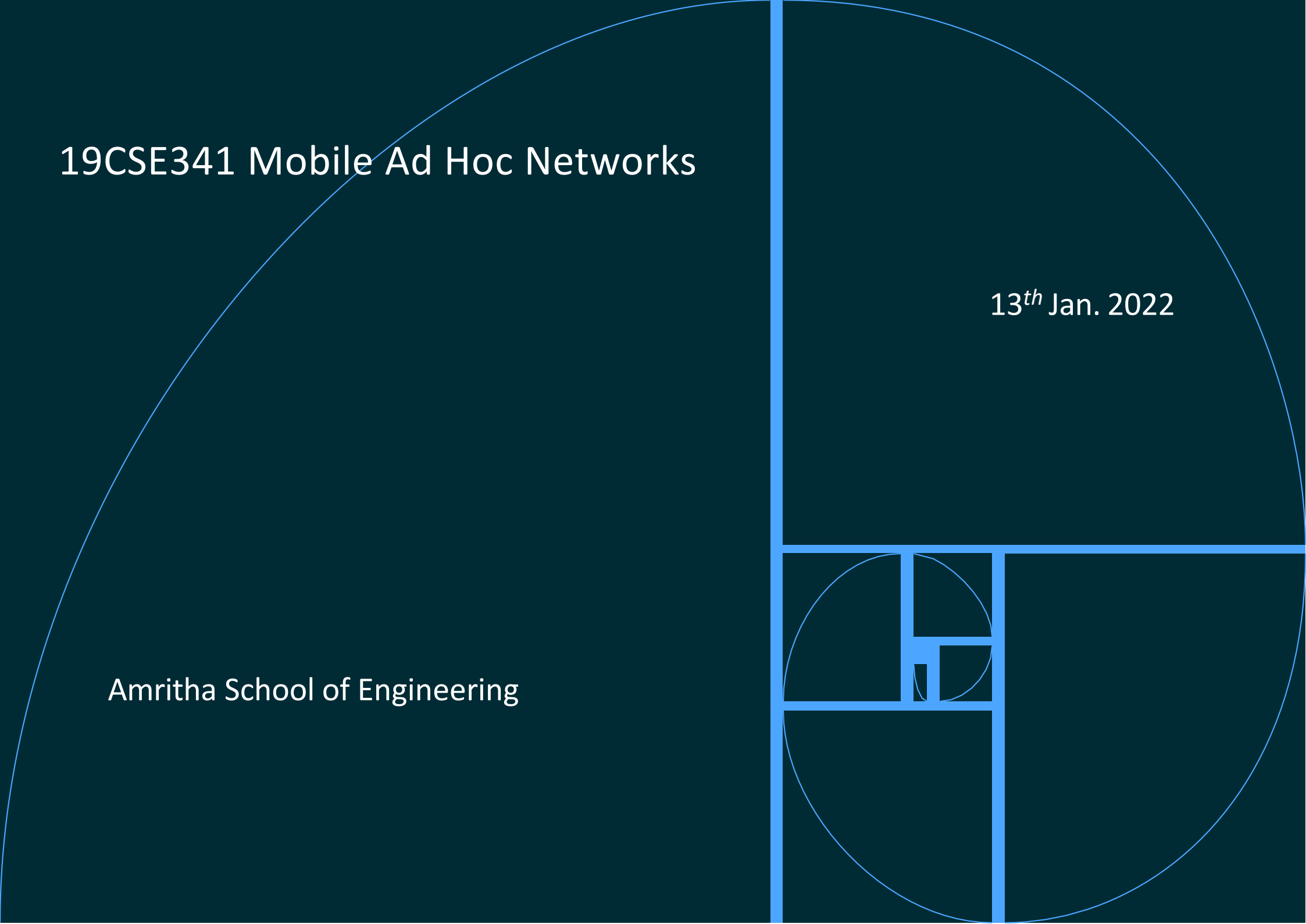


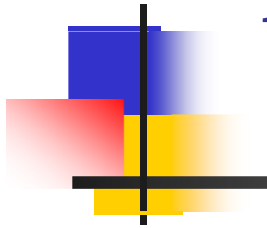
19CSE341 Mobile Ad Hoc Networks

13th Jan. 2022

Amritha School of Engineering



MAC Protocols for Ad Hoc Wireless Networks





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

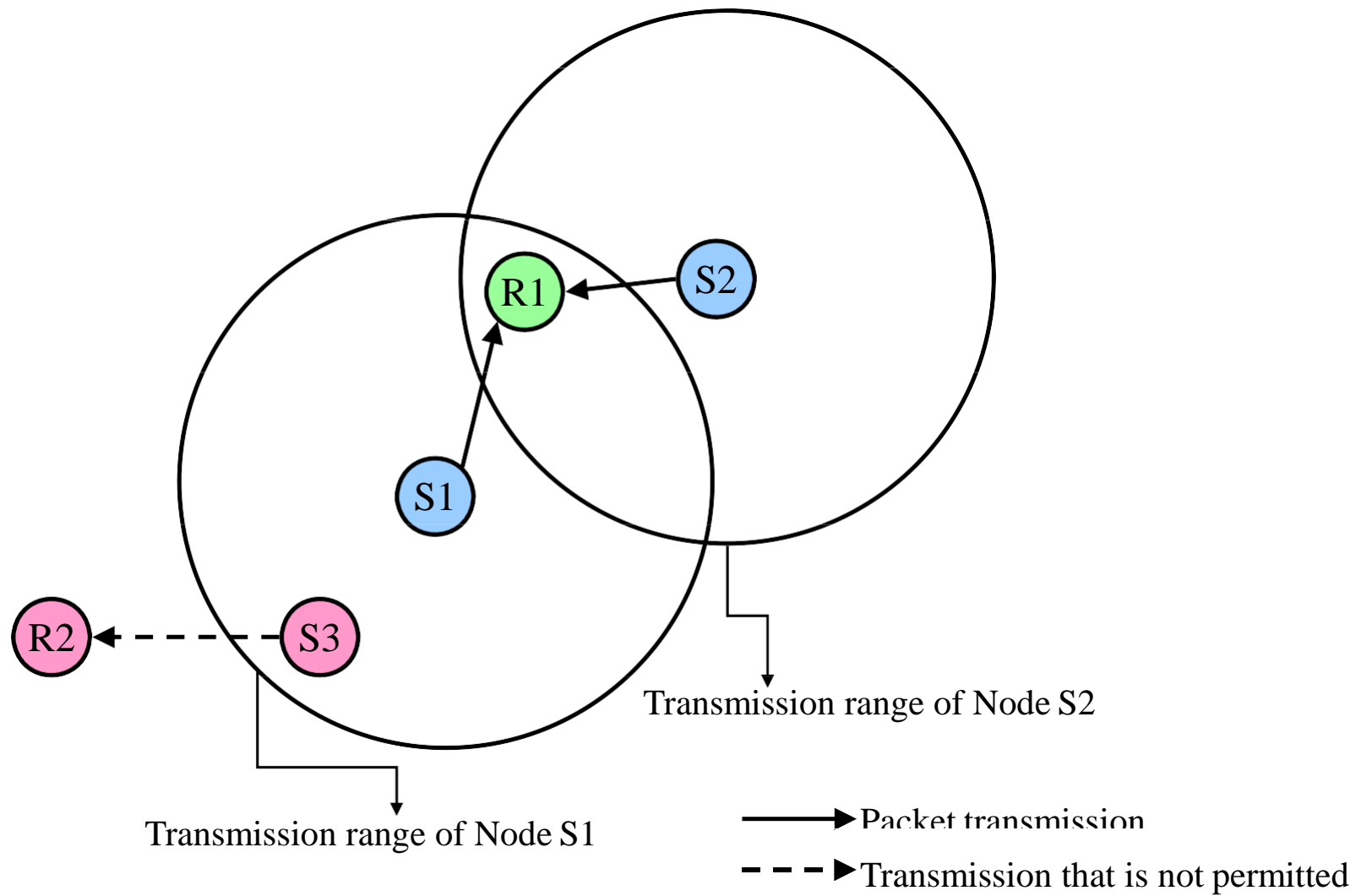


Figure 6.1 Hidden and exposed terminal problems



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



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

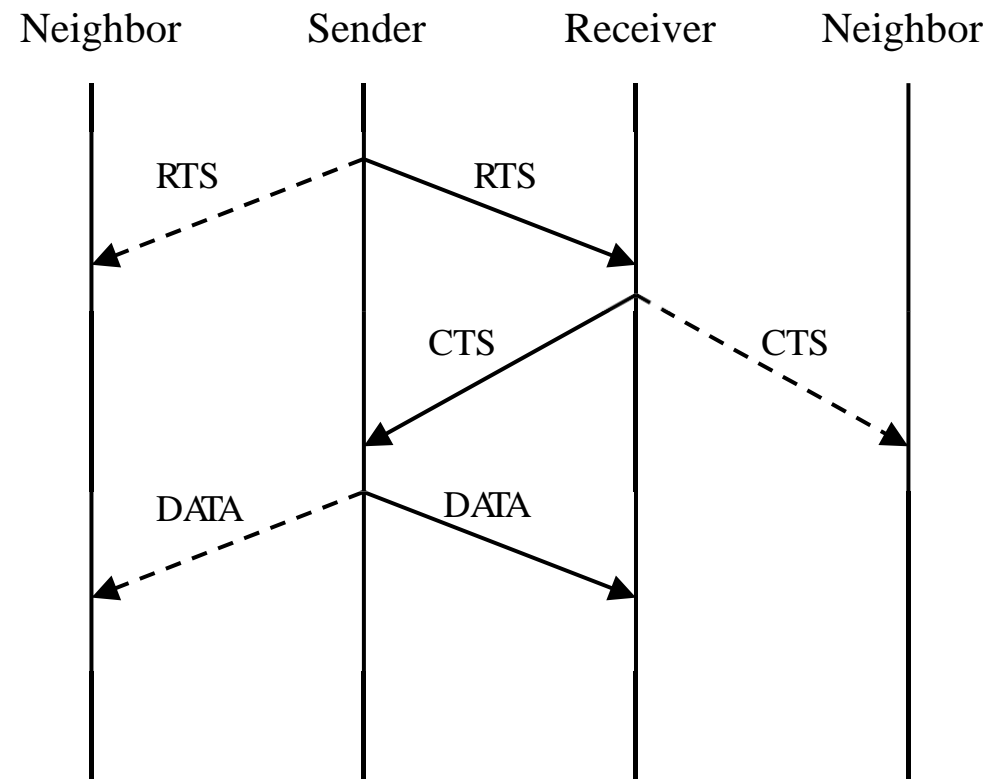


Figure 6.3 Packet transmission in MACA



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

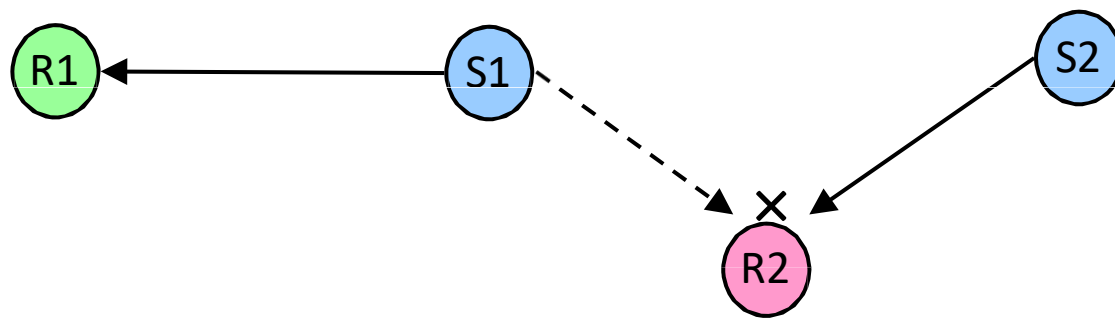


Figure 6.4 Example topology



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

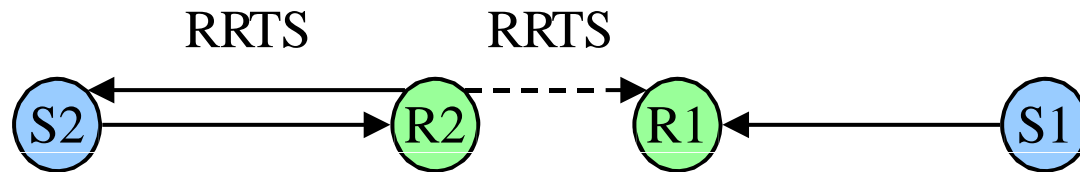


Figure 6.6 Example topology.



MACAW Protocol (cont.)

- Another control packet: request for request to send (RTTS), 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 RTTS
- Figure 6.7 shows the operation of the MACAW protocol
 - RTS-CTS-DS-DATA-ACK

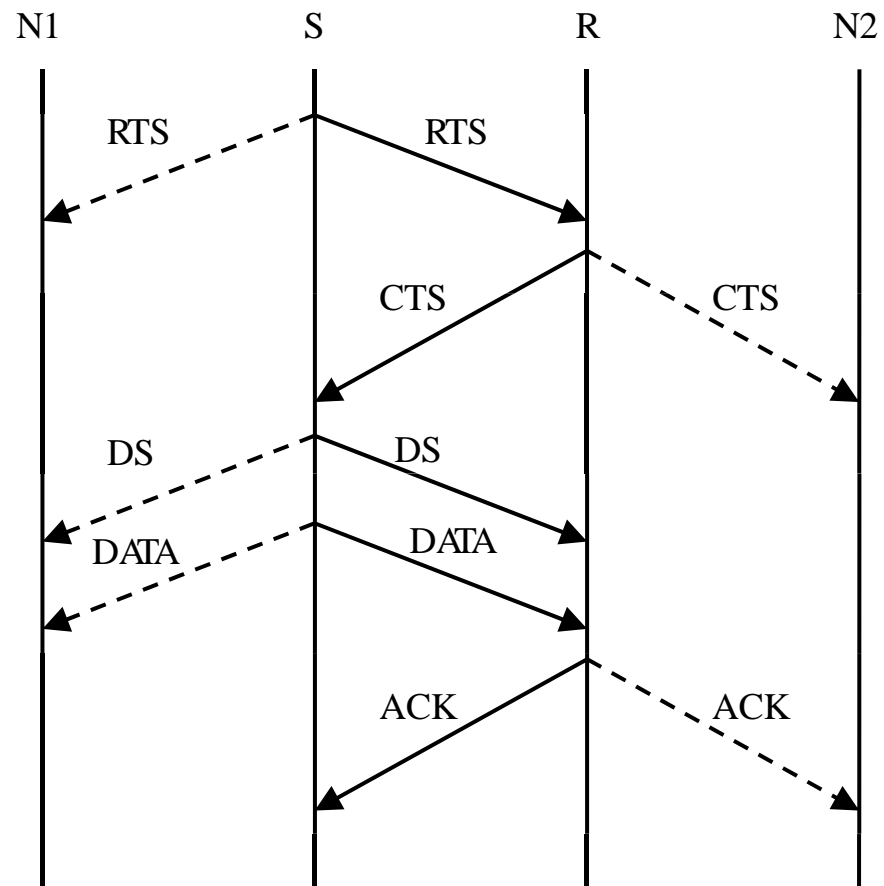


Figure 6.7 Packet exchange in MACAW.



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 τ 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)

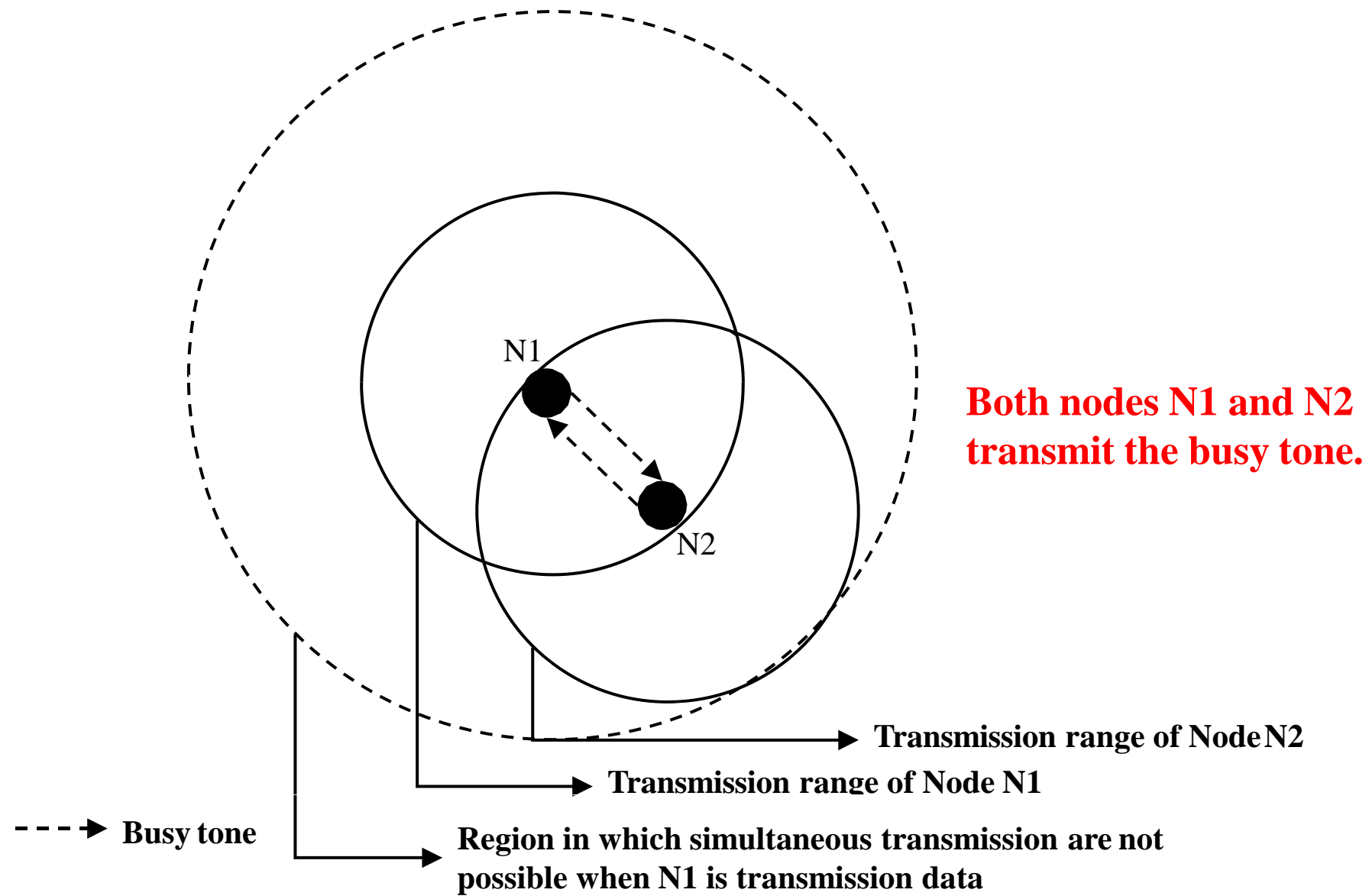


Figure 6.8 Transmission in BTMA.



DBTMA: Dual Busy Tone Multiple Access Protocol

- The transmission channel is divided into:
 - The data channel ① data packet transmission
- The control channel ① 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

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 ① transmit RTS packet
 - On receiving the RTS packets, checks whether the BT_t tone is active
 - No BT_t signal ① Sending CTS packet and turn on the BT_r signal
 - Sender: receive CTS ① turn on BT_t signal ① start data
① turn off BT_t signal
 - Receiver: receive data ① turn off BT_r signal
- DBTMA has better network utilization than RTS/CTS based protocol (why?)

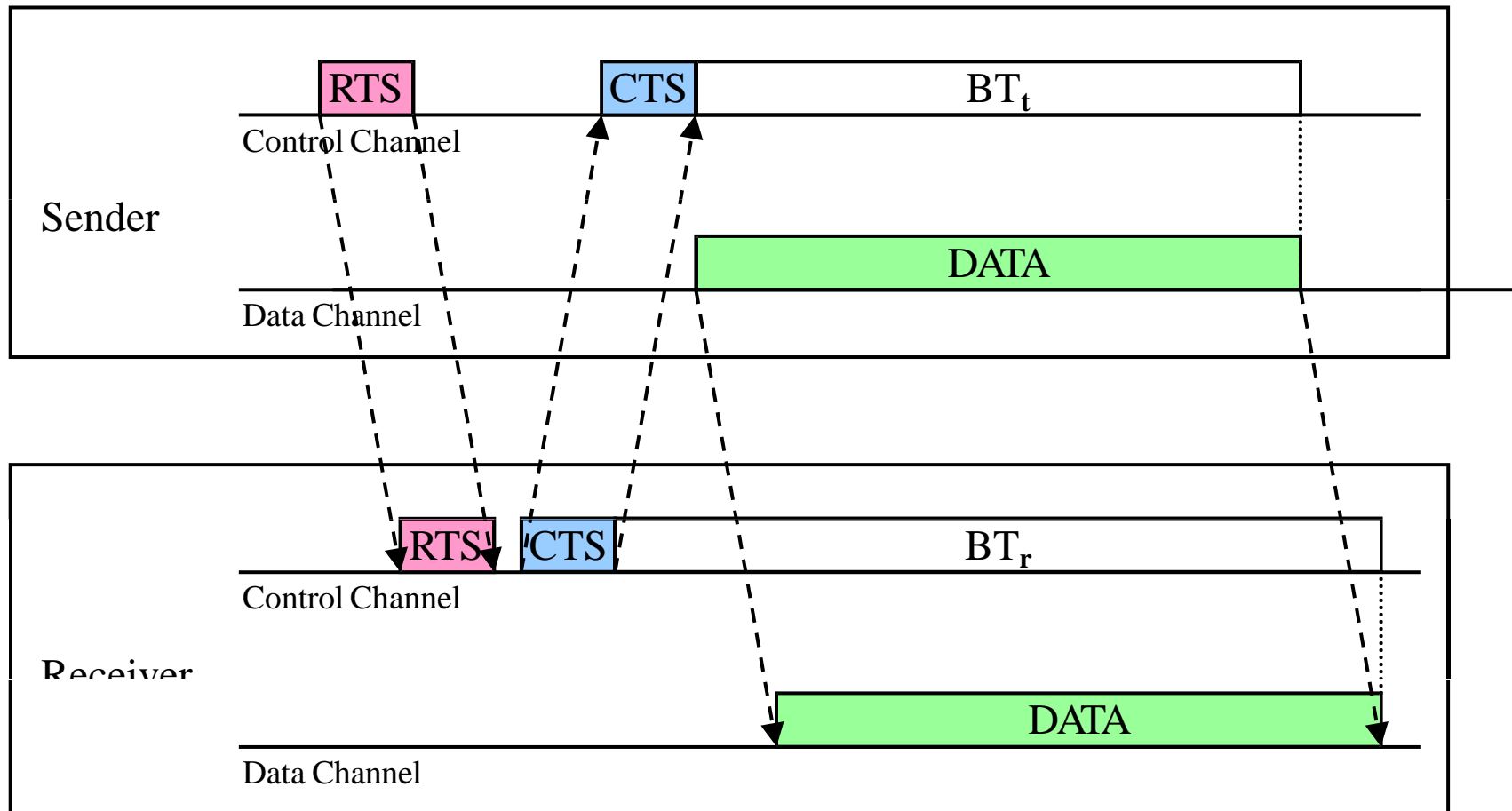


Figure 6.9 Packet transmission in DBTMA.



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

- The available bandwidth is divided into two slotted channels:
 - The data channel ① data packet transmission
 - Only if it finds the busy tone to be absent on the control channel
 - The control channel ② 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 ① packets that suffer collisions cannot be retransmitted
 - the controlled protocol
 - Backlogged mode ① backlog buffer is non-empty
 - Backlog buffers: transmitting a backlogged packet in the next idle slot with a probability q (why?)
 - Non-backlogged mode ① transmitting a non-backlogged ~~pk~~ packet in the next idle slot with a probability p (why?)

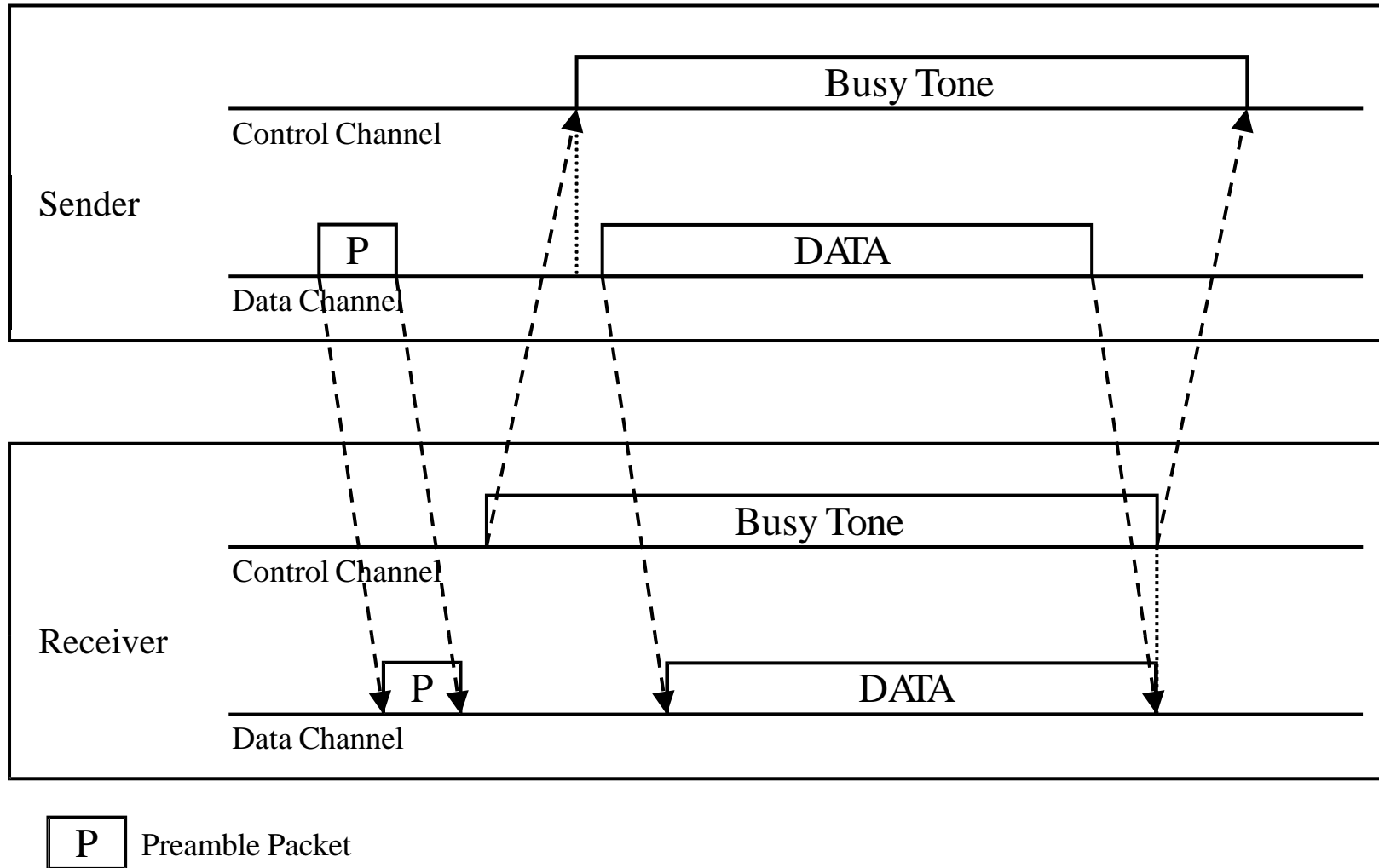


Figure 6.10 Packet transmission in RI-BTMA.



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)

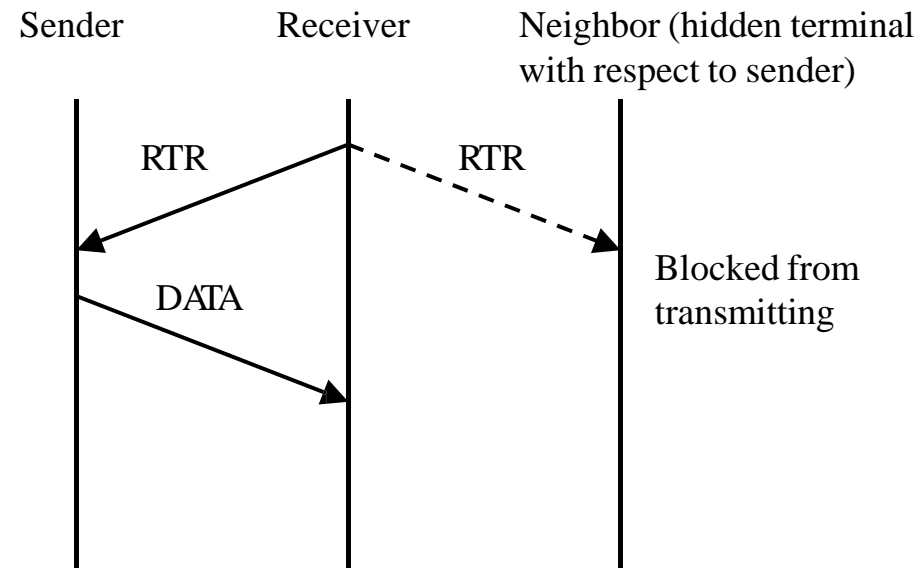
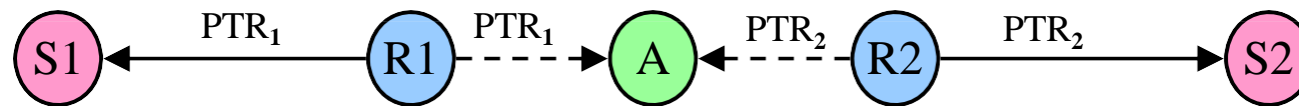


Figure 6.11 Packet transmission in MACA-BI



S1, S2 — Sendernodes

R1, R2 — Receivernodes

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 ① CTS ① DATA ① RTS ① C T S ① . . .
 - MARCH: RTS ① CTS₁ ① DATA ① CTS₂ ① DATA ① ... (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

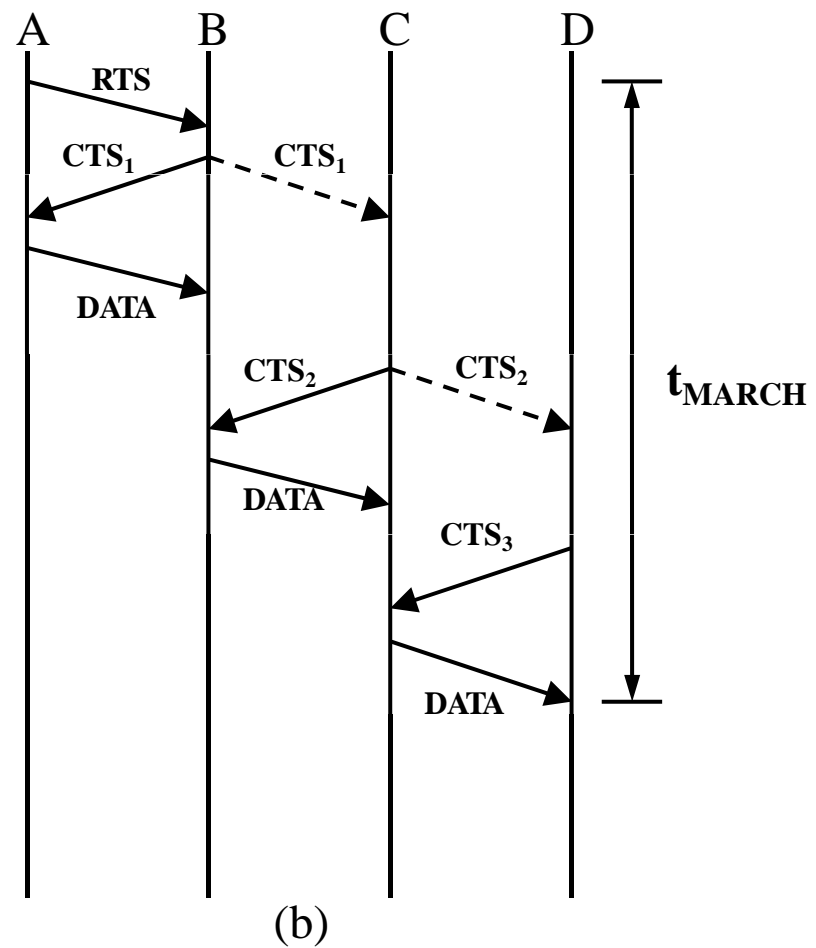
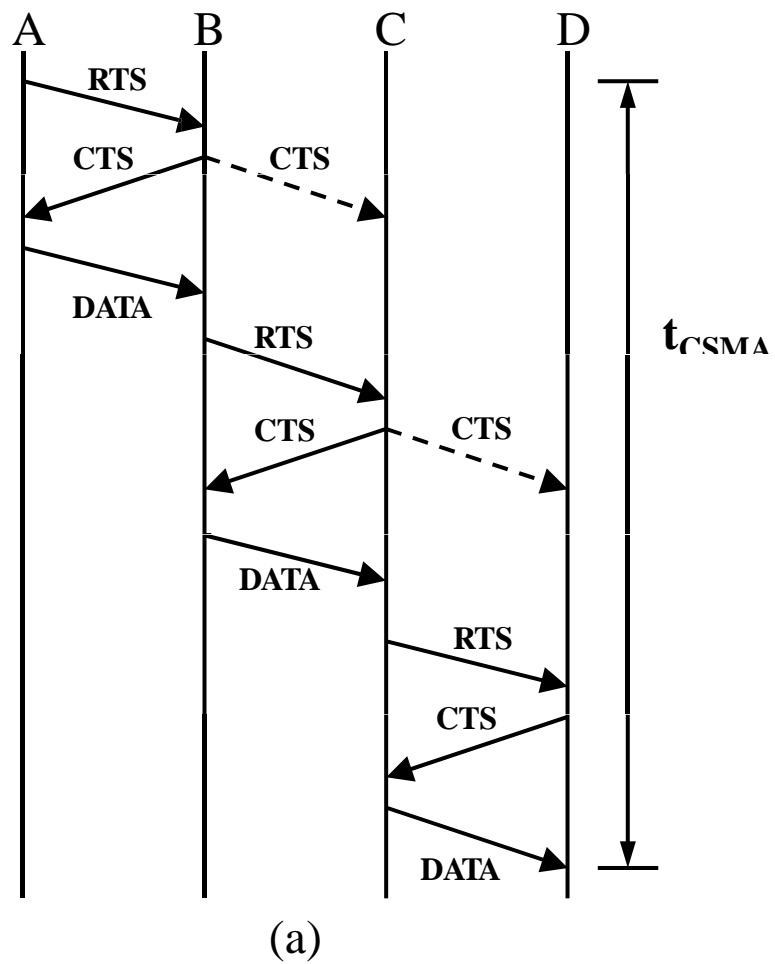


Figure 6.13 Handshake mechanism in (a) MACA and (b) MARCH

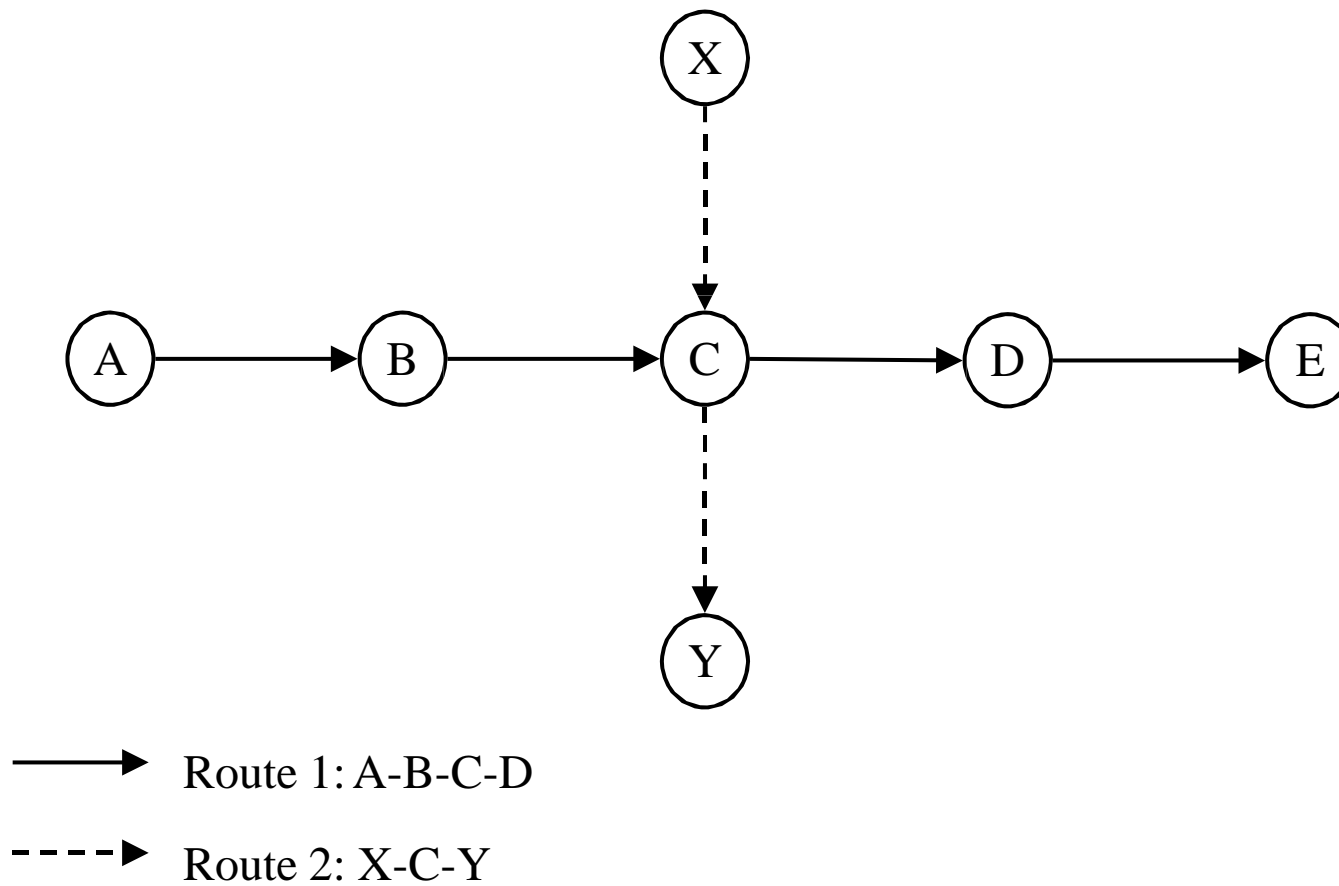


Figure 6.14 Example Topology

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

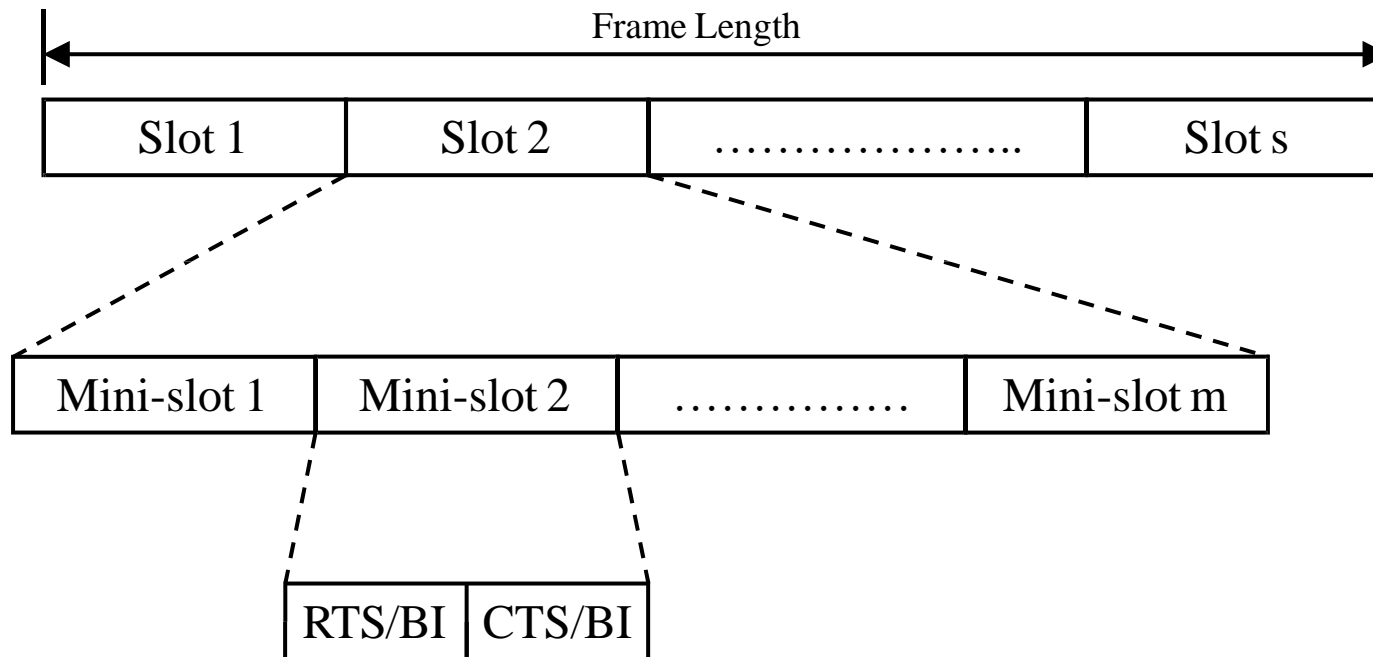


Figure 6.15 Frame structure in D-PRMA



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

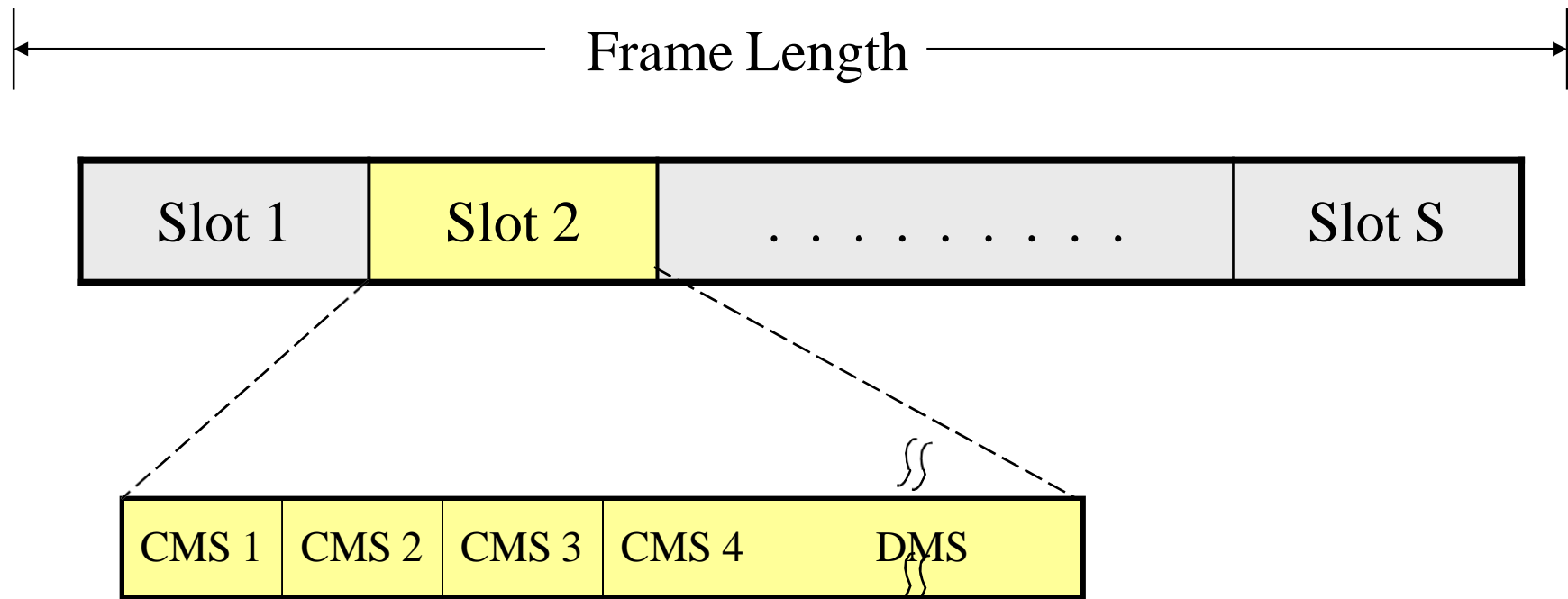


Figure 6.16. Frame format in CATA.



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 channel (See Figure 6.17)
- Assumptions
 - L : frequency channels
 - f_0 : dedicated synchronized channel frequency
 - The remaining $L - 1$ frequencies are divided into $M = \left\lceil \frac{(L-1)\omega}{2} \right\rceil$ frequency pairs denoted by

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

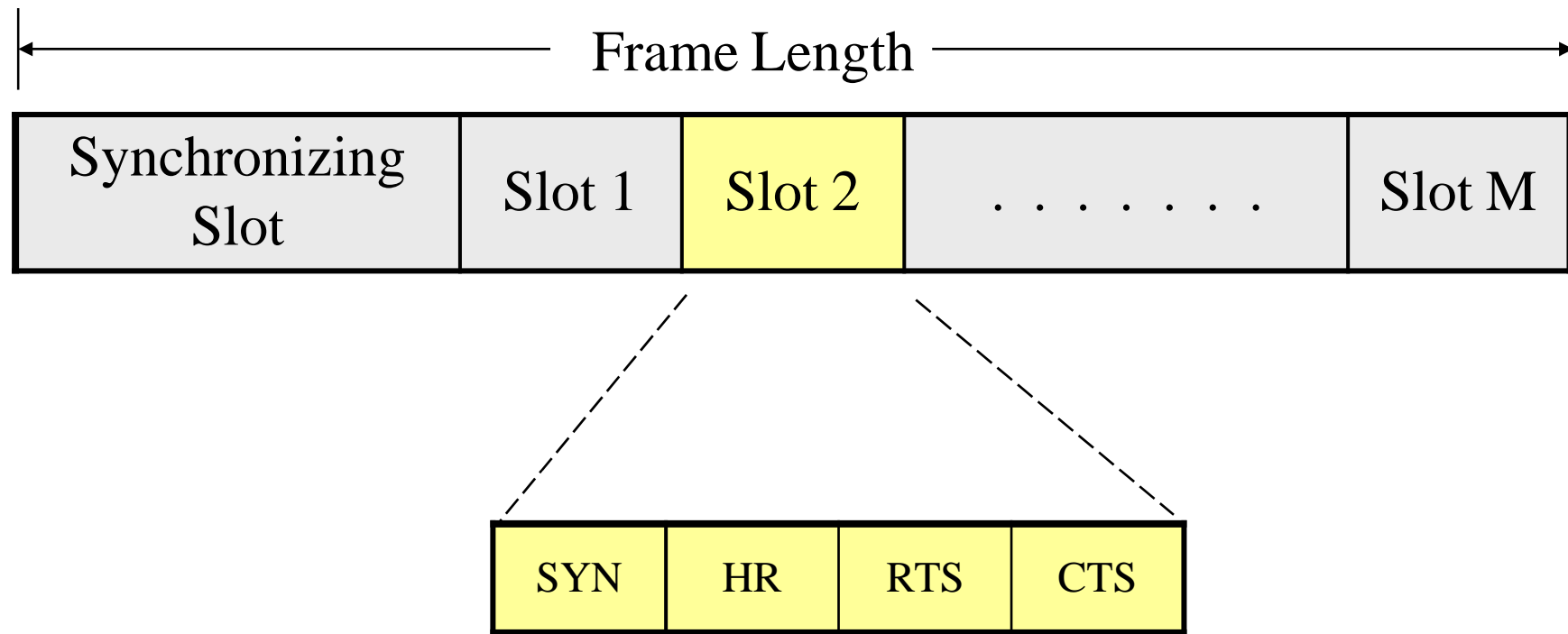


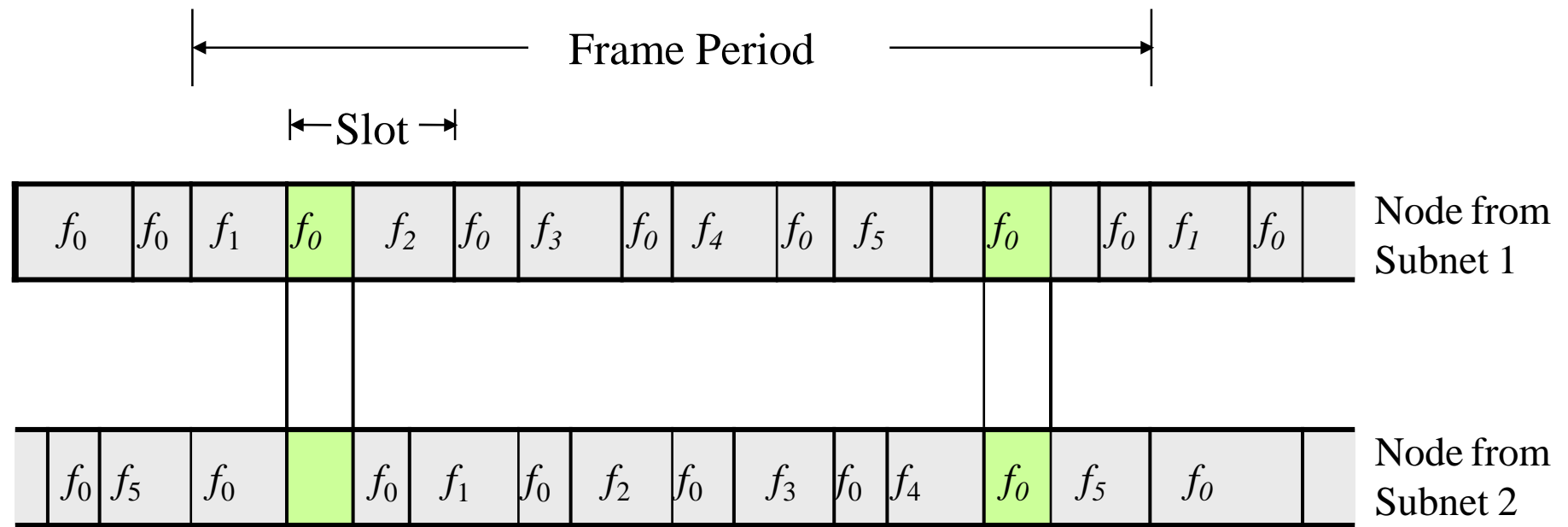
Figure 6.17. Frame format in HRMA.



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 μ_s on the frequency f_0 (See Figure 6.18)

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 $\mu + \mu_s$



f_0 synchronizing frequency

$M = 5$

Figure 6.18. Merging of subnets.



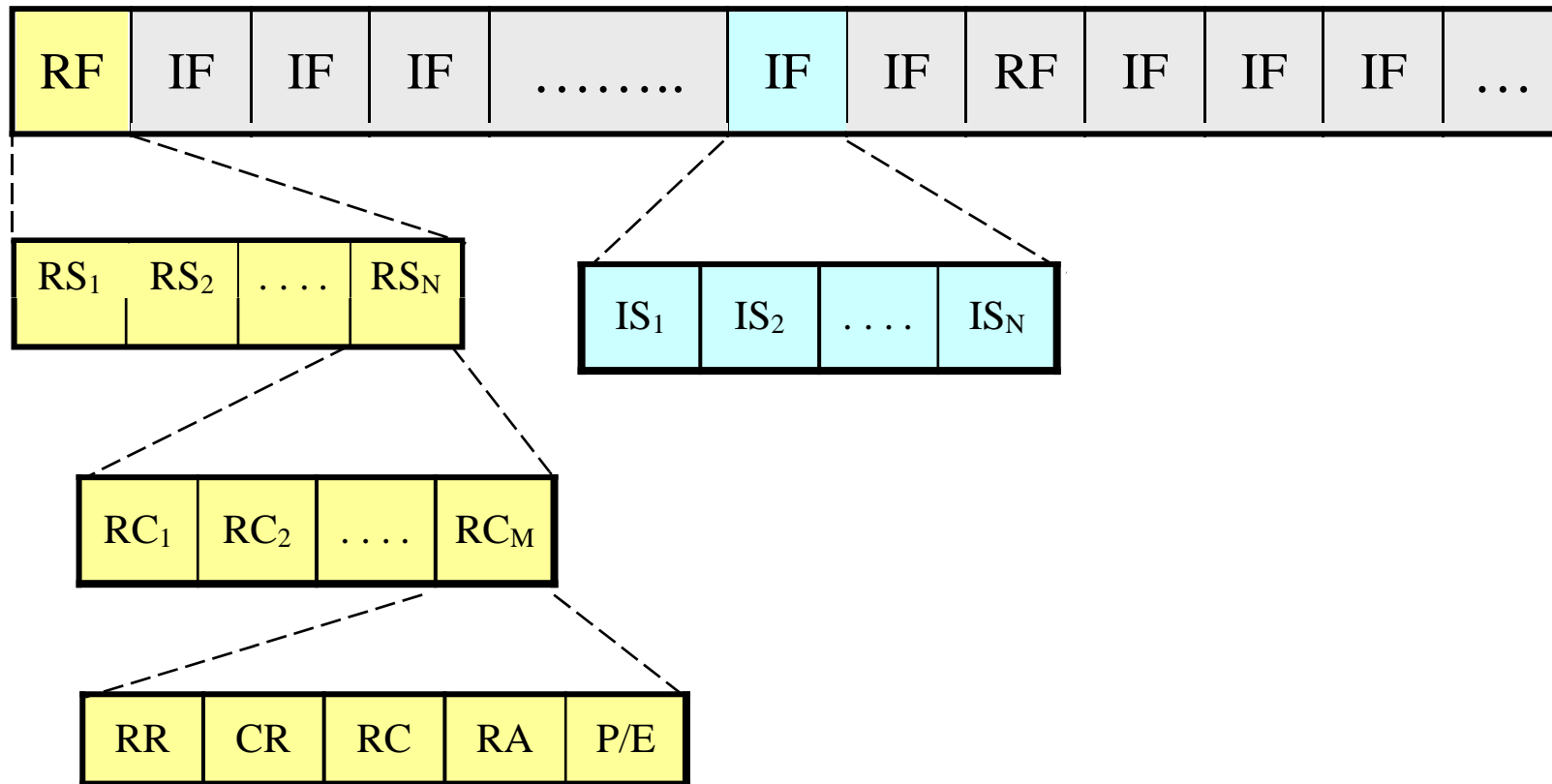
HRMA (cont.)

- 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

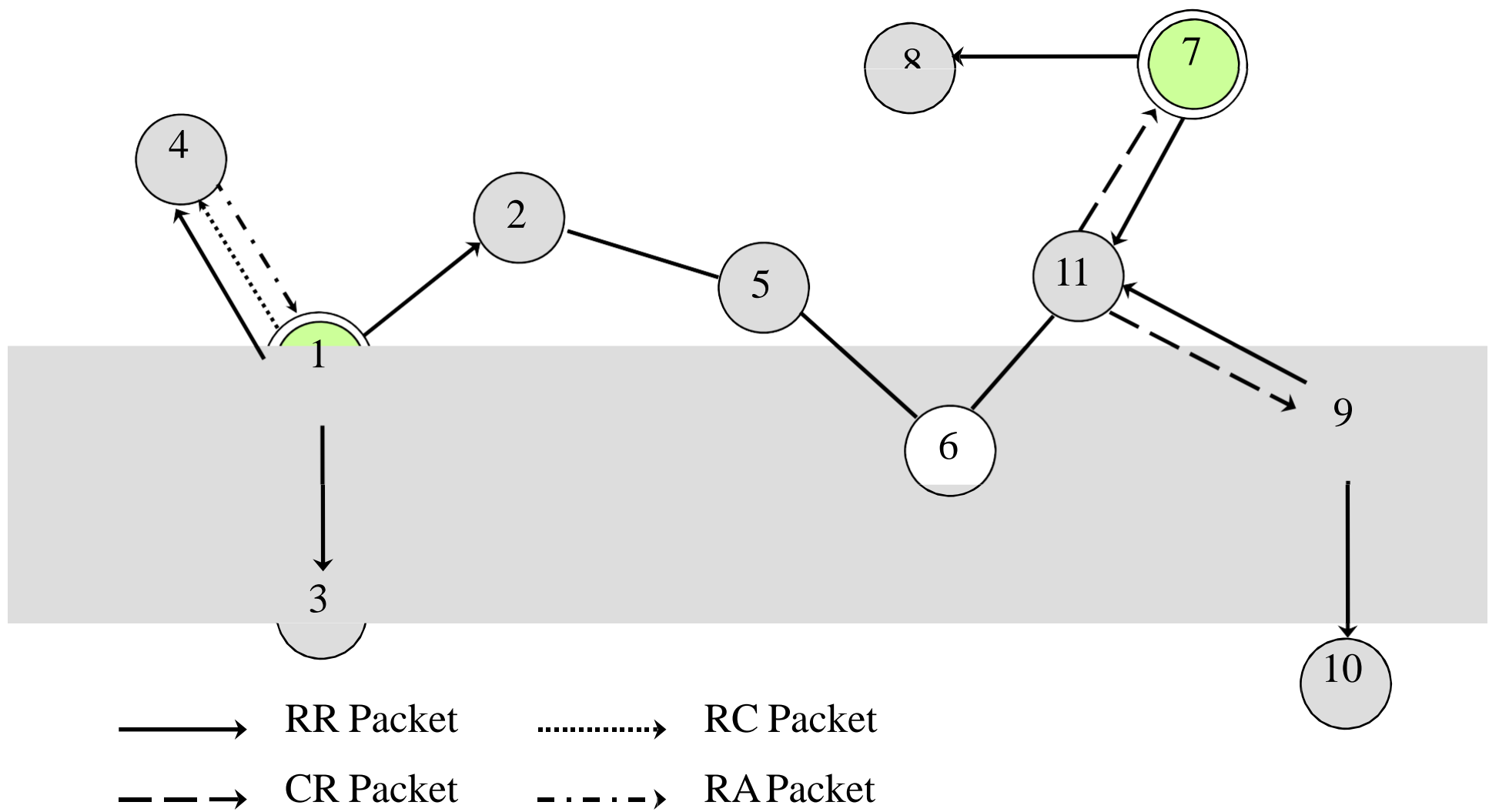


Figure 6.22. FPRP - Example.



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 ① RTS ① CTS ① DATA
① ACK



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

- Real time packet:
 - Transmit real time packets at certain regular intervals (say CYCLE)
 - R T S ◎ C T S ◎ D A T A (carry reservation info to next data) ◎ A C K ◎ ... ◎ D A T A (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

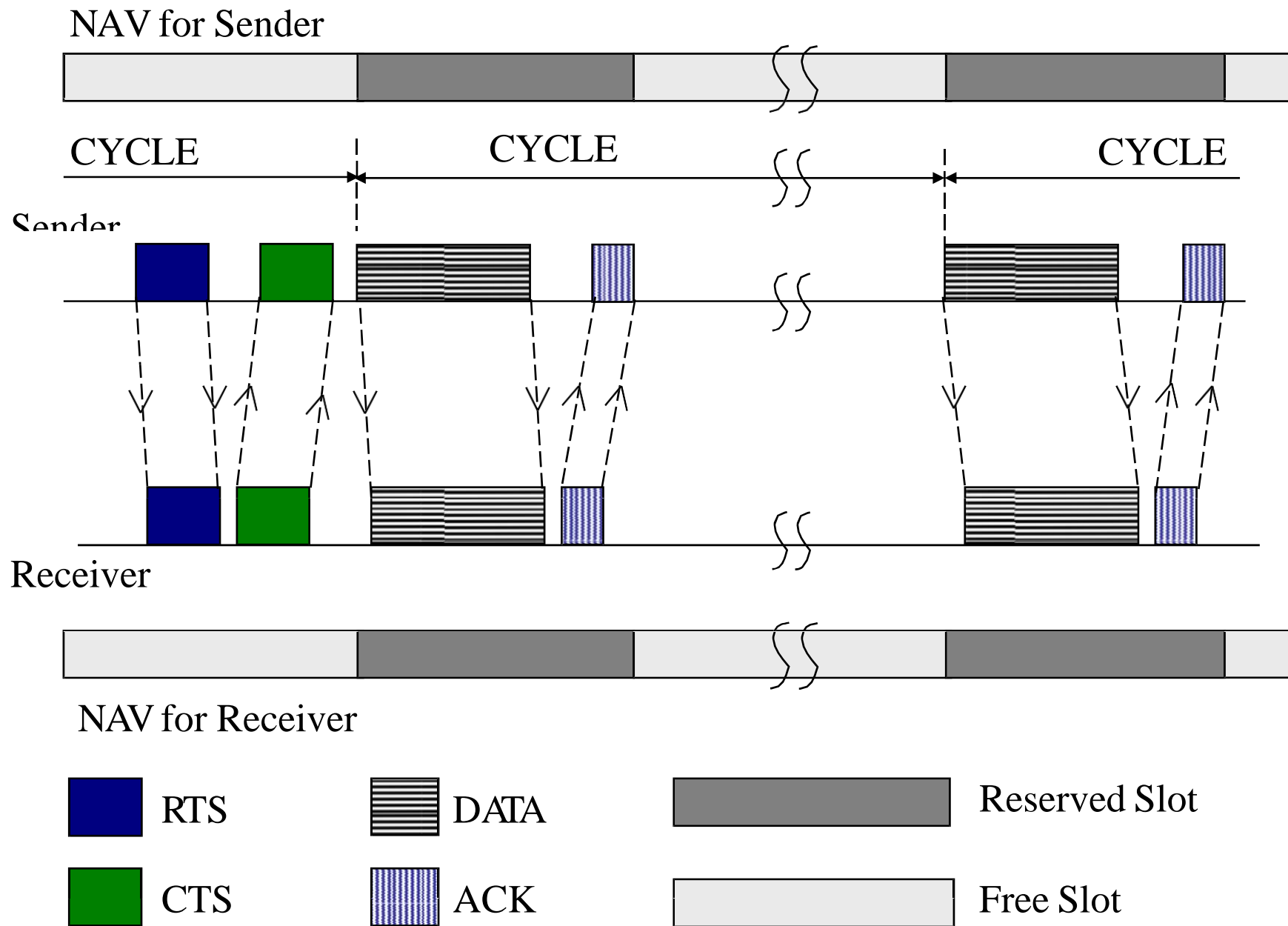


Figure 6.23. Packet transmission in MACA / PR.



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)

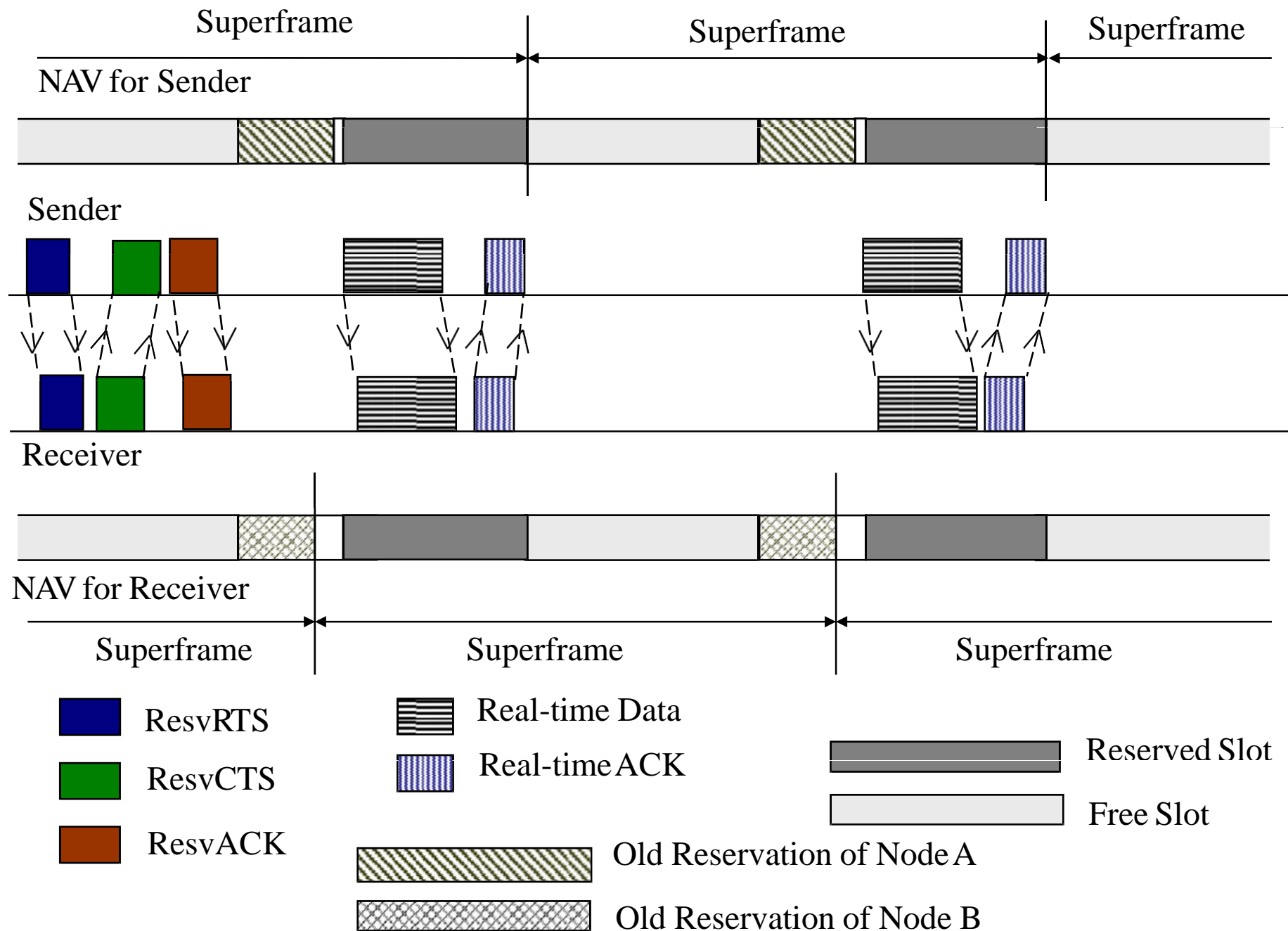
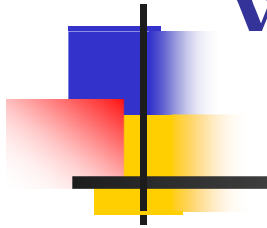


Figure 6.24. Reservation mechanism in RTMAC.

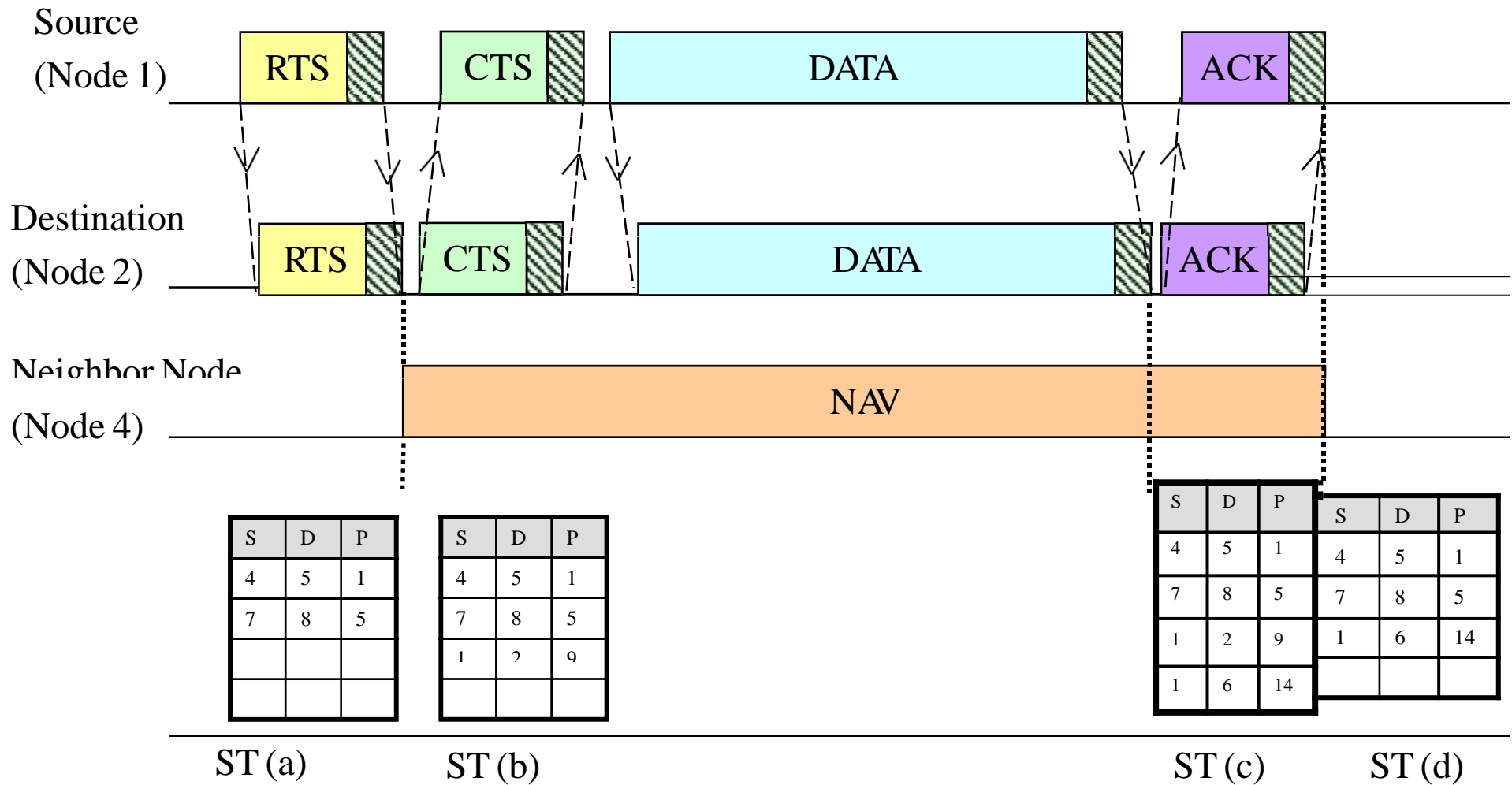
Contention-Based MAC Protocols with Scheduling Mechanisms





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

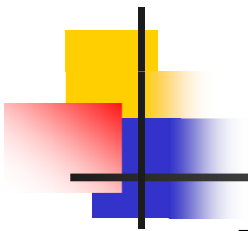
 Piggy-backed priority information

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



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

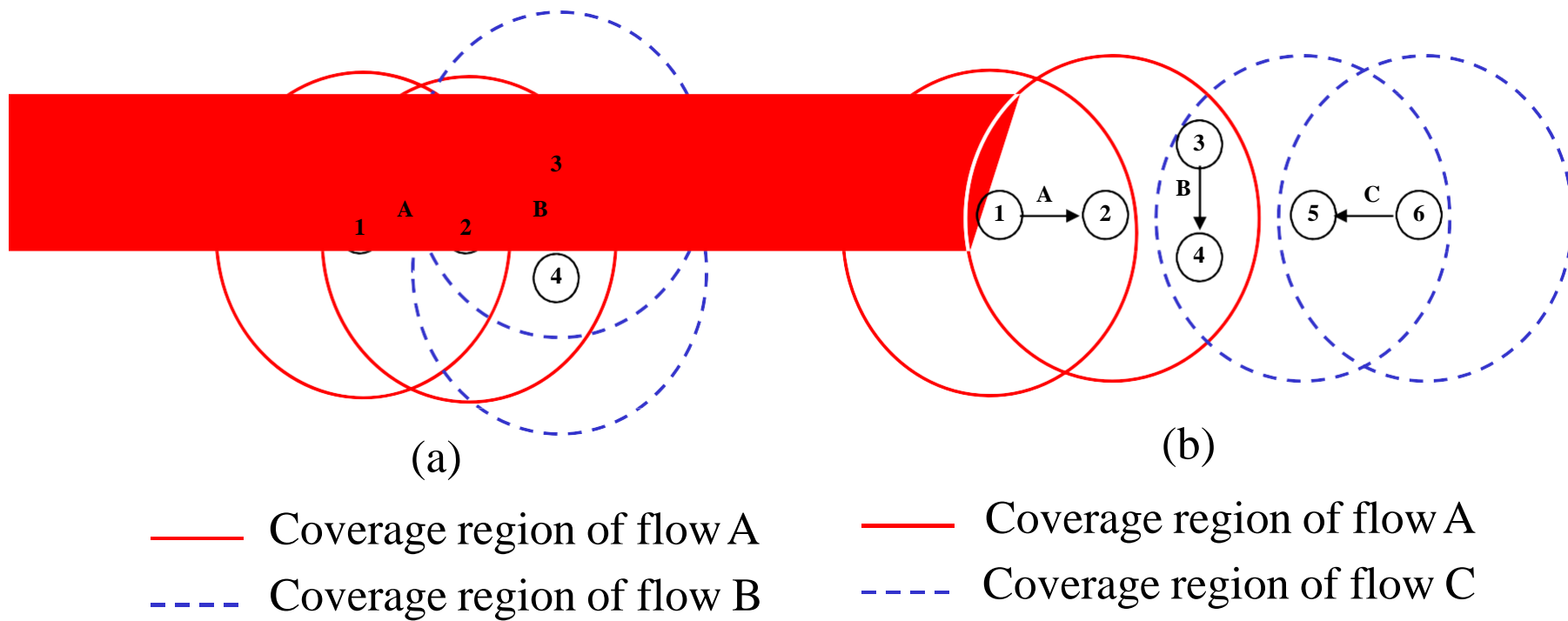


Figure 6.26 (a) Information asymmetry.

(b) Perceived collisions.