Ad hoc and Sensor Networks
Chapter 5: Medium access control protocols

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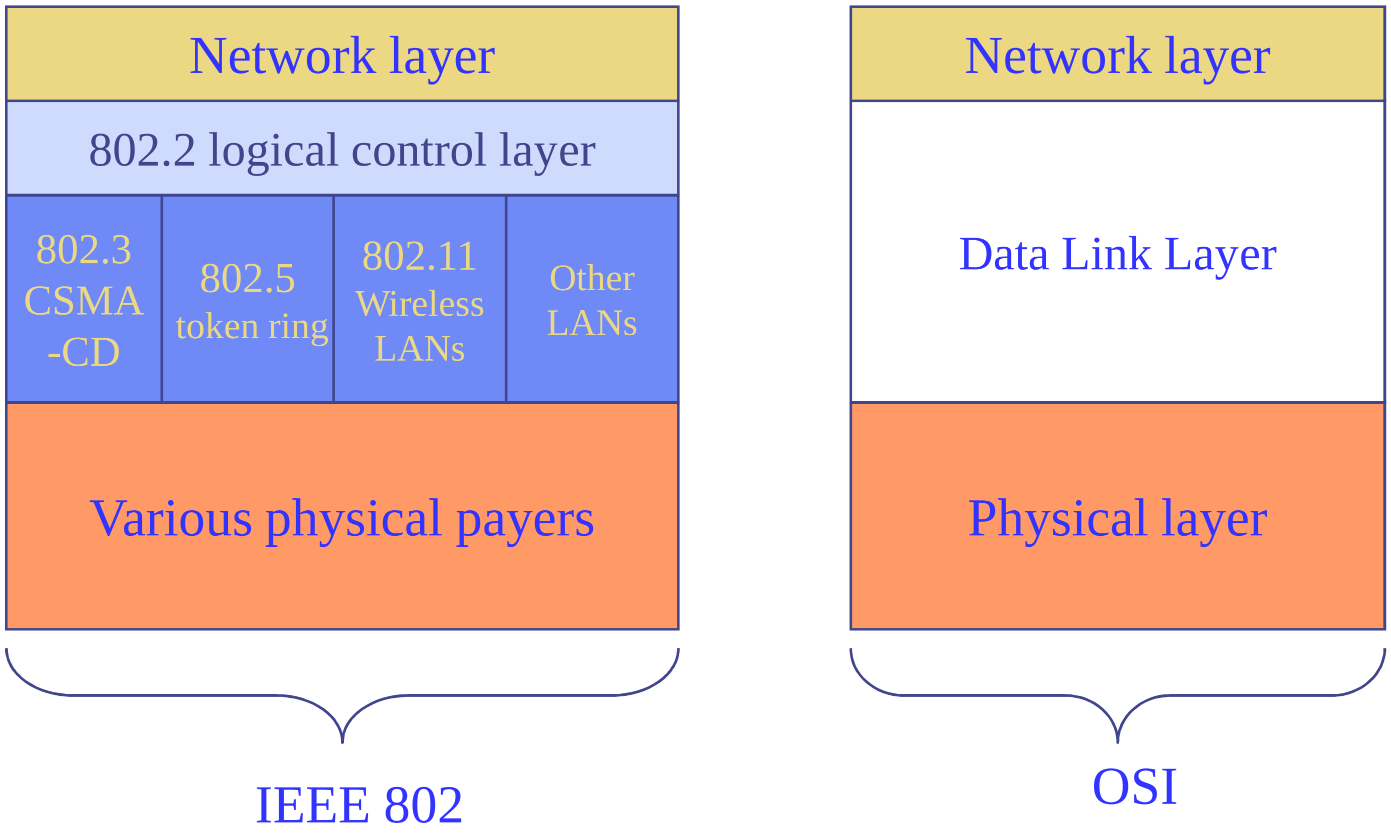
The Protocol Stacks

- MAC sublayer and OSI (open systems interconnection) reference model



Goals of this chapter

- Controlling when to send a packet and when to listen for a packet are perhaps the two most important operations in a wireless network
  - Especially, idly waiting wastes huge amounts of energy
- This chapter discusses schemes for this medium access control that are
  - Suitable to mobile and wireless networks
  - Emphasize energy-efficient operation

Overview

- ***Principal options and difficulties***
- Contention-based protocols
- Schedule-based protocols
- IEEE 802.15.4

Principal options and difficulties

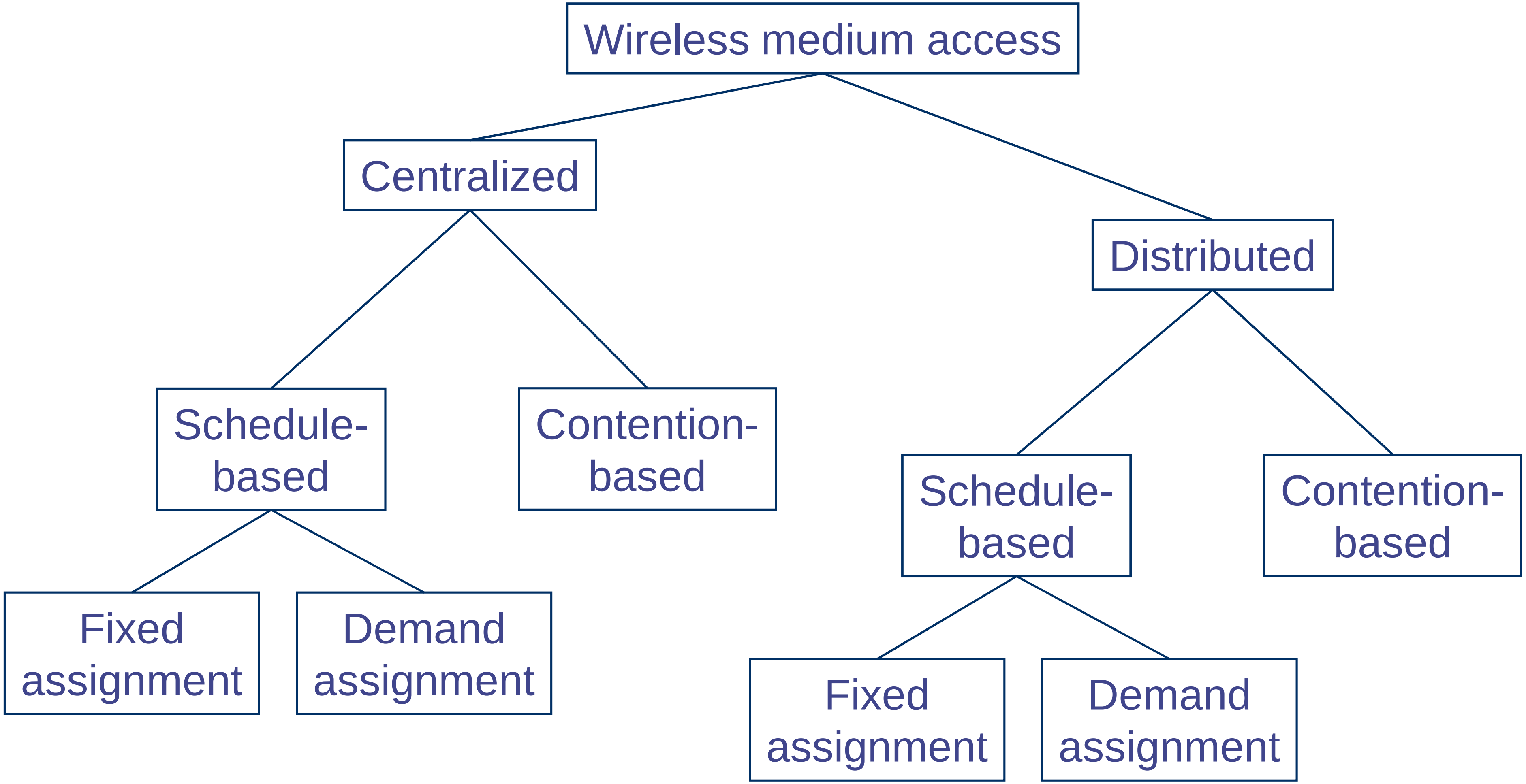
- Medium access in wireless networks is difficult mainly because of
  - Impossible (or very difficult) to send and receive at the same time
  - Interference situation at receiver is what counts for transmission success, but can be very different from what sender can observe
  - High error rates (for signaling packets) compound the issues

- Requirement
  - As usual: high throughput, low overhead, low error rates, …
  - Additionally: energy-efficient, handle switched off devices!

Requirements for energy-efficient MAC protocols

- Recall
  - Transmissions are costly
  - Receiving about as expensive as transmitting
  - Idling can be cheaper but is still expensive
- Energy problems
  - ***Collisions*** – wasted effort when two packets collide
  - ***Overhearing*** – waste effort in receiving a packet destined for another node
  - ***Idle listening*** – sitting idly and trying to receive when nobody is sending
  - ***Protocol overhead***
- Always nice: Low complexity solution

Main options



Centralized medium access

- Idea: Have a central station control when a node may access the medium
  - Example: Polling, centralized computation of TDMA schedules
  - Advantage: Simple, quite efficient (e.g., no collisions), burdens the central station

- Not directly feasible for non-trivial wireless network sizes
- But: Can be quite useful when network is somehow divided into smaller groups
  - Clusters, in each cluster medium access can be controlled centrally – compare Bluetooth piconets, for example

! Usually, distributed medium access is considered

Schedule- vs. contention-based MACs

- ***Schedule-based*** MAC
  - A ***schedule*** exists, regulating which participant may use which resource at which time (TDMA component), frequency (FDMA)
  - Typical resource: frequency band in a given physical space (with a given code, CDMA)
  - Schedule can be ***fixed*** or computed ***on demand***
  - Usually, collisions, overhearing, idle listening no issues
  - Needed: time synchronization!
- ***Contention-based*** protocols
  - Risk of colliding packets is deliberately taken
  - Hope: coordination overhead can be saved, resulting in overall improved efficiency
  - Mechanisms to handle/reduce probability/impact of collisions required
  - Usually, ***randomization*** used somehow

Overview

- Principal options and difficulties
- ***Contention-based protocols***
  - MACA
  - S-MAC, T-MAC
  - Preamble sampling, B-MAC
  - PAMAS
- Schedule-based protocols
- IEEE 802.15.4

Distributed, contention-based MAC

- Basic ideas for a distributed MAC
  - ALOHA – no good in most cases
  - Listen before talk ***(Carrier Sense Multiple Access, CSMA) –*** better, but suffers from ***sender*** not knowing what is going on at ***receiver***, might destroy packets despite first listening for a while
- CSMA/CA: carrier sense multiple access with collision avoidance
  - a station wishing to send must sense the medium
  - mandate a minimum gap between continuous frames
  - collision avoidance: a random back-off after the medium is sensed idle
  - only decrement the back-off interval while the medium is free
  - all non-broadcast uses immediate ACK
    - if no ACK is received, the frame is repeated immediately

CD vs. CA

- CD = collision detection
- CA = collision avoidance
- CD will not function properly because the STA may not be able to detect the collision while transmitting.

Hidden-Terminal and Exposed-Terminal Problems

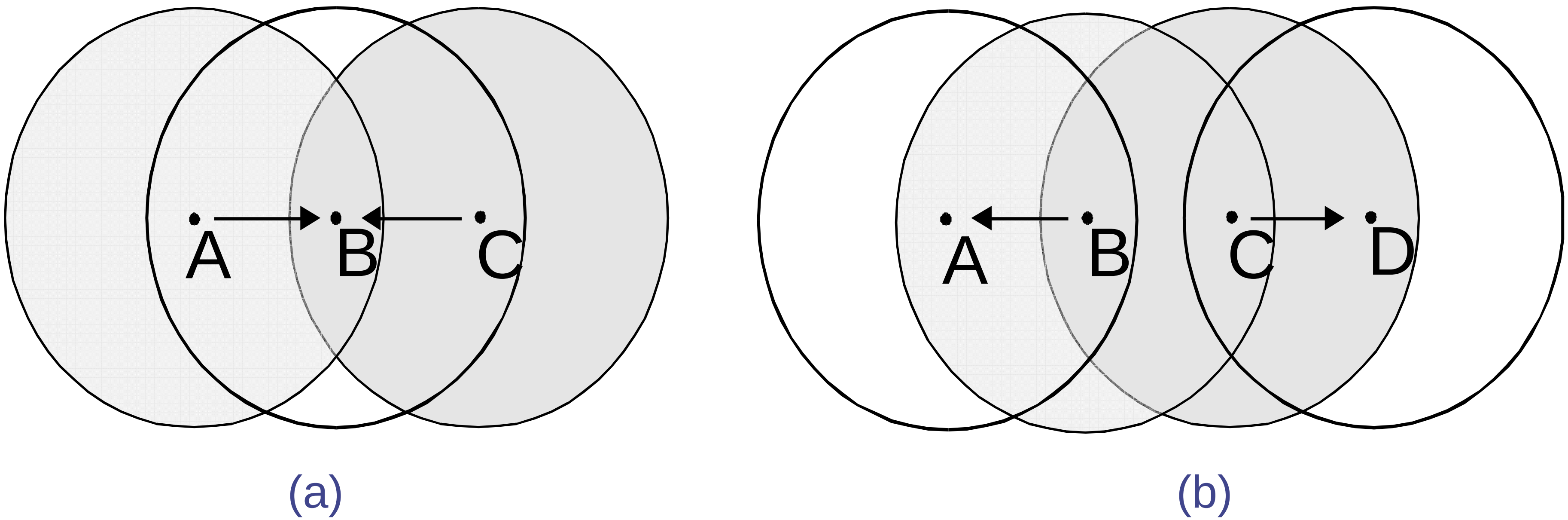


Fig. 1: (a) the hidden terminal problem,
(b) the exposed terminal problem

Main options to shut up senders

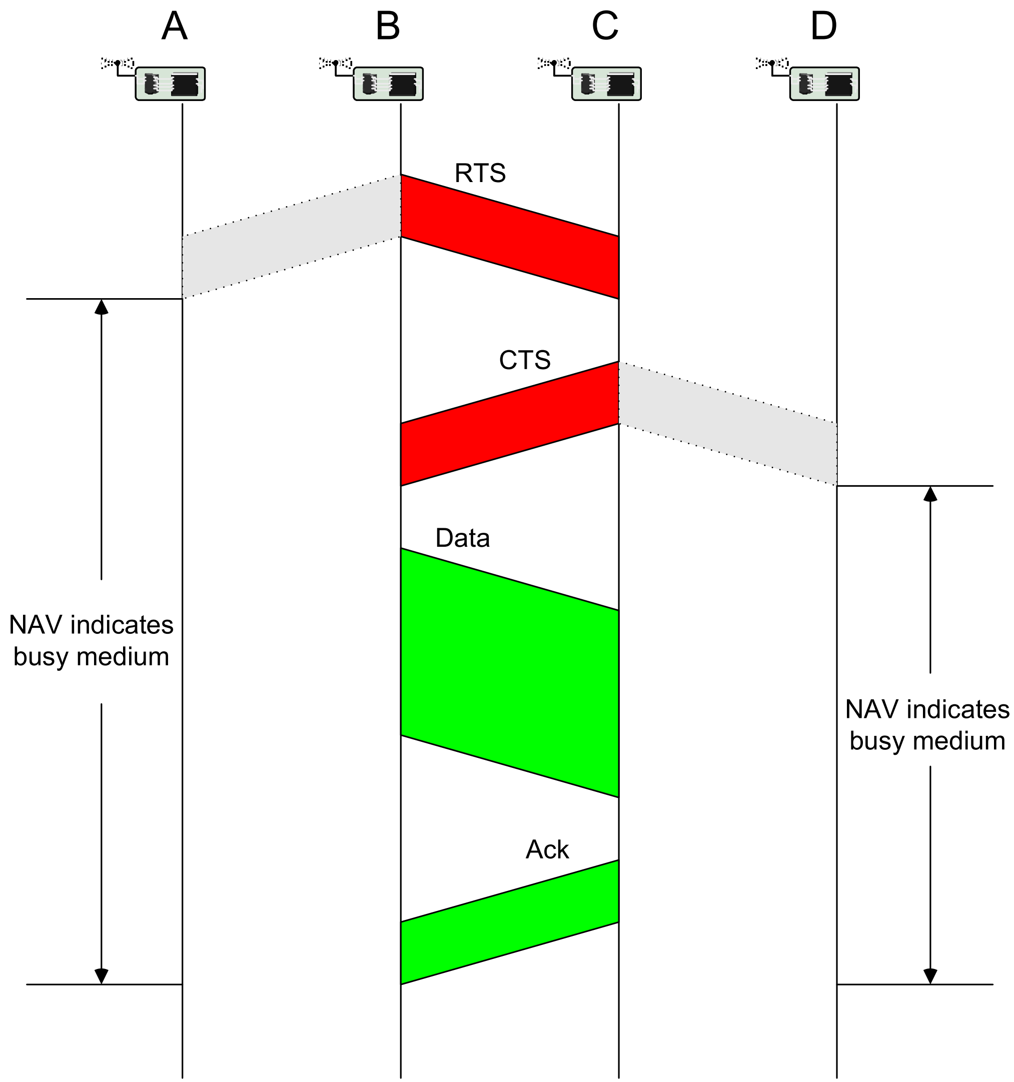
- Receiver informs potential interferers ***while*** a reception is on-going
  - By sending out a signal indicating just that
  - Problem: Cannot use same channel on which actual reception takes place

  ! Use separate channel for signaling
  - ***Busy tone*** protocol
- Receiver informs potential interferers ***before*** a reception is on-going
  - Can use same channel
  - Receiver itself needs to be informed, by sender, about impending transmission
  - Potential interferers need to be aware of such information, need to store it

Receiver informs interferers before transmission – MACA

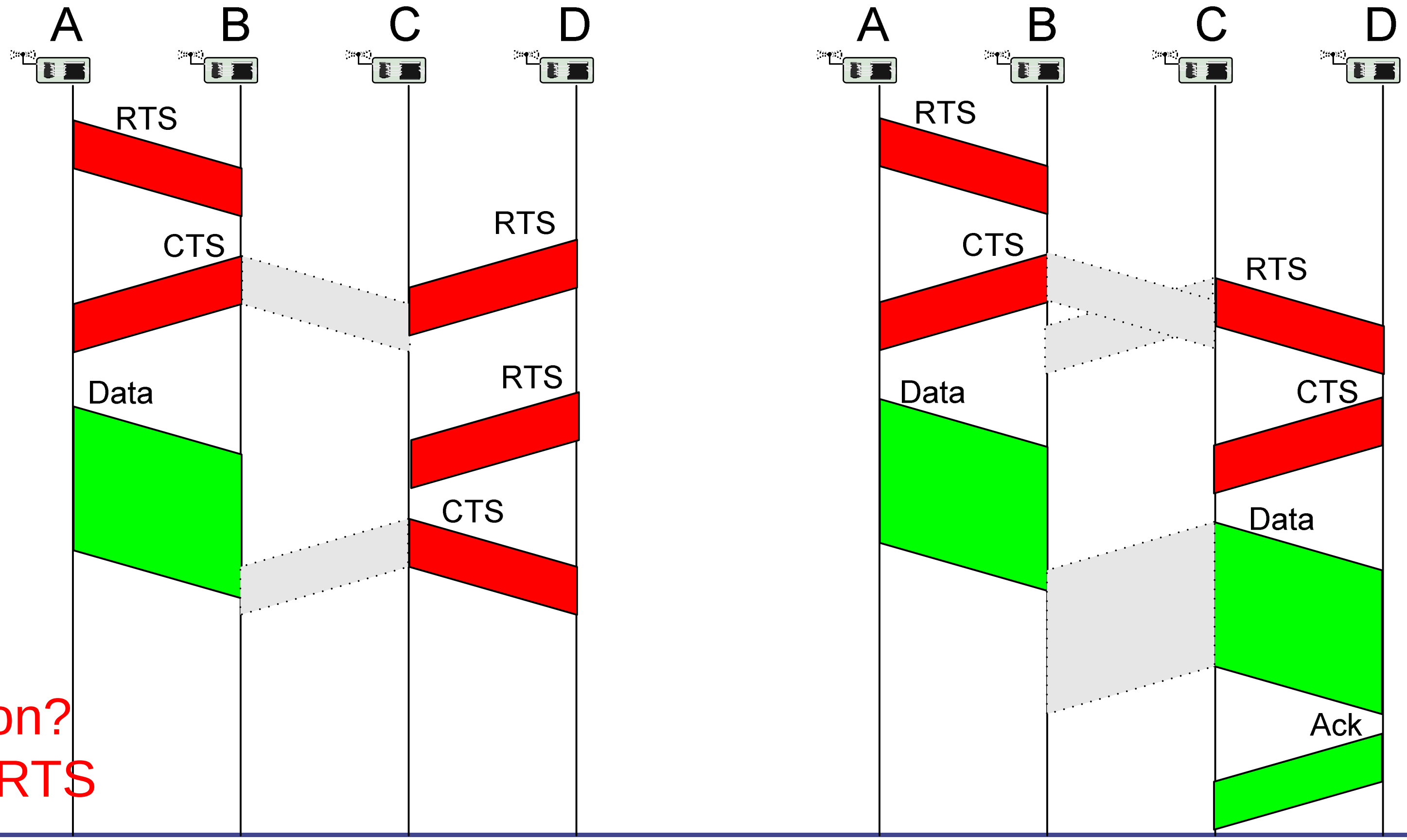
- Sender B asks receiver C whether C is able to receive a transmission
  Request to Send (RTS)
- Receiver C agrees, sends out a ***Clear to Send*** (***CTS***)
- Potential interferers overhear either RTS or CTS and know about impending transmission and for how long it will last
  - Store this information in a ***Network Allocation Vector (NAV)***
- B sends, C acks

! ***MACA protocol*** (used e.g. in ***IEEE 802.11***)



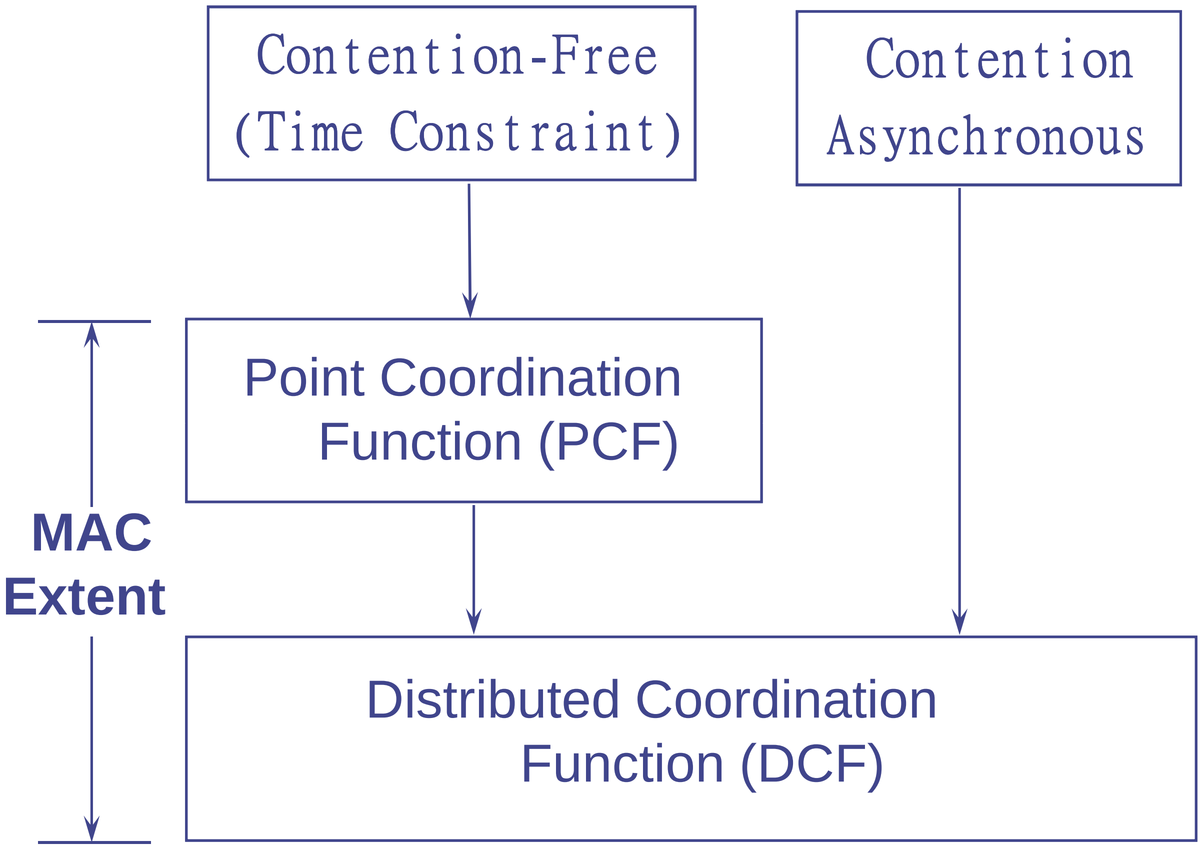
RTS/CTS

- RTS/CTS improve, but do not solve hidden/exposed terminal problems
- Example problem cases:



Solution?
CTS > RTS

802.11 MAC Architecture



MAC Architecture

- Distributed Coordination Function (DCF)
  - The fundamental access method for the 802.11 MAC, known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA).
  - Shall be implemented in ALL stations and APs.
  - Used within both ad hoc and infrastructure configurations.
- Point Coordination Function (PCF)
  - An alternative access method
  - Shall be implemented on top of the DCF
  - A point coordinator (polling master) is used to determine which station currently has the right to transmit.
  - Shall be built up from the DCF through the use of an access priority mechanism.

Distribution Coordination Function (DCF)

- CSMA+CA (RTS/CTS)
  - As CSMA/CA sense the medium is busy or idle
  - Exchange short control frames(RTS/CTS)to further minimize collisions
- Random Back-off
  - Using a random back-off procedure to resolve contention conflicts
- Priority Scheme (SIFS,PIFS,DIFS,EIFS)

Priority Scheme in MAC

- Priorities of frames are distinguished by the IFS (inter-frame spacing) incurred between two consecutive frames.
- 4 IFS's:
  - SIFS: the highest priority
    - ACK, CTS, the second or subsequent MPDU (MAC Protocol Data Unit) of a fragmented burst, and to respond to a poll from the PCF.
  - PIFS (PCF-IFS): 2nd highest
    - by PCF to send any of the Contention Free Period frames.
  - DIFS (DCF-IFS): 3nd highest
    - by the DCF to transmit MPDUs or MMPDUs
  - EIFS (Extended-IFS): lowest
    - by the DCF to retransmit a frame

DCF: the Random Backoff Time

- Before transmitting asynchronous data packets, a node shall use the carrier sense (CS) function to determine the medium state.
- If idle, the node
  - defer a DIFS gap
  - transmit data packet
- If busy, the node
  - defer a DIFS gap
  - then generate a random back-off period (within the contention window CW) for an additional deferral time to resolve contention.

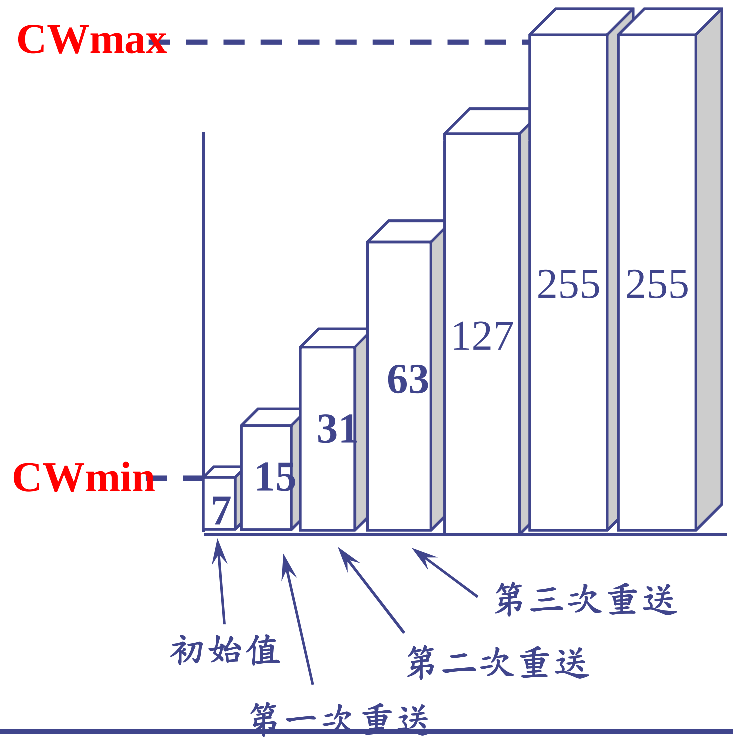
DCF: the Random Backoff Time (Cont.)

Back-off time = CW* Random() * Slot time

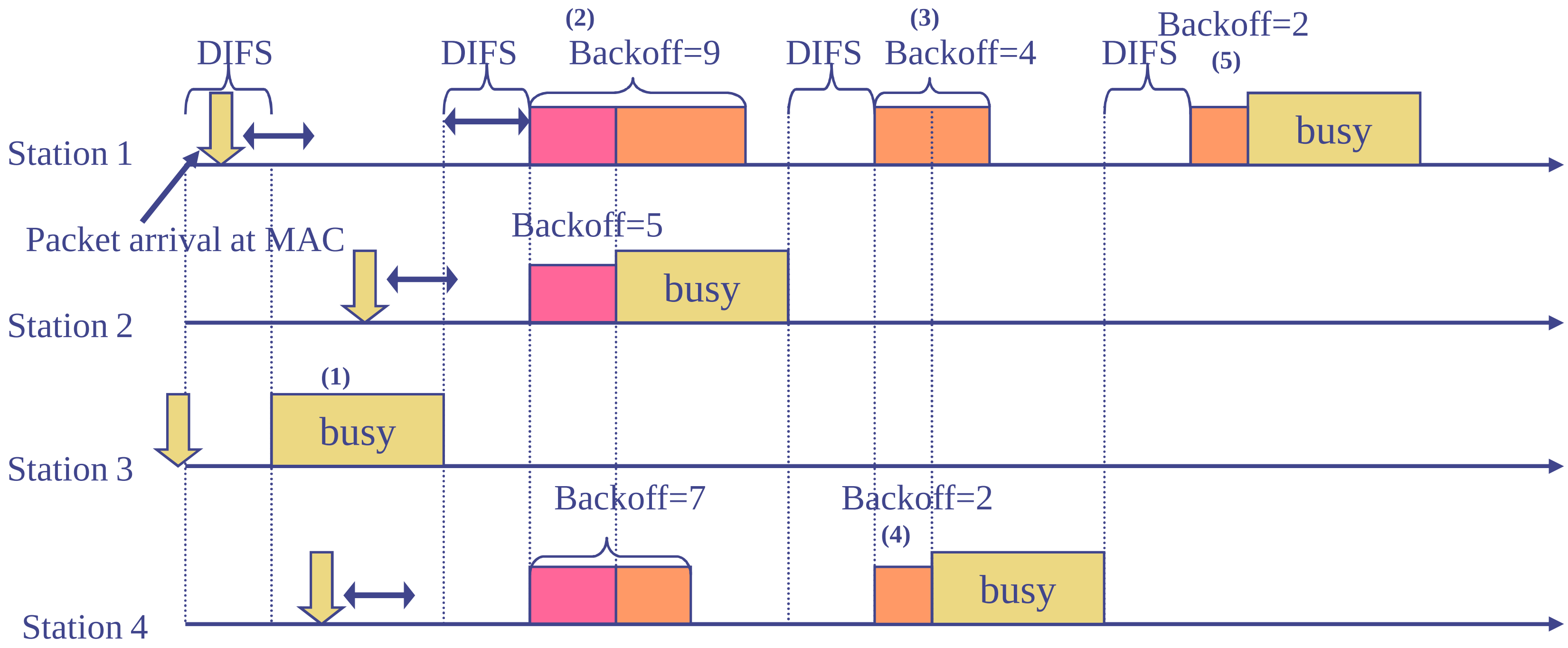
where CW = starts at CWmin, and doubles after each failure until reaching CWmax and remains there in all remaining retries (e.g., CWmin = 7, CWmax = 255)

Random() = (0,1)

Slot Time = Transmitter turn-on delay +
medium propagation delay +
medium busy detect response time



Example of Back-off Intervals



(1) After packet arrival at MAC, station 3 senses medium free for DIFS, so it starts transmission immediately (without backoff interval).

(2) For station 1,2, and 4, their DIFS intervals are interrupted by station 3. Thus, backoff intervals for station 1,2, and 4, are generated randomly (i.e. 9,5, and 7, respectively).

(3) After transmission of station 2, the remaining backoff interval of station 1 is (9-5)=4.

(4) After transmission of station 2, the remaining backoff interval of station 4 is (7-5)=2.

(5) After transmission of station 4, the remaining backoff interval of station 1 is (4-2)=2.

Backoff Procedure

- The Backoff Timer should be frozen when medium is busy.
- The timer should be resumed only when the medium is free for a period > DIFS.
- Transmission shall commence whenever the Back-off Timer reaches 0.
- To ensure fairness and stability:
  - a STA that has just transmitted a frame and has another queued frame, shall perform the back-off procedure.

Setting and resetting the NAV

STAs receiving a valid frame shall update their NAV with the information received in the Duration/ID field

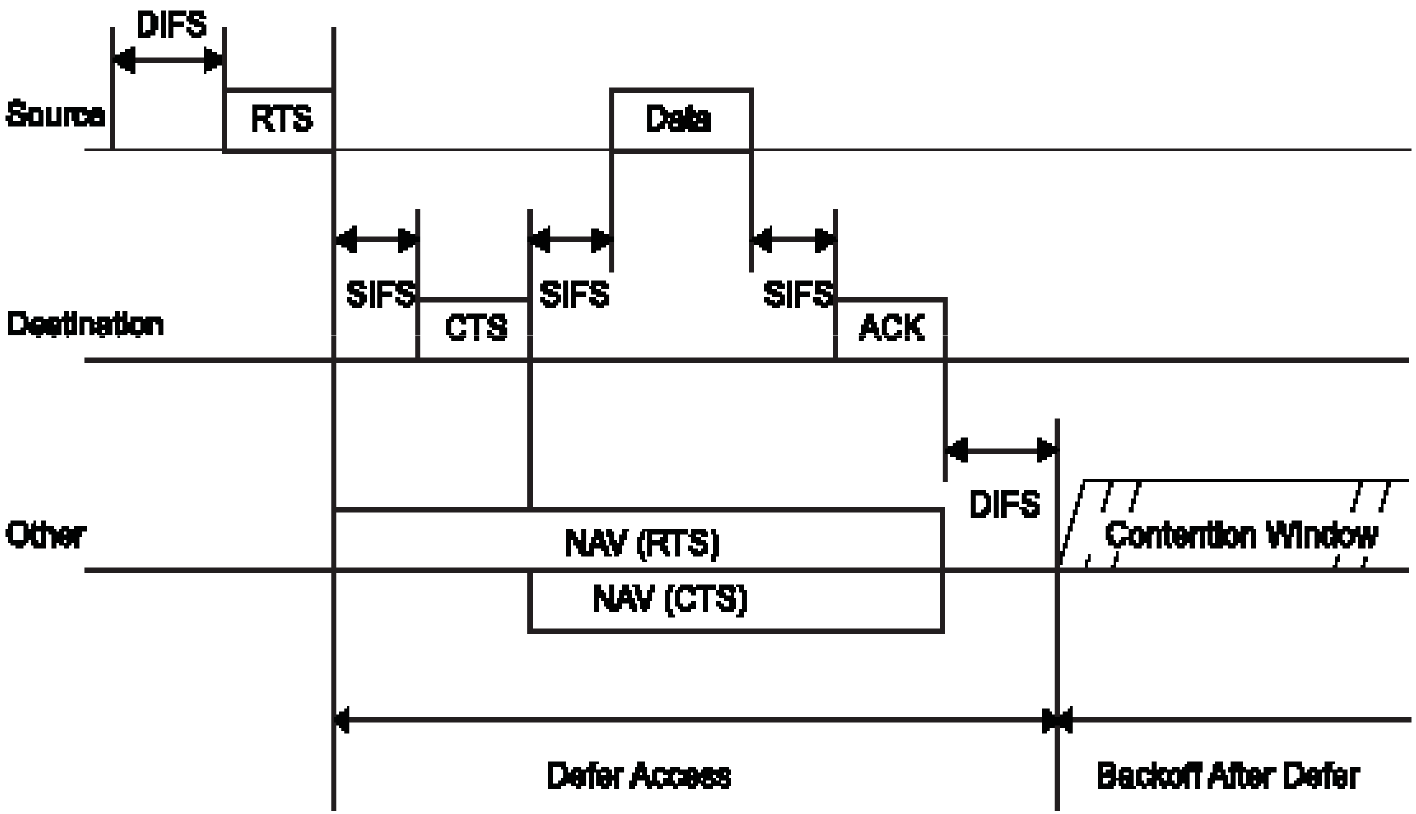
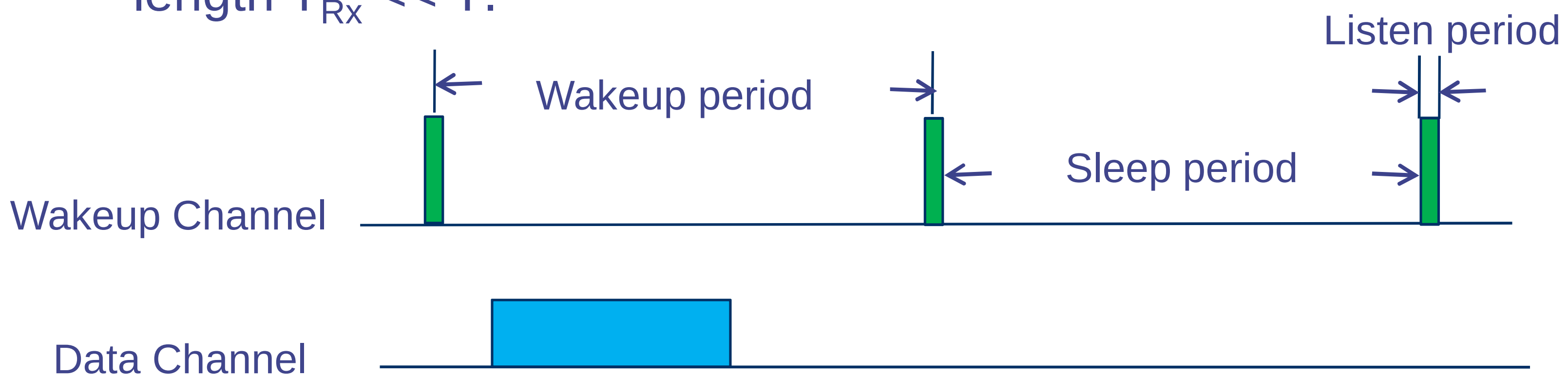


Figure 53—RTS/CTS/data/ACK and NAV setting

Spare Topology and Energy Management (STEM)

- MACA's idle listening is particularly unsuitable if average data rate is low
  - Most of the time, nothing happens
- Idea: Two different channels are used: the wakeup channel and data channel
  - Data channel always in sleep mode except when transmitting or receiving data packet
  - Wakeup channel is divided into fixed-length wakeup periods of length T. A wakeup period is subdivided into a listen period of length $T_{Rx} << T$.

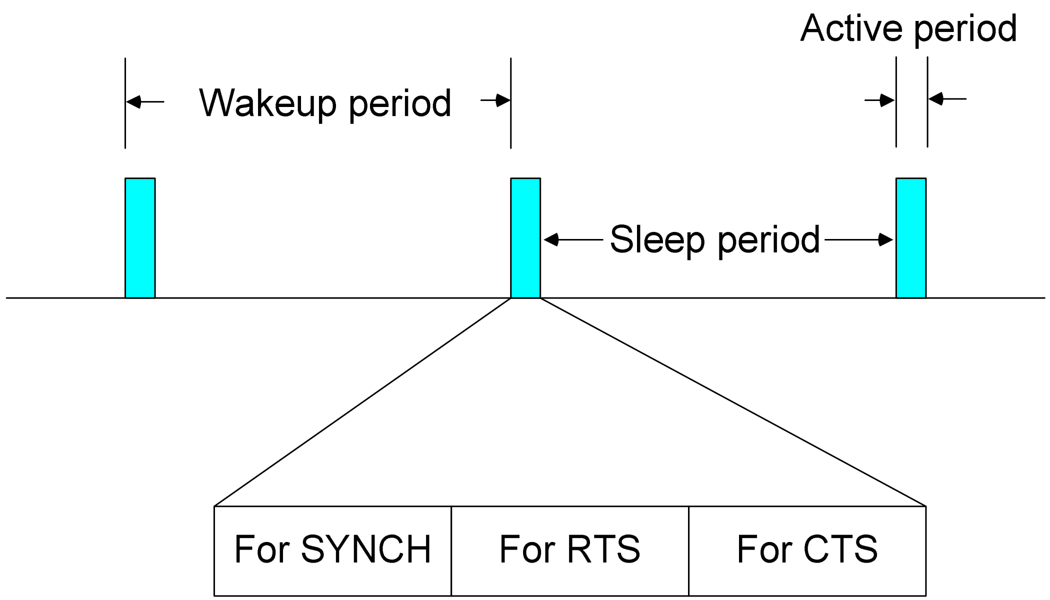


Spare Topology and Energy Management (STEM)

- STEM-B: the transmitter issues beacons (indicates the MAC address of receiver) on the wakeup channel periodically. As soon as the receiver picks up the beacon, it sends an Ack back on the wakeup channel and switches to data channel.
- STEM-T: the transmitter sends out a simple busy tone on the control channel. All the transmitter’s neighbors receiving the busy tone switch on their data channel, without sending an Ack.

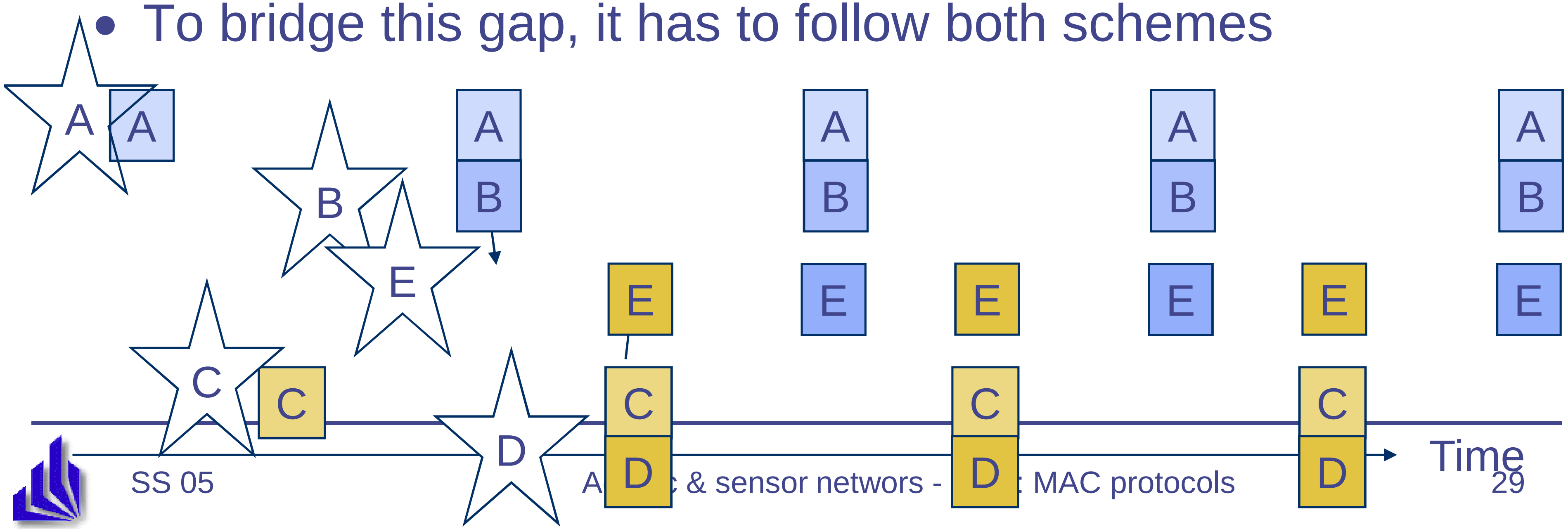
Sensor-MAC (S-MAC)

- Idea: Switch nodes off, ensure that neighboring nodes turn on simultaneously to allow packet exchange (rendezvous)
  - Only in these ***active periods***, packet exchanges happen
  - Need to also exchange wakeup schedule between neighbors
  - When awake, essentially perform RTS/CTS
- Use SYNCH, RTS, CTS phases



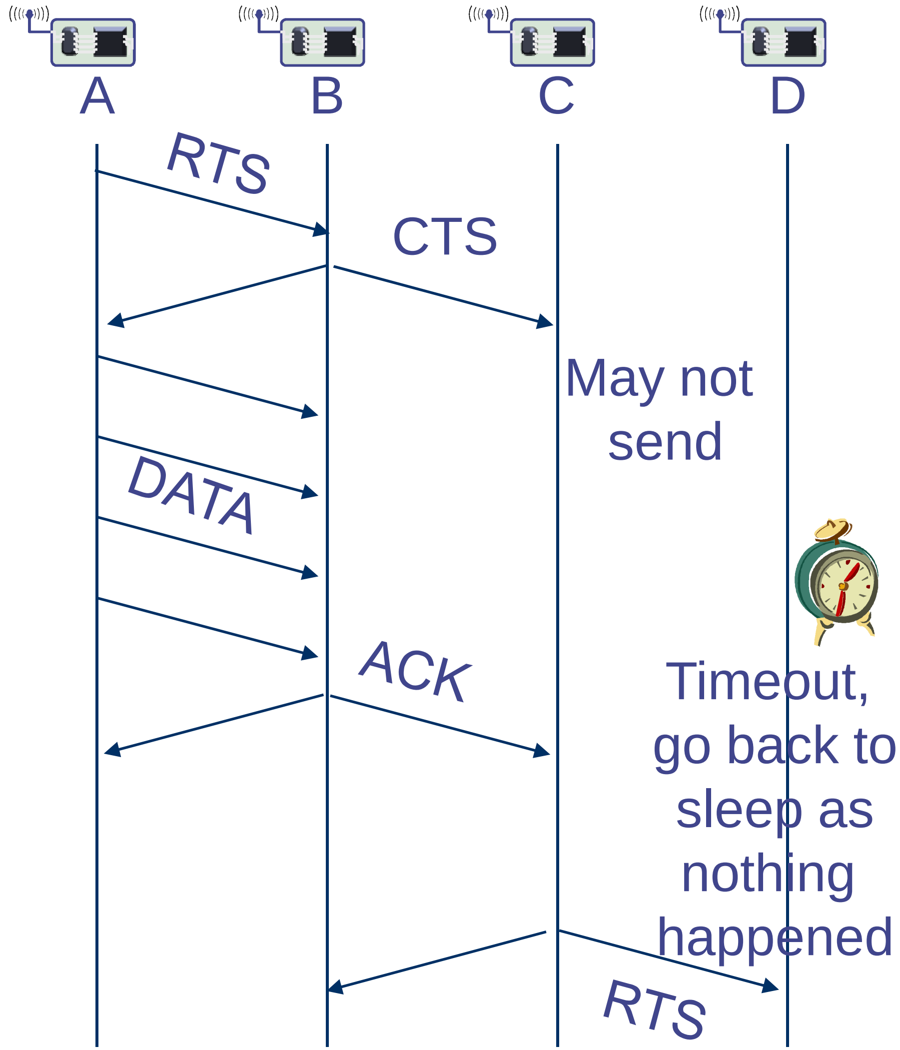
S-MAC synchronized islands

- Nodes try to pick up schedule synchronization from neighboring nodes
- If no neighbor found, nodes pick some schedule to start with
- If additional nodes join, some node might learn about two different schedules from different nodes
  - "Synchronized islands"
- To bridge this gap, it has to follow both schemes



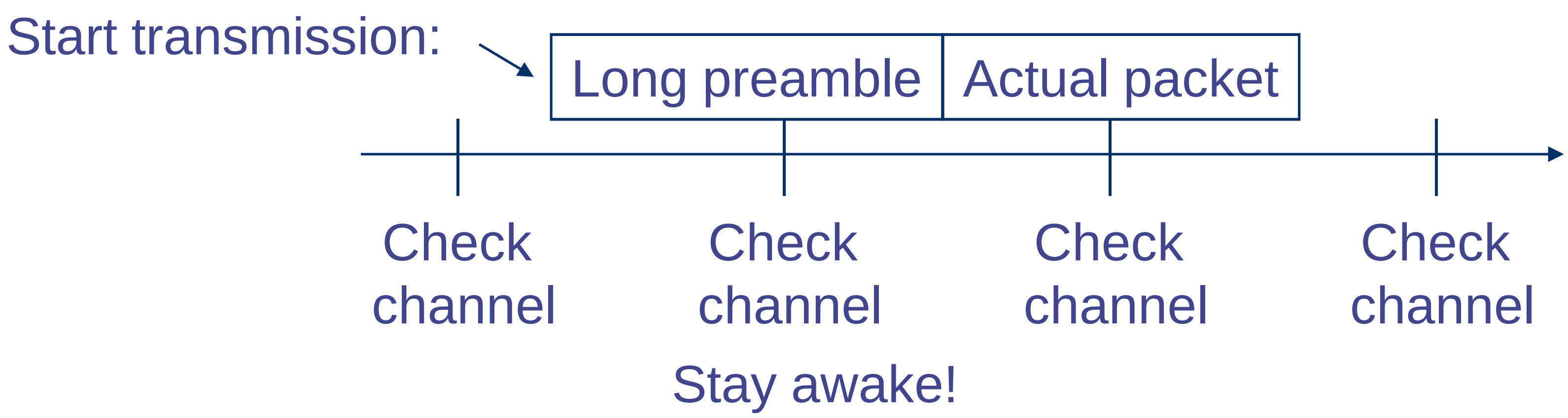
Timeout-MAC (T-MAC)

- In S-MAC, active period is of constant length
- What if no traffic actually happens?
  - Nodes stay awake needlessly long
- Idea: Prematurely go back to sleep mode when no traffic has happened for a certain time (=timeout) ! T-MAC
  - Adaptive duty cycle!
- One ensuing problem: Early sleeping
  - C wants to send to D, but is hindered by transmission A! B



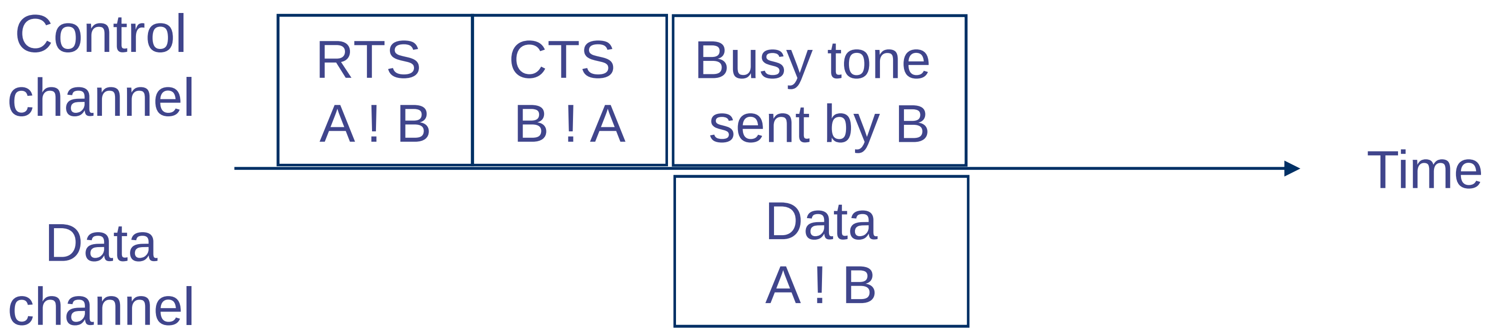
Preamble Sampling

- So far: Periodic sleeping supported by some means to synchronize wake up of nodes to ensure rendezvous between sender and receiver
- Alternative option: Don’t try to explicitly synchronize nodes
  - Have receiver sleep and only periodically sample the channel
- Use ***long preambles*** to ensure that receiver stays awake to catch actual packet
  - Example: WiseMAC



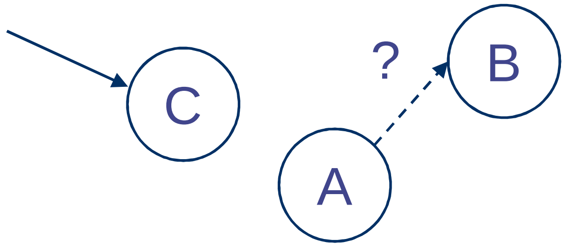
Power Aware Multiaccess with Signaling – PAMAS

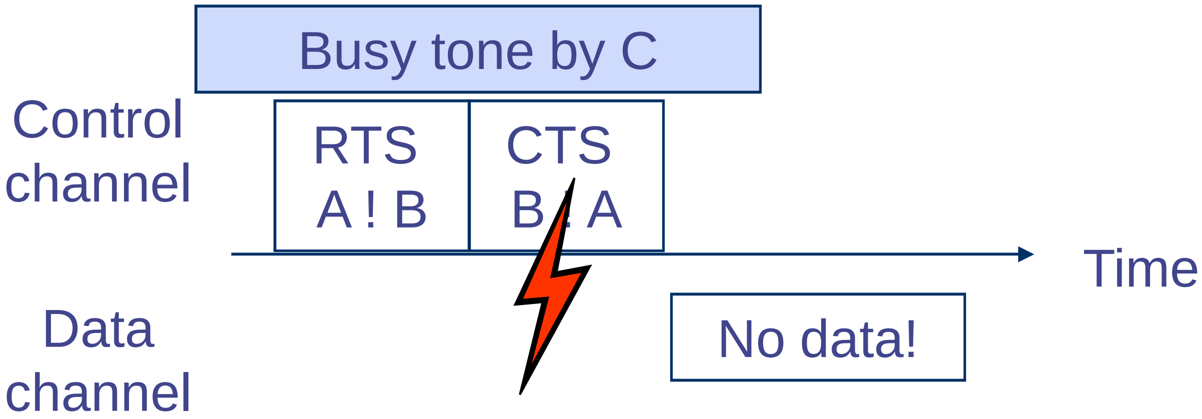
- Idea: combine busy tone with RTS/CTS
  - Results in detailed overhearing avoidance, does not address idle listening
  - Uses separate ***data*** and ***control channels***
- Procedure
  - Node A transmits RTS on control channel, does not sense channel
  - Node B receives RTS, sends CTS on control channel if it can receive and does not know about ongoing transmissions
  - B sends busy tone as it starts to receive data



PAMAS – Already ongoing transmission

- Suppose a node C in vicinity of A is already receiving a packet when A initiates RTS
- Procedure
  - A sends RTS to B
  - C is sending busy tone (as it receives data)
  - CTS and busy tone collide, A receives no CTS, does not send data





Similarly: Ongoing transmission near B destroys RTS by busy tone

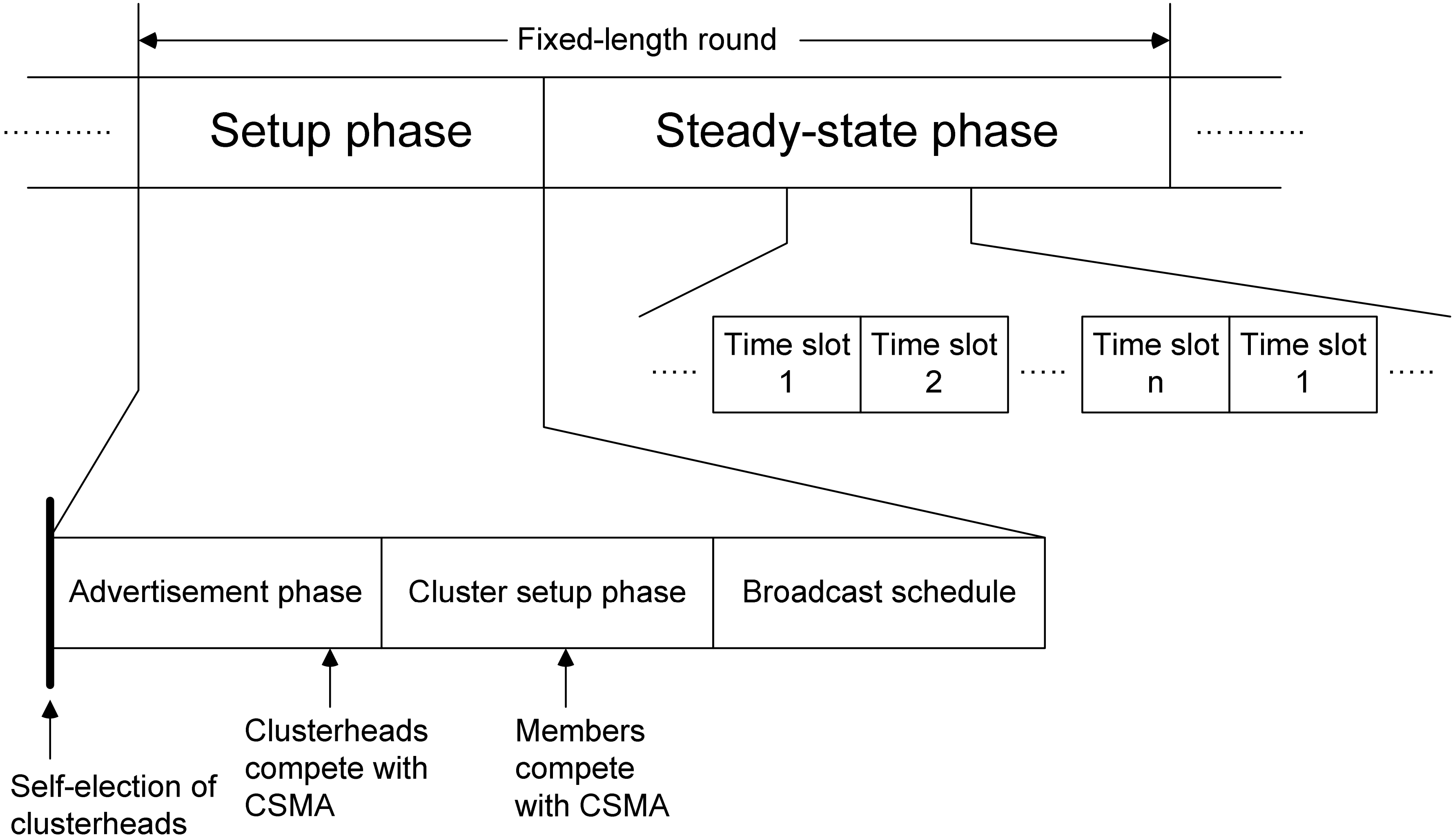
Overview

- Principal options and difficulties
- Contention-based protocols
- ***Schedule-based protocols***
  - LEACH
  - SMACS
  - TRAMA
- IEEE 802.15.4

Low-Energy Adaptive Clustering Hierarchy (LEACH)

- Given: dense network of nodes, reporting to a central sink, each node can reach sink directly
- Idea: Group nodes into "***clusters***", controlled by ***clusterhead***
  - Setup phase; details: later
  - About 5% of nodes become clusterhead (depends on scenario)
  - Role of clusterhead is rotated to share the burden
  - Clusterheads advertise themselves, ordinary nodes join CH with strongest signal
  - Clusterheads organize
    - CDMA code for all member transmissions
    - TDMA schedule to be used within a cluster
- In steady state operation
  - CHs collect & aggregate data from all cluster members
  - Report aggregated data to sink using CDMA

LEACH rounds

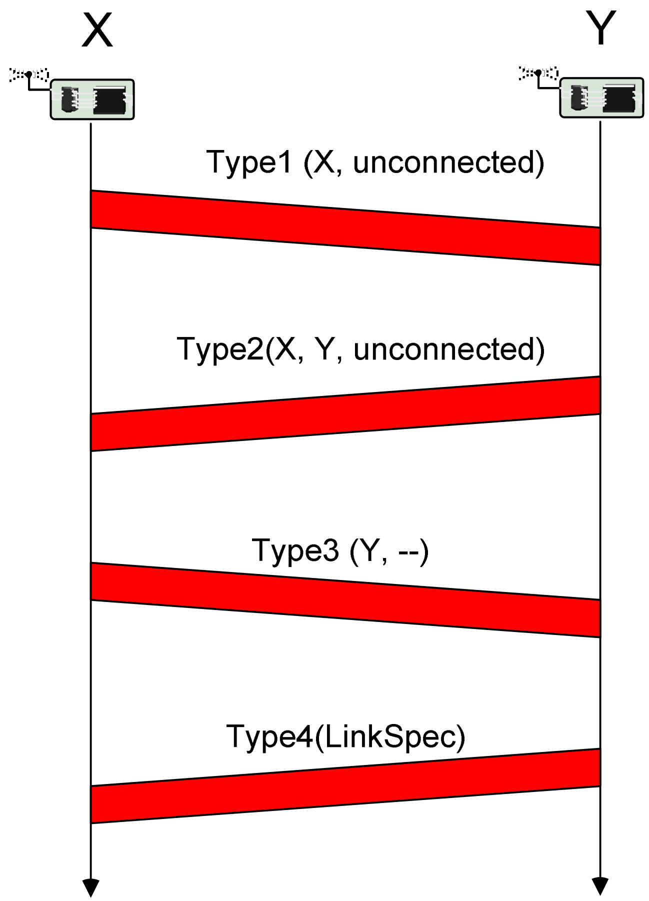


Self-Organizing MAC for Sensor Network (SMACS)

- Given: many radio channels, superframes of known length (not necessarily in phase, but still time synchronization required!)
- Goal: set up directional ***links*** between neighboring nodes
  - Link: radio channel + time slot (TDMA) at both sender and receiver
  - Free of collisions at receiver
  - Channel picked randomly, slot is searched greedily until a collision-free slot is found
- Receivers sleep and only wake up in their assigned time slots, once per superframe
- In effect: a local construction of a schedule

SMACS link setup

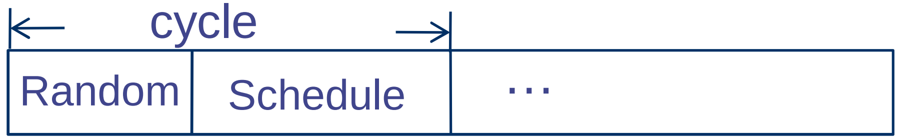
- Case 1: Node X, Y both so far unconnected
  - Node X sends invitation message
  - Node Y answers, telling X that is unconnected to any other node
  - Node X tells Y to pick slot/frequency for the link
  - Node Y sends back the link specification
- Case 2: X has some neighbors, Y not
  - Node X will construct link specification and instruct Y to use it (since Y is unattached)
- Case 3: X no neighbors, Y has some
  - Y picks link specification
- Case 4: both nodes already have links
  - Nodes exchange their schedules and pick free slots/frequencies in mutual agreement



Message exchanges protected by randomized backoff

Traffic-Adaptive Medium Access Protocol: TRAMA

- Nodes are synchronized
- Time divided into cycles, divided into
  - Random access periods
  - Scheduled access periods



- Nodes exchange neighborhood information
  - Learning about their two-hop neighborhood
  - Using ***neighborhood exchange protocol***: In random access period, send small, incremental neighborhood update information in randomly selected time slots
- Nodes exchange schedules
  - Using ***schedule exchange protocol***
  - Similar to neighborhood exchange
- Adaptive election

TRAMA – adaptive election

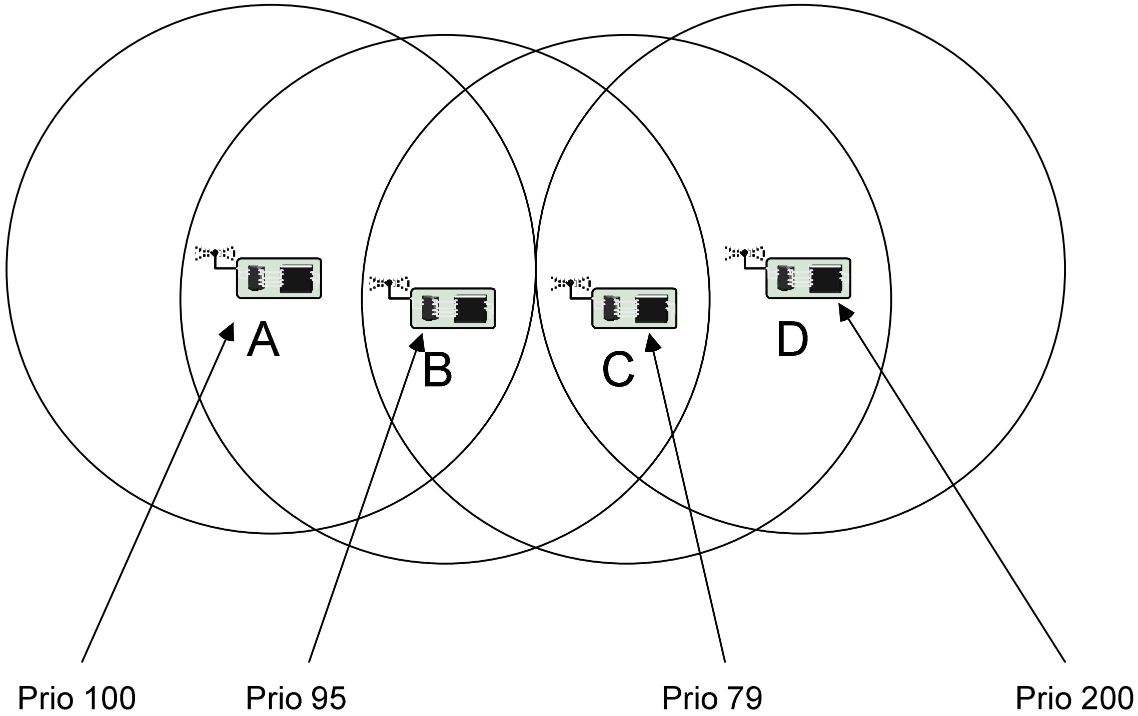
- Given: Each node knows its two-hop neighborhood and their current schedules
- How to decide which slot (in scheduled access period) a node can use?
  - Use ***node identifier*** x and globally known ***hash function*** h
  - For time slot t, compute ***priority*** $p = h(x \oplus t)$
  - Compute this priority for next k time slots for node itself and all two-hop neighbors
  - Node uses those time slots for which it has the highest priority

Priorities of node A and its two neighbors B & C

	t = 0	t = 1	t = 2	t=3	t = 4	t = 5
A	14	23	9	56	3	26
B	33	64	8	12	44	6
C	53	18	6	33	57	2

TRAMA – possible conflicts

- When does a node have to receive?
  - Easy case: one-hop neighbor has won a time slot and announced a schedule packet for it
  - The last winning slot is used to broadcast next schedule
  - But complications exist – compare example
- What does B believe?
  - A thinks it can send
  - B knows that D has higher priority in its 2-hop neighborhood!
- Rules for resolving such conflicts are part of TRAMA?



Comparison: TRAMA, S-MAC

- Comparison between TRAMA & S-MAC
  - Energy savings in TRAMA depend on load situation
  - Energy savings in S-MAC depend on duty cycle
  - TRAMA (as typical for a TDMA scheme) has higher delay but higher maximum throughput than contention-based S-MAC
- TRAMA disadvantage: substantial memory/CPU requirements for schedule computation

Overview

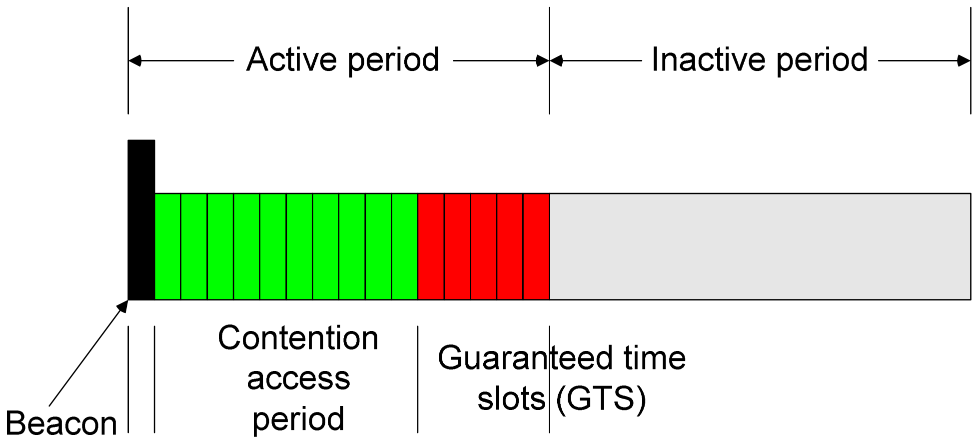
- Principal options and difficulties
- Contention-based protocols
- Schedule-based protocols
- ***IEEE 802.15.4***

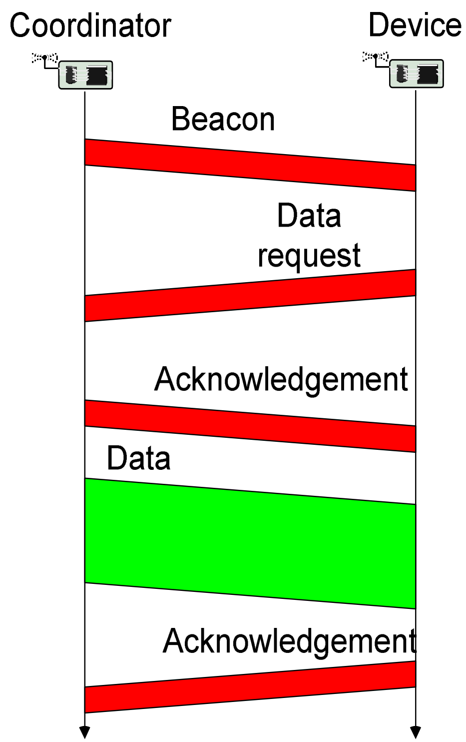
IEEE 802.15.4

- IEEE standard for low-rate WPAN applications
- Goals: low-to-medium bit rates, moderate delays without too stringent guarantee requirements, low energy consumption
- Physical layer
  - 20 kbps over 1 channel @ 868-868.6 MHz
  - 40 kbps over 10 channels @ 905 – 928 MHz
  - 250 kbps over 16 channels @ 2.4 GHz
- MAC protocol
  - Single channel at any one time
  - Combines contention-based and schedule-based schemes
  - Asymmetric: nodes can assume different roles

IEEE 802.15.4 MAC overview

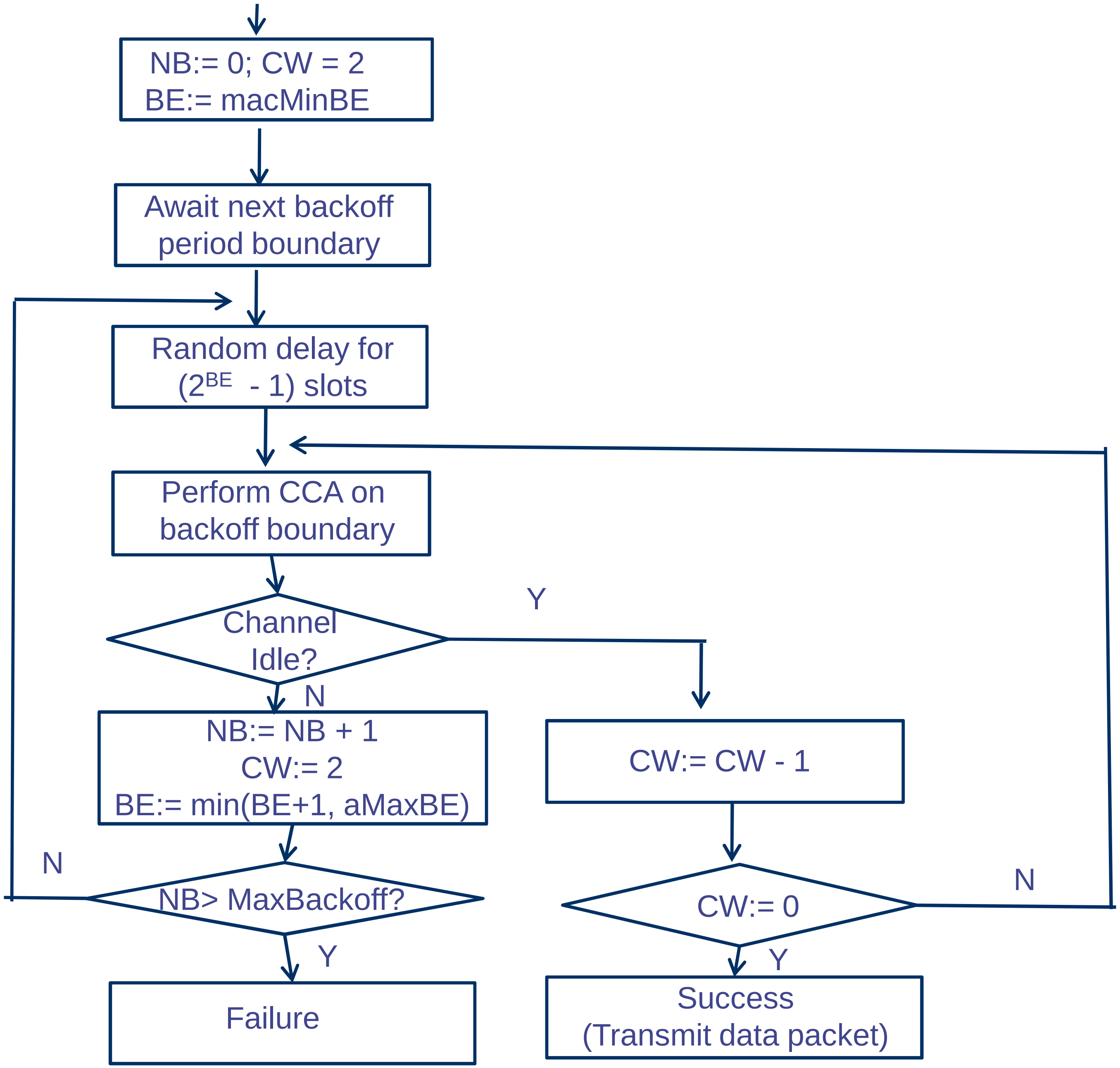
- Star networks: ***devices*** are associated with ***coordinators***
  - Forming a PAN, identified by a PAN identifier
- Coordinator
  - Bookkeeping of devices, address assignment, generate beacons
  - Talks to devices and peer coordinators
- Beacon-mode superframe structure
  - GTS assigned to devices upon request





Slotted CSMA-CA protocol

- Node uses the slotted CSMA-CA protocol in CAP to send data or control message
  - CSMA-CA = CSMA + Random Back-off
  - NB: number of back-off
  - BE: binary exponent
  - CCA: clear channel assessment


NB:= 0; CW = 2
BE:= macMinBE
Await next backoff period boundary
Random delay for (2^{BE} - 1) slots
Perform CCA on backoff boundary
Channel Idle?
Y
N
NB:= NB + 1
CW:= 2
BE:= min(BE+1, aMaxBE)
CW:= CW - 1
N
NB> MaxBackoff?
Y
CW:= 0
N
Y
Failure
Success
(Transmit data packet)

Further protocols

- MAC protocols for ad hoc/sensor networks is one the most active research fields
  - Tons of additional protocols in the literature
  - Examples: STEM, mediation device protocol, many CSMA variants with different timing optimizations, protocols for multi-hop reservations (QoS for MANET), protocols for multiple radio channels, …
  - Additional problems, e.g., reliable multicast
- This chapter has barely scratched the surface…

Summary

- Many different ideas exist for medium access control in MANET/WSN
- Comparing their performance and suitability is difficult
- Especially: clearly identifying interdependencies between MAC protocol and other layers/applications is difficult
  - Which is the best MAC for which application?

- Nonetheless, certain “common use cases” exist
  - IEEE 802.11 DCF for MANET
  - IEEE 802.15.4 for some early “commerical” WSN variants
  - B-MAC for WSN research not focusing on MAC