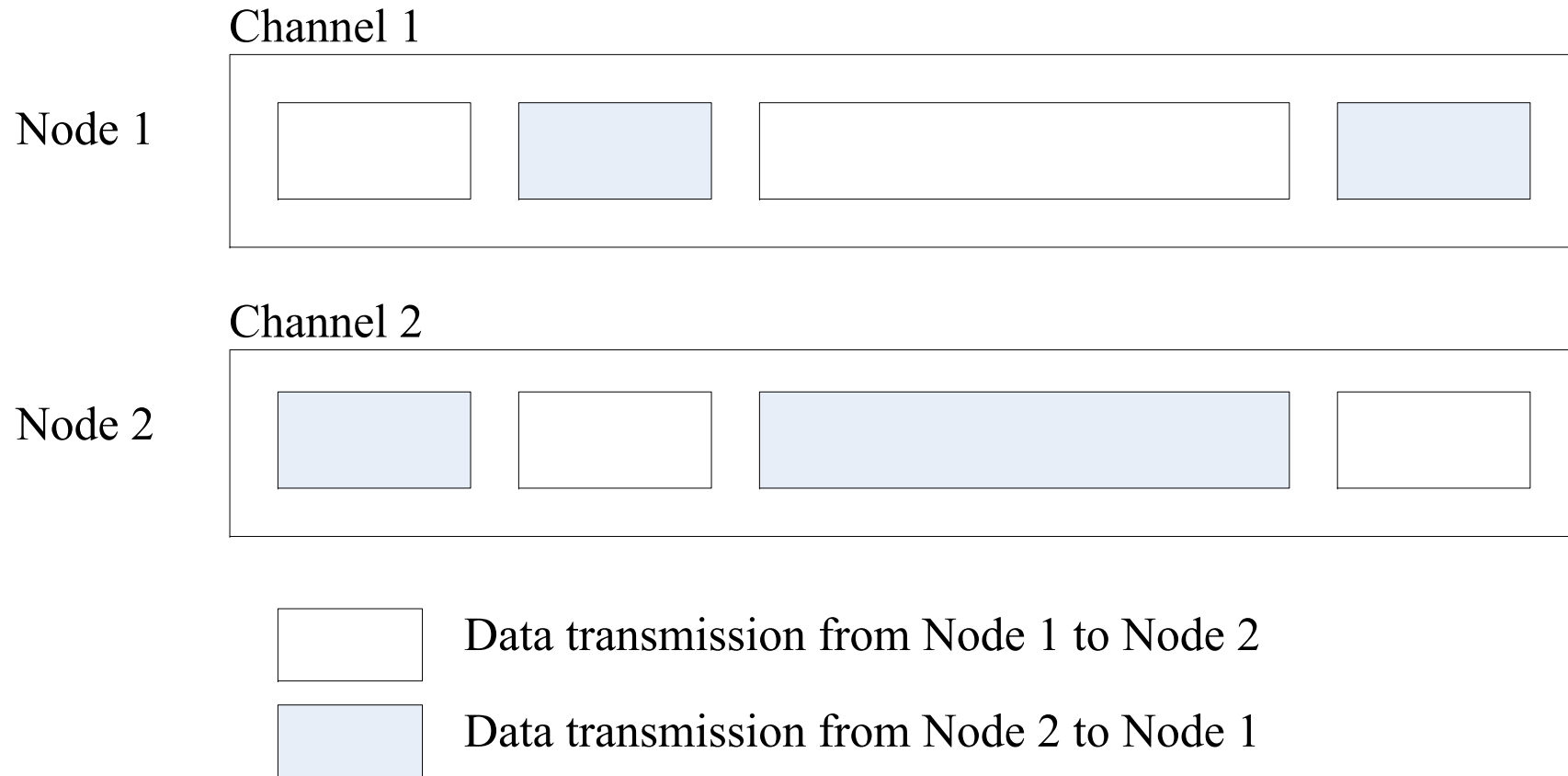Figure 6.39. (a) Packet transmissions in 802.11 DCF

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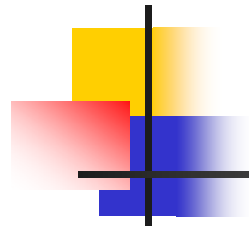Figure 6.39. (b) Packet transmissions in ICSMA.

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

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Exercises

- 1, 4, 5, 10, 14, 15

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