Autonomous Networking

Gaia Maselli
Dept. of Computer Science

*Some slides in this course are readapted from lecture slides from **Prof. Tommaso Melodia** (Northeastern University, Boston)*

Today's plan

- MAC protocols
  - CSMA/CA
  - S-MAC
- Routing protocols
  - proactive
  - reactive

Energy efficiency

- Wireless sensor networks use battery-operated computing and sensing devices. A network of these devices will collaborate for a common application such as environmental monitoring.
- Sensor nodes are typically battery powered
- **Batteries** have **finite power**
- Battery replacement is a costly process to be avoided as much as possible, especially for large-scale deployments and it is often very difficult to change or recharge batteries for these nodes.
- Low power communication is required
- Sensor networks are typically deployed in an ad hoc fashion, with individual nodes *remaining largely inactive for long periods of time*, but then becoming suddenly active when something is detected.
- **Prolonging network lifetime** is a critical issue.

Reasons of energy waste

- ***Collision**:* When a node receives more than one packet at the same time, these packets are termed collided, even when they coincide only partially. All packets that cause the *collision* have to be discarded and retransmissions of these packets are required, which increase the energy consumption.
- ***Overhearing***: meaning that a node receives packets that are destined to other nodes.
- ***Control-packet overhead**:* A minimal number of control packets should be used to make a data transmission.
- ***Idle listening***: listening to an idle channel in order to receive possible traffic.
- ***Overemitting***: caused by the transmission of a message when the destination node is not ready.

Communication patterns

- **Broadcast** or **interest dissemination (1 to all)**
  - A broadcast pattern is generally used by a base station (sink) to transmit some information to all the sensor nodes of the network.
  - All nodes of the network are intended receivers
  - Broadcasted information may include *queries, program updates* for sensor nodes, or *control packets* for the whole system.
- **Convergecast** or **data gathering** (**All/many to 1**)
  - All or a group of sensors communicate to the sink.
  - Typically used to collect sensed data
-

Properties of a well-defined mac protocol

- To design a good MAC protocol for wireless sensor networks, the following attributes must be considered
- **Energy efficiency:** energy-efficient proto-cols in order to prolong the network lifetime must be defined
- **Scalability** and **adaptability to changes**: changes in network size, node density, and topology should be handled rapidly and effectively for successful adaptation
- Latency, throughput, and bandwidth utilization may be secondary in sensor networks, but desirable

Techniques for WSN MAC

SAPIENZA
UNIVERSITÀ DI ROMA

Contention based	Scheduled based: Fixed assignment or on demand
• On-demand allocation for those that have frames for transmission • Sensing the carrier before attempting a transmission • **Scalable / no need for central authority** • **Idle listening / Interference / Collisions / Traffic fluctuations -> Energy consumption** • **Multi-hop topologies (hidden / exposed terminal problem)**	• Schedule that specifies when, and for how long, each node may transmit over the shared medium • **Energy efficient** • **Interference, collisions are not a problem** • **Synchronization** • **Central authority**

Contention-based MAC Protocols

- There is a contention to access channel (it is not assigned)
- Channel access through **carrier sense** mechanism
- Provide robustness and scalability to the network
- Collision probability increases with increasing node density

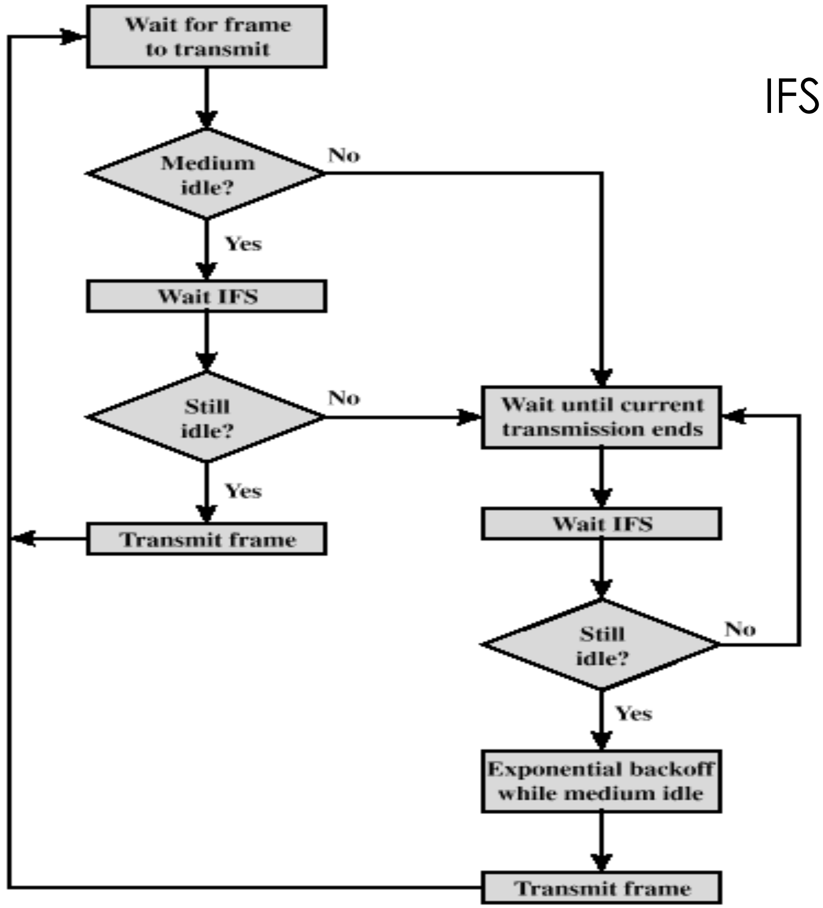
Contention-Based MAC Protocols: CSMA/CA (IEEE 820.11)

CSMA/CA

- Carrier Sense Multiple Access with Collision Avoidance
- In wireless networks it is not possible to detect collisions (interrupt a transmission)
- CSMA/~~CD~~
- Goal: if you cannot detect collision then you must try to **avoid** them as much as possible!
- Distributed protocol (no central entity!)

CSMA/CA

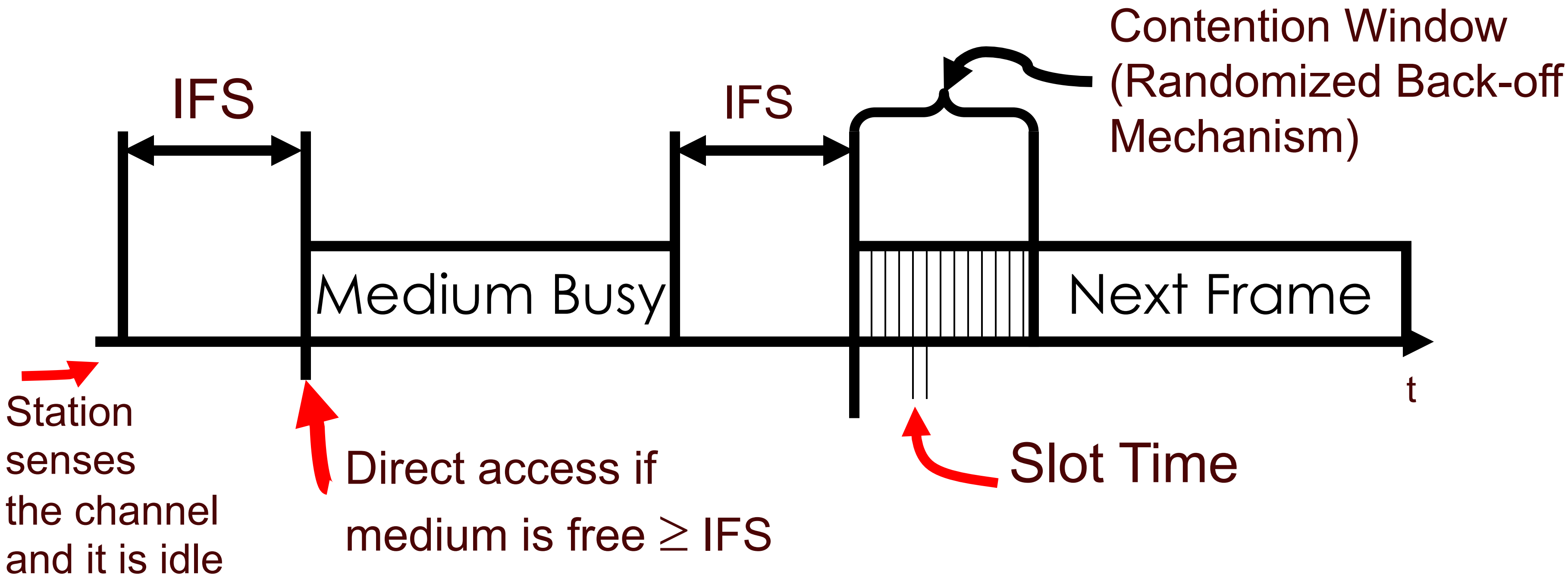
IEEE 802.11 Distributed Coordination Function



IFS: interframe space

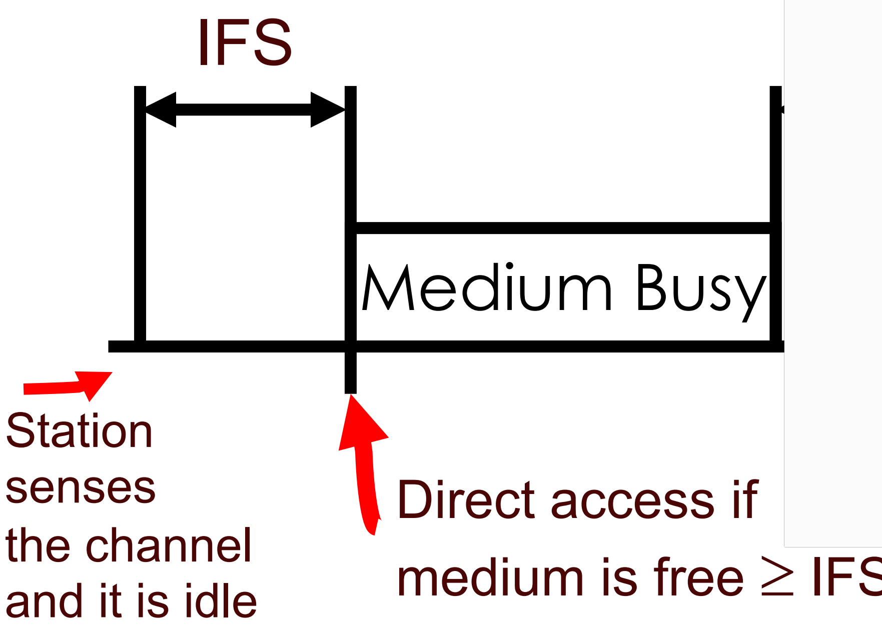
IEEE 802.11, "Wireless LAN medium access control (MAC) and physical layer (PHY) specifications," 1999

Basic CSMA/CA



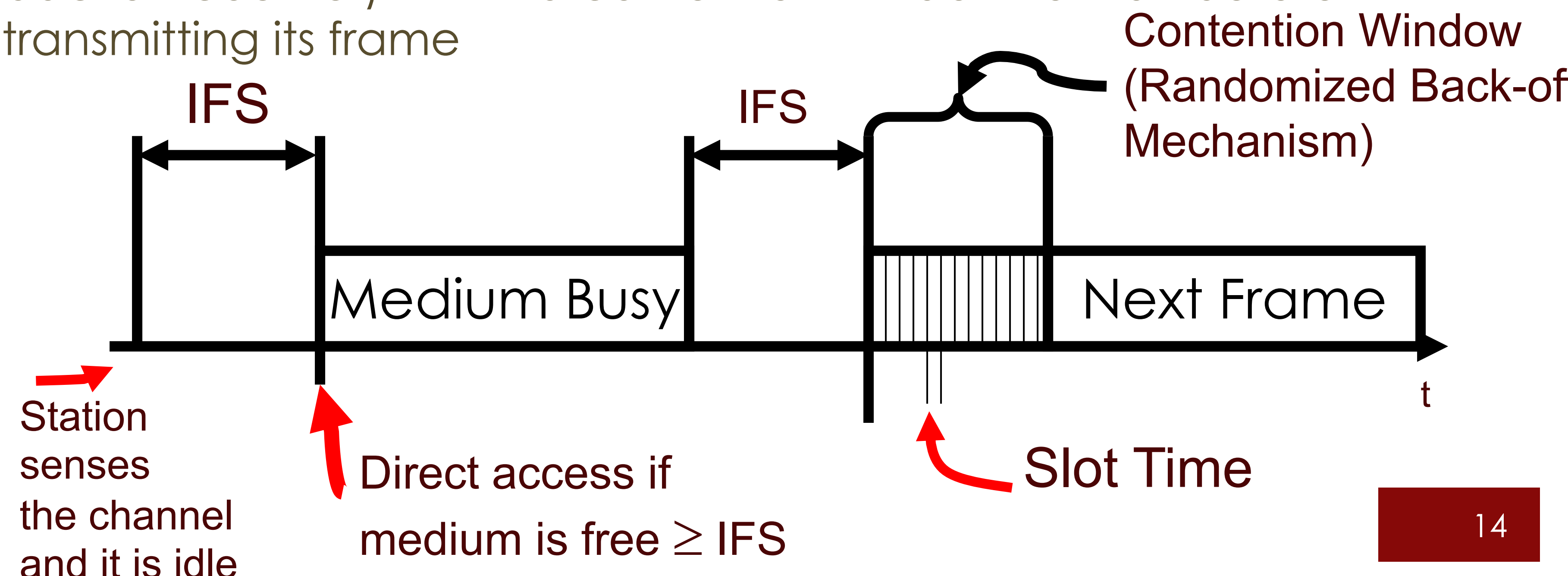
Basic CSMA/CA

- A station with a frame to transmit senses the medium (channel)
- IF IDLE -> waits to see if the channel remains idle for a time equal to IFS (inter-frame spacing). If so, the station may transmit immediately
- IF BUSY -> (either because the station initially finds the channel busy or because the channel becomes busy during the IFS idle time), the station defers transmission and continues to monitor the channel until the current transmission is over



Basic CSMA/CA

- Once the current transmission is over, the station delays another IFS
- If the medium remains idle for this period, the station backs off using a binary exponential backoff scheme and again keeps sensing the medium
- The station picks up a random number of slots (the initial value of backoff counter) within a contention window to wait before transmitting its frame



Basic CSMA/CA

- MAC runs a random number generator to set a BACKOFF CLOCK for every contending station

- The backoff clock is randomly chosen between [0, CW-1], where CW represents a CONTENTION WINDOW
- During contention, all stations having packets for transmission run down their BACKOFF clocks

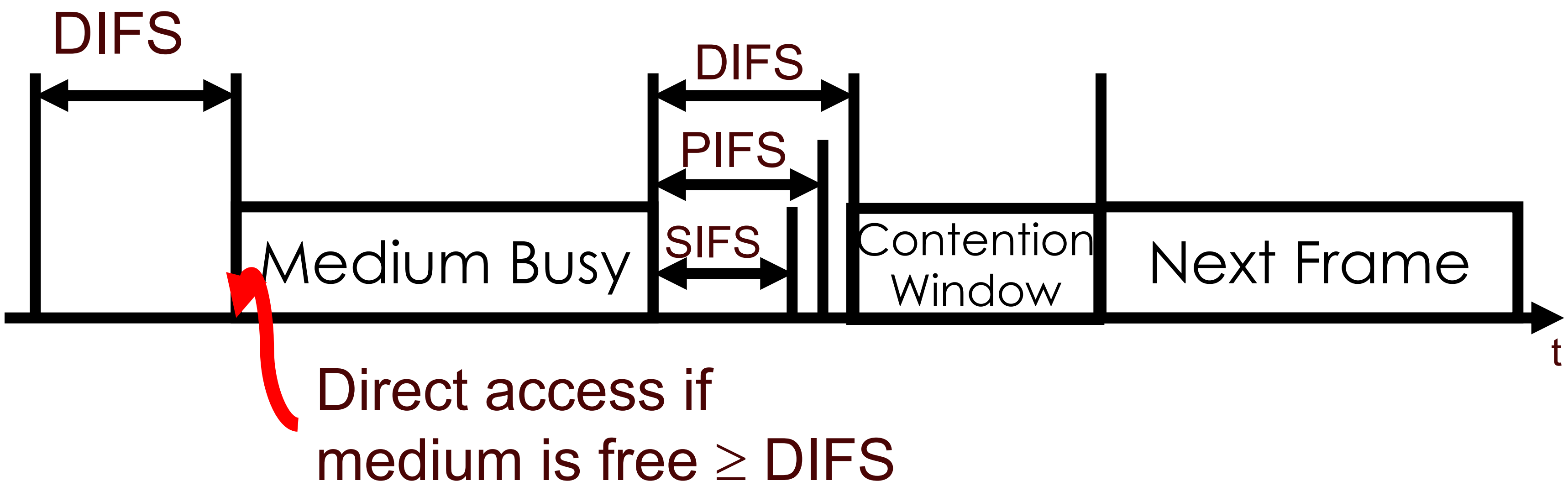
- The first station whose clock expires starts transmission

- Other terminals sense the new transmission and freeze their clocks to be restarted after the completion of the current transmission in the next contention period

CSMA/CA Algorithm

- If Collisions (Control or Data)
- Binary exponential increase (doubling) of CW
- Length of backoff time is exponentially increased as the station goes through successive retransmissions

Inter-frame Spaces (IFS)



Inter-frame Spaces (IFS)

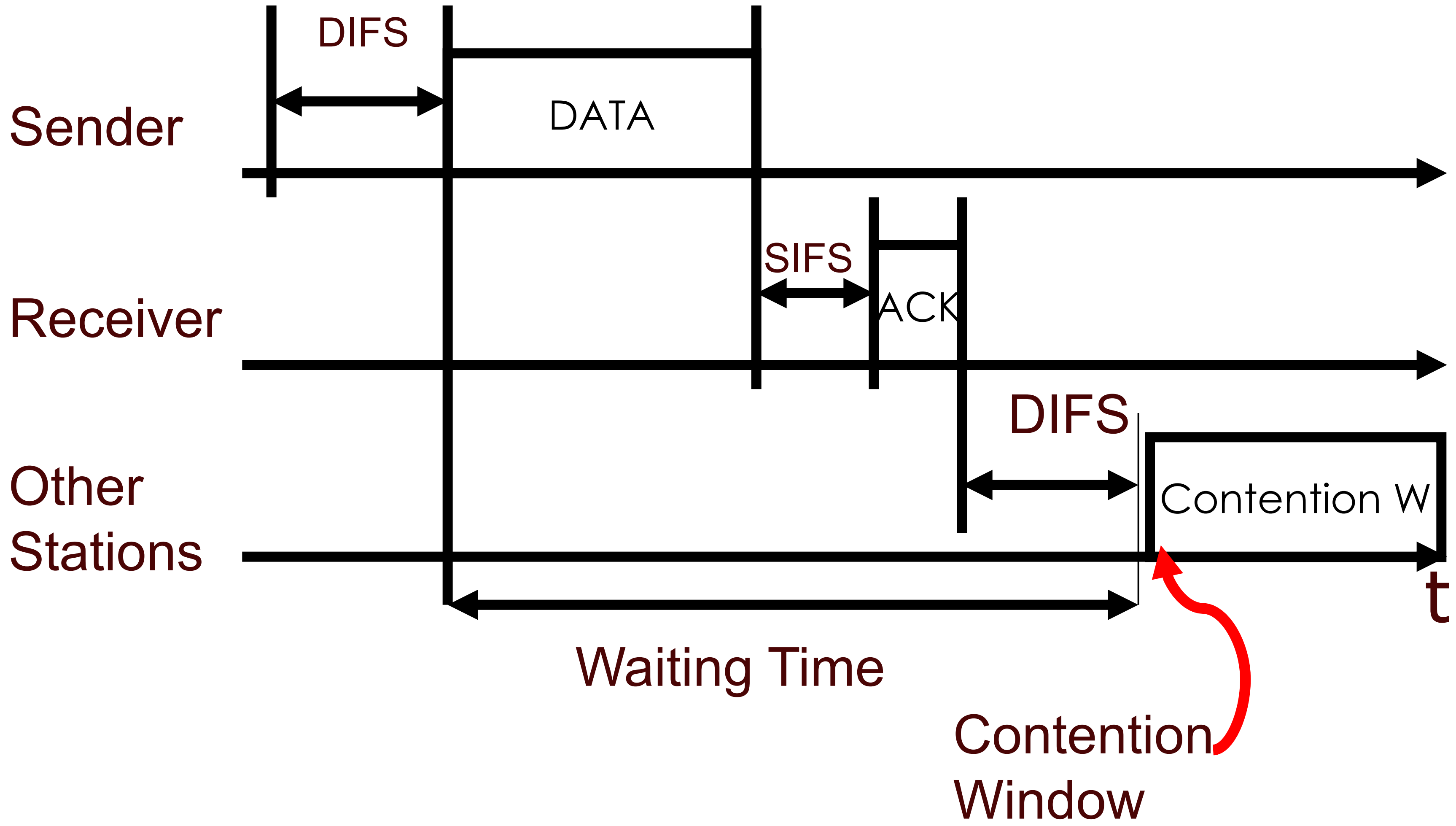
- Priorities are defined through different inter frame spaces

- SIFS (Short Inter Frame Spacing)
  - Highest priority packets such as ACK, CTS, polling response
  - **Used for immediate response actions**
- PIFS (PCF IFS, Point Coordination Function Inter Frame Spacing)
  - Medium priority, for real time service using PCF
  - SIFS + One slot time
  - Used by centralized controller in PCF scheme when using polls
- DIFS (DCF, Distributed Coordination Function IFS)
  - Lowest priority, for asynchronous data service
  - SIFS + Two slot times
  - **Used as minimum delay of asynchronous frames contending for access**

DCF CSMA/CA with ACK

- Station has to wait for DIFS before sending data
- Receiver ACKs immediately (after waiting for SIFS < DIFS) if the packet was received correctly (CRC))
- Receiver transmits ACK without sensing the medium
- If ACK is lost, retransmission done
- Automatic retransmission of data packets in case of transmission errors

DCF CSMA/CA with ACK

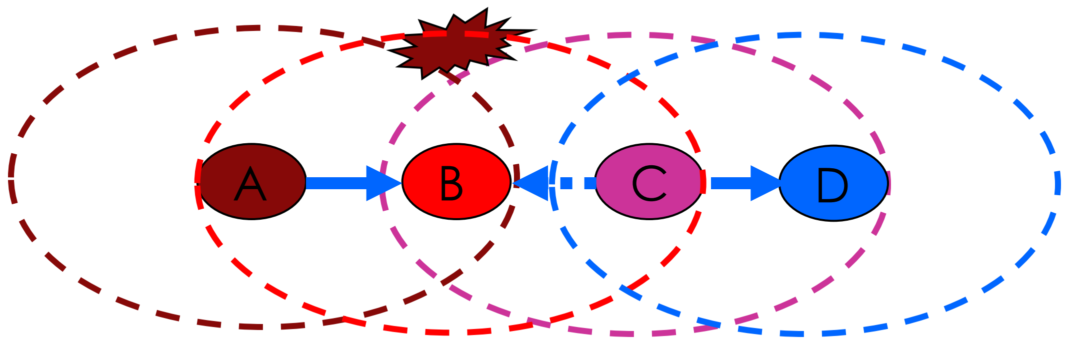


CSMA/CA

Dealing with

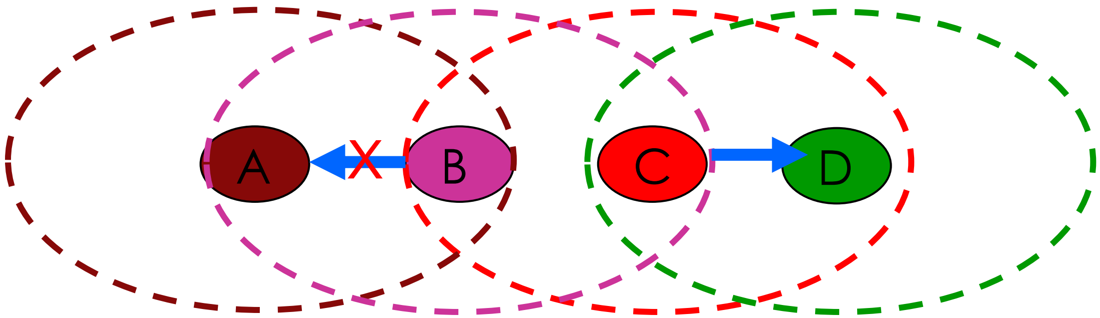
- Hiddent terminal
- Exposed terminal

Hidden Terminal Problem



- Node B can communicate with A and C
- A and C cannot hear each other
- When A transmits to B, C cannot detect the transmission using the carrier sense mechanism
- If C transmits to D, collision will occur at B

Exposed Terminal Problem

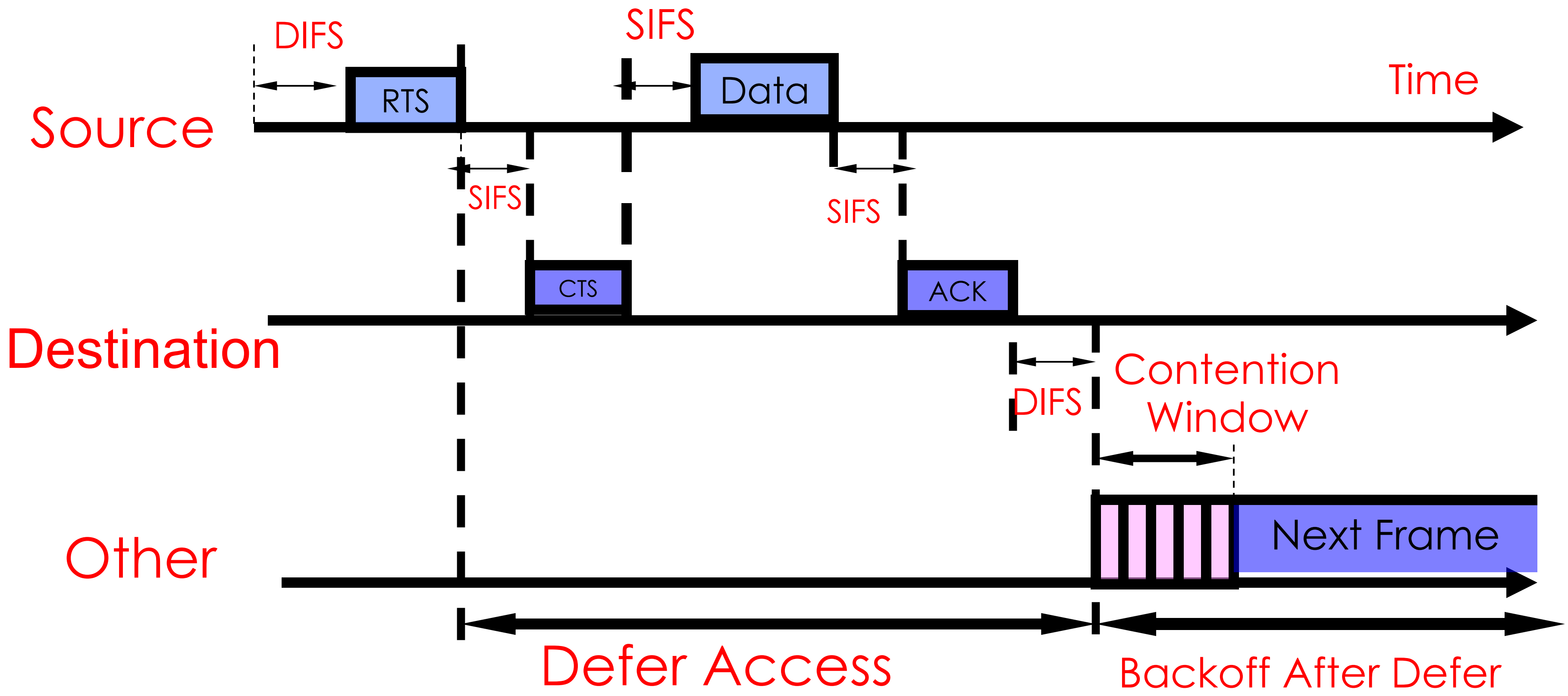


- Node C can communicate with B and D
- Node B can communicate with A and C
- Node A cannot hear C
- Node D can not hear B
- When C transmits to D, B detects the transmission using the carrier sense mechanism and postpones transmission to A, even though such transmission would not cause collision

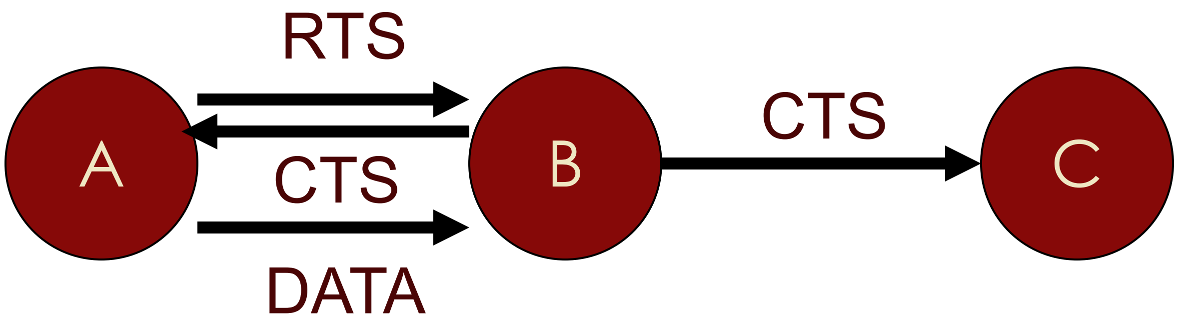
RTS/CTS

- Transmitter sends an RTS (Request To Send) after medium has been idle for time interval more than DIFS
- Receiver responds with CTS (Clear To Send) after medium has been idle for SIFS
- Data is transmitted
- RTS/CTS is used for **reserving channel** for data transmission so that the collision can only occur in control message

DCF CSMA/CA with RTS/CTS

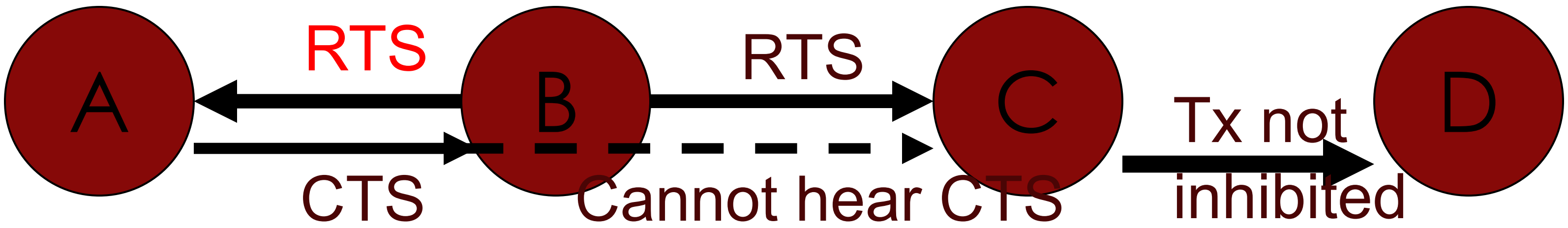


Hidden Terminal Problem Solved



- A sends RTS
- B sends CTS
- C overhears CTS
- C inhibits its own transmitter
- A successfully sends DATA to B

Exposed Terminal Problem Solved



- B sends RTS to A (overheard by C)
- A sends CTS to B
- C cannot hear A's CTS
- C assumes A is either down or out of range
- C does not inhibit its transmissions to D

Collisions

- Still possible – RTS packets can collide!

- Binary exponential backoff performed by stations that experience RTS collisions

- RTS collisions not as bad as data collisions in CSMA (since RTS packets are typically much smaller than DATA packets)

Network Allocation Vector (NAV)

- Both Physical Carrier Sensing and Virtual Carrier Sensing used in 802.11

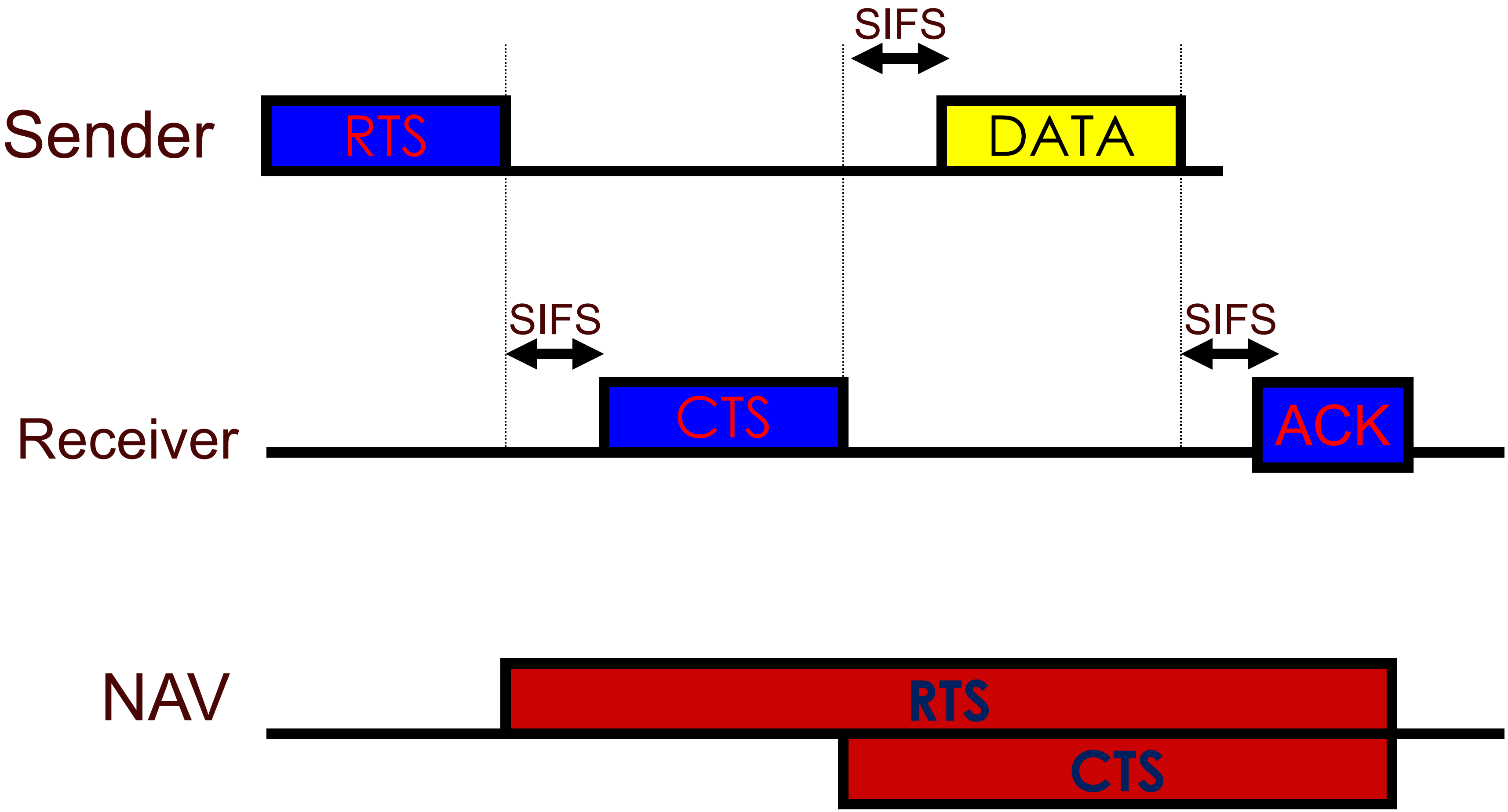
- If either function indicates that the medium is busy, 802.11 treats the channel to be busy

- Virtual Carrier Sensing is provided by the NAV (Network Allocation Vector)

Network Allocation Vector (NAV)

- Most 802.11 frames carry a duration field which is used to **reserve the medium for a fixed time period**
- Tx sets the NAV to the time for which it expects to use the medium
- Other stations start counting down from NAV to 0
- As long as NAV > 0, the medium is busy
- CHANNEL VIRTUALLY BUSY -> a NAV SIGNAL is turned on!
- Transmission will be delayed until the NAV signal has disappeared
- When the channel is virtually available, then MAC checks for PHY condition of the channel

Illustration



CSMA/CA with RTS/CTS (NAV)

- If receiver receives RTS, it sends CTS (Clear to Send) after SIFS
- CTS again contains duration field and all stations receiving this packet need to adjust their NAV
- Sender can now send data after SIFS, acknowledgement via ACK by receiver after SIFS

CSMA/CA with RTS/CTS (NAV)

- Every station receiving the RTS that is not addressed to it, will go to the Virtual Carrier Sensing Mode for the entire period identified in the RTC/CTS communication, by setting their NAV signal on
- Network Allocation Vector (NAV) is set in accordance with the duration of the field
- NAV specifies the earliest point at which the station can try to access the medium
- Thus, the source station sends its packet without contention
- After completion of the transmission, the destination terminal sends an ACK and NAV signal is terminated, opening the contention for other users

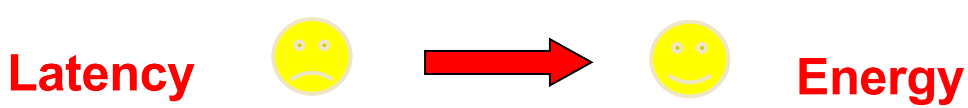
Contention-Based Mac Protocols: S-MAC

S-MAC: Sleep MAC

- Problem: “**Idle Listening**” consumes significant energy (Measurements have shown that idle listening consumes 50%–100% of the energy required for receiving)

- Solution: **Periodic listen and sleep**

- During sleeping, **radio is turned off**
- Reduce duty cycle to ~ 10% (Listen for 200ms and sleep for 2s)



W. Ye, J. Heidemann, D. Estrin, , “Medium Access Control with Coordinated Adaptive Sleeping for Wireless Sensor Networks,“ IEEE/ACM Trans. on Networking, June 2004.

S-MAC

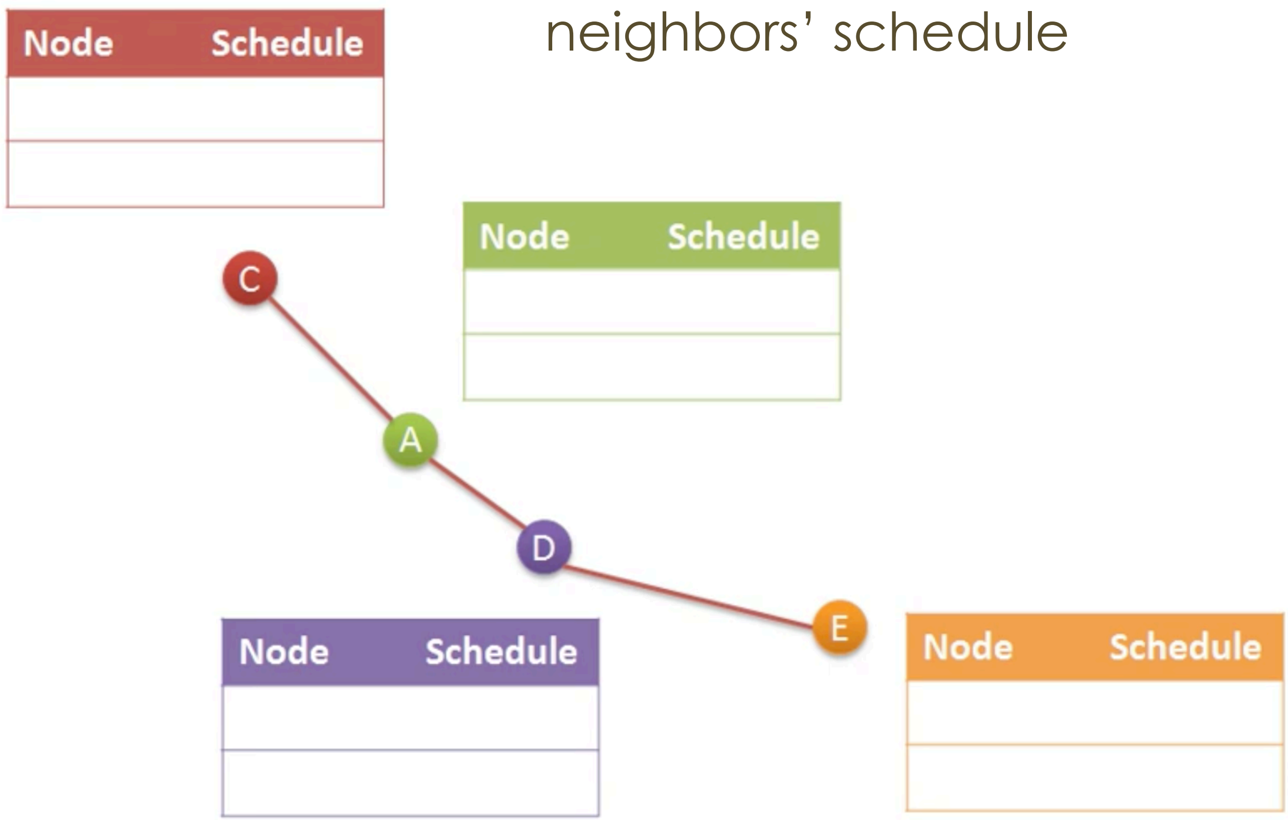
- Each node goes into periodic sleep mode during which it switches the radio off and sets a timer to awake later
- When the timer expires it wakes up and listens to see if any other node wants to talk to it
- The duration of the sleep and listen cycles are application dependent and they are set the same for all nodes
- Requires a **periodic synchronizatio**n among nodes

Periodic Sleep and Listen

- All nodes are free to choose their own listen/sleep schedules
- To reduce control overhead, **neighboring nodes are synchronized together** (they listen at the same time and go to sleep at the same time)
- Neighboring nodes form virtual clusters so as to set up a common sleep schedule.

Schedule maintainance

Eac node maintaines a table with neighbors' schedule



Synchronization

- SYNC packets are exchanged periodically to maintain schedule synchronization

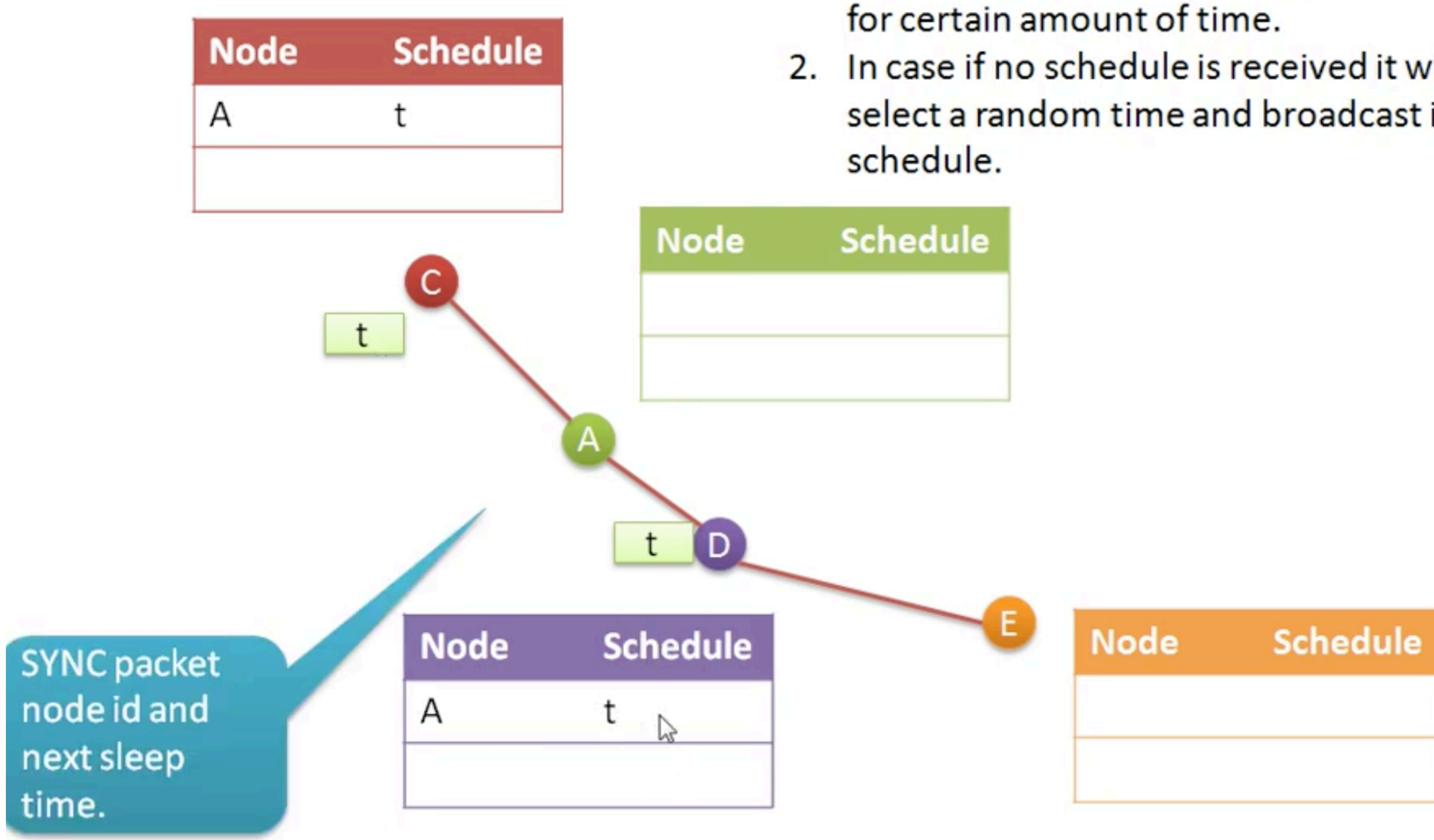
SYNC PACKET

Sender Node ID	Next Sleep Time

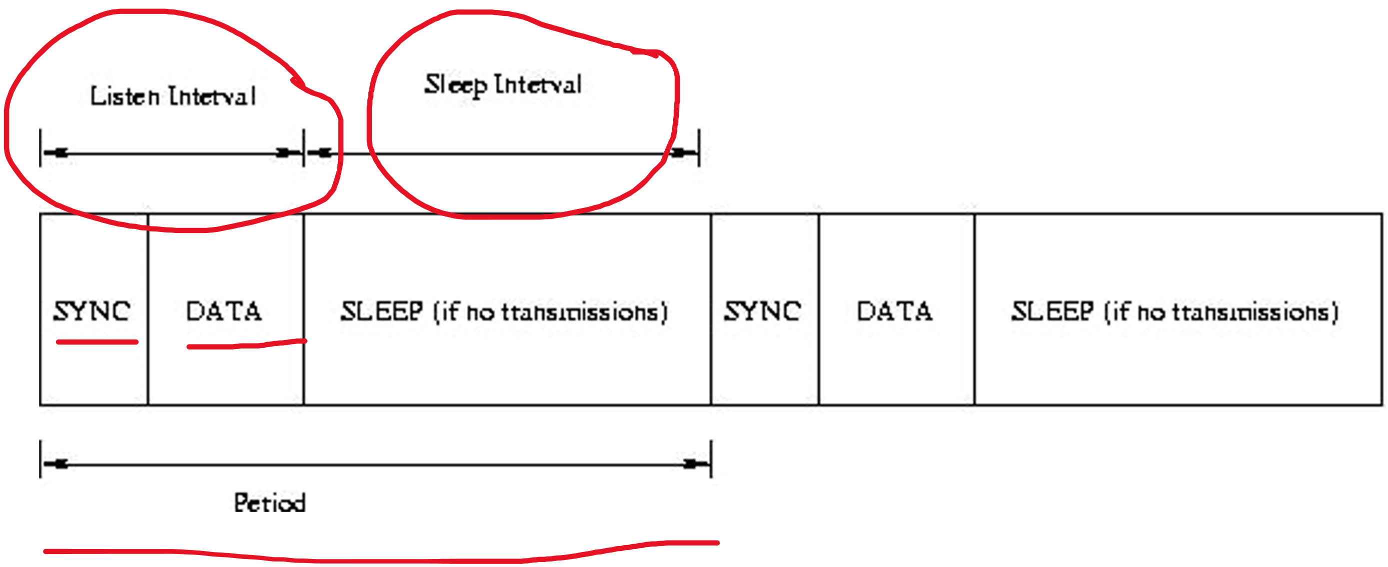
- SYNCHRONIZATION PERIOD: Period for a node to send a SYNC packet
- Receivers will adjust their timer counters immediately after they receive the SYNC packet

Schedule maintainance

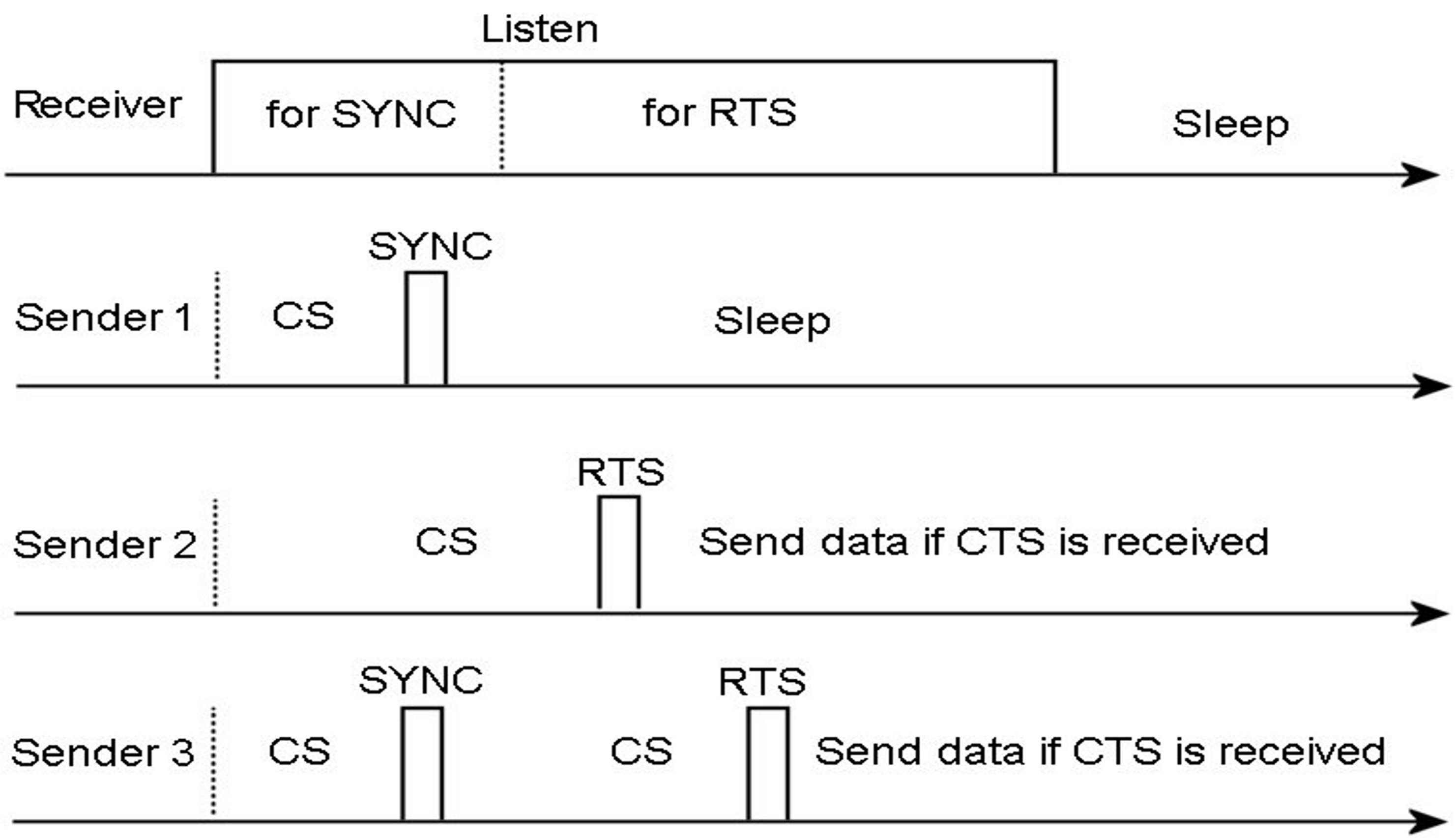
1. Node will listen for incoming schedules for certain amount of time.
2. In case if no schedule is received it will select a random time and broadcast it's schedule.



Periodic Listen and Sleep



Maintaining Synchronization



CS: carrier sense (to avoid collisions)

Choosing and Maintaining Schedules

- Each node maintains a **schedule table** that stores schedules of all its known neighbors

- For initial schedule, do:

1. A node first listens to the medium for a certain amount of time (at least the synchronization period)

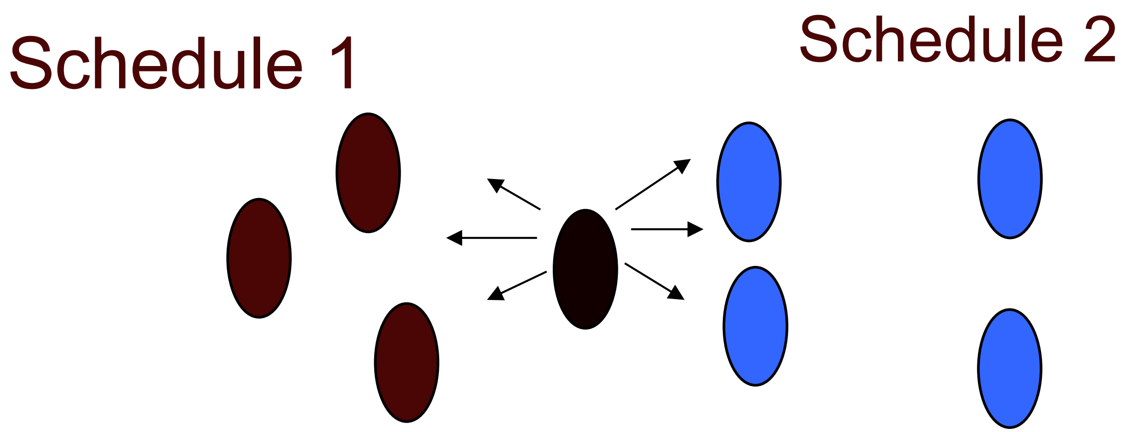
2. If it does not hear a schedule from another node, it randomly chooses a schedule and broadcasts its schedule with a SYNC packet immediately

3. This node is called a Synchronizer

4. If a node receives a schedule from a neighbor before choosing its own schedule, it just follows this neighbor's schedule, i.e. becomes a Follower, waits for a random delay and broadcasts its schedule

Coordinated Sleeping

- Of course, in a large network, we cannot guarantee that all nodes follow the same schedule
- The node on the border will follow both schedules
- When it broadcasts a packet, it needs to do it twice, first for nodes on schedule 1 and then for those on schedule 2



Collision Avoidance

- S-MAC is based on **contention**, i.e., if multiple neighbors want to talk to a node at the same time, they will try to send when the node starts listening
- Similar to IEEE 802.11, i.e. use RTS/CTS mechanism to address the hidden terminal problem
- Perform **carrier sense** before initiating a transmission

Collision Avoidance

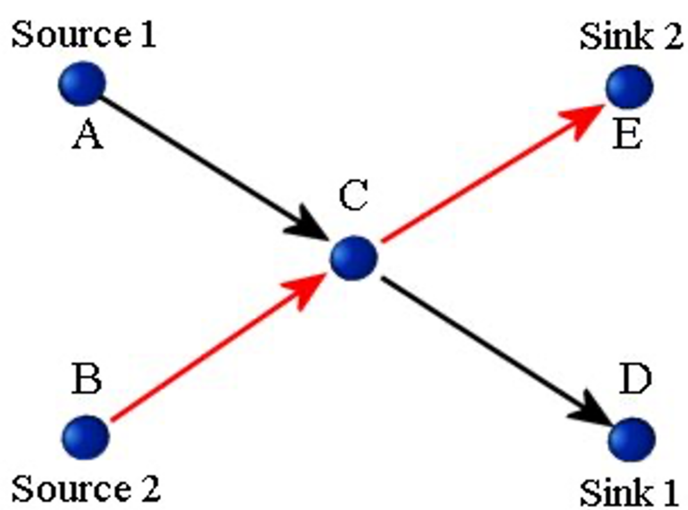
- If a node fails to get the medium, it goes to sleep and wakes up when the receiver is free and listening again
- Broadcast packets are sent without using RTS/CTS
- Unicast data packets follow the sequence of RTS/CTS/DATA/ACK between the sender and receiver
- Duration field in each transmitted packet indicates how long the remaining transmission will be so if a node receives a packet destined to another node, it knows how long it has to keep silent
- The node records this value in network allocation vector (NAV) and sets a timer for it

Collision Avoidance

- When a node has data to send, it first looks at NAV
- If this value is not zero, then medium is busy (virtual carrier sense)
- The medium is determined as free if both virtual and physical carrier sense indicate the medium is free
- All immediate neighbors of both the sender and receiver should sleep after they hear RTS or CTS packet until the current transmission is over

S-MAC Performance Evaluation

- Topology: Two-hop network with two sources and two sinks
- Sources periodically generate a sensing message which is divided into fragments
- Traffic load is changed by varying the inter-arrival period of the messages: (for inter-arrival period of 5s, message is generated every 5s by each source. Here it varies between 1-10s)

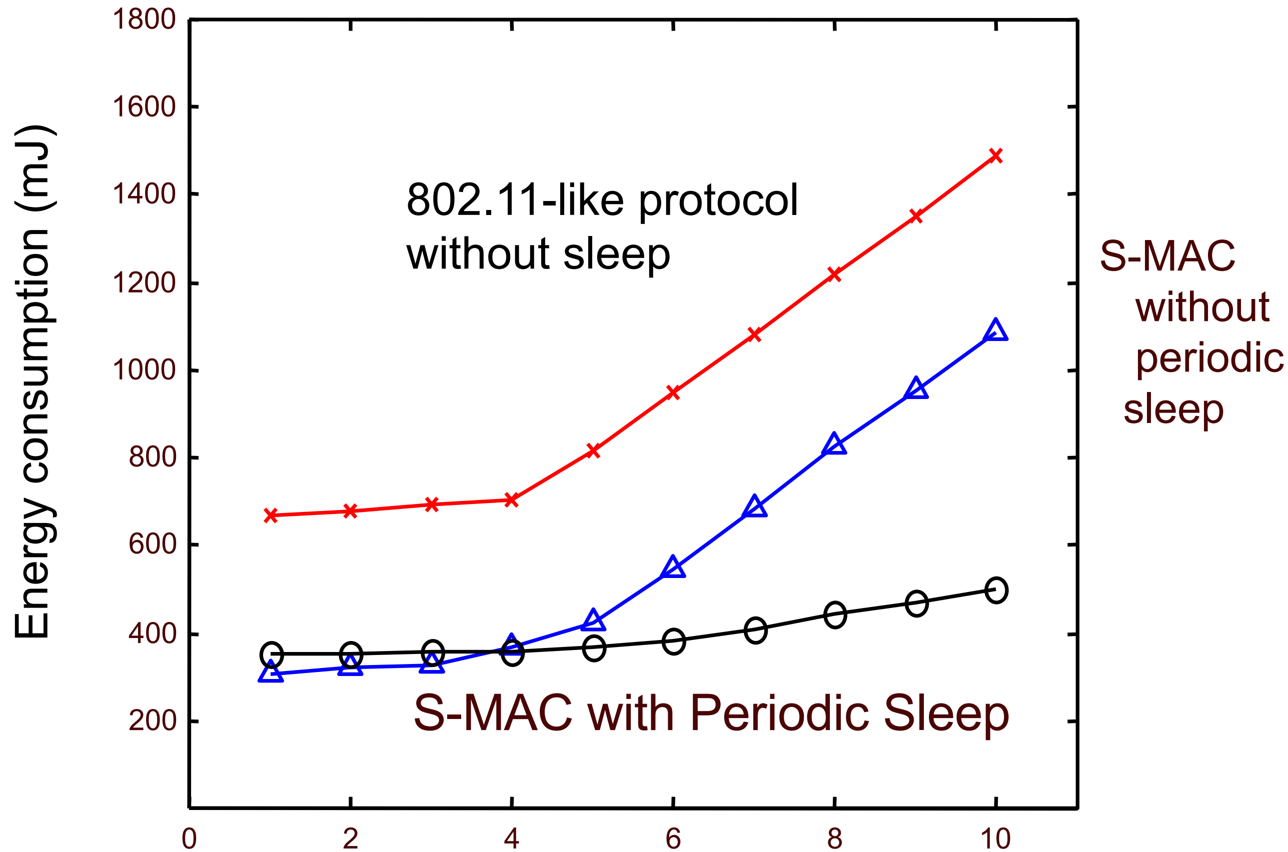


S-MAC – Example

- In each test, there are 10 messages generated on each source node
- Each message has 10 fragments, and each fragment has 40 bytes (200 data packets to be passed from sources to sinks)
- The total energy consumption of each node is measured for sending this fixed amount of data

Experiments

Average energy consumption in the source nodes A&B



Message inter-arrival period (traffic load) (second)
(small value → heavy traffic load)

Experiments

- S-MAC consumes much less energy than 802.11-like protocol without sleeping
- At heavy load, idle listening rarely happens, energy savings from sleeping is very limited.
- At light load, periodic sleeping plays a key role

S-MAC - Conclusions

- A mainly static network is assumed
- Trades off latency for reduced energy consumption
- Redundant data is still sent with increased latency

Other MAC approaches

- There are other approaches and many other solutions
- For an overview:

- Questions?

Routing

Routing

- Routing technique is needed for sending the data between the sensor nodes and the base stations, so as to establish communication