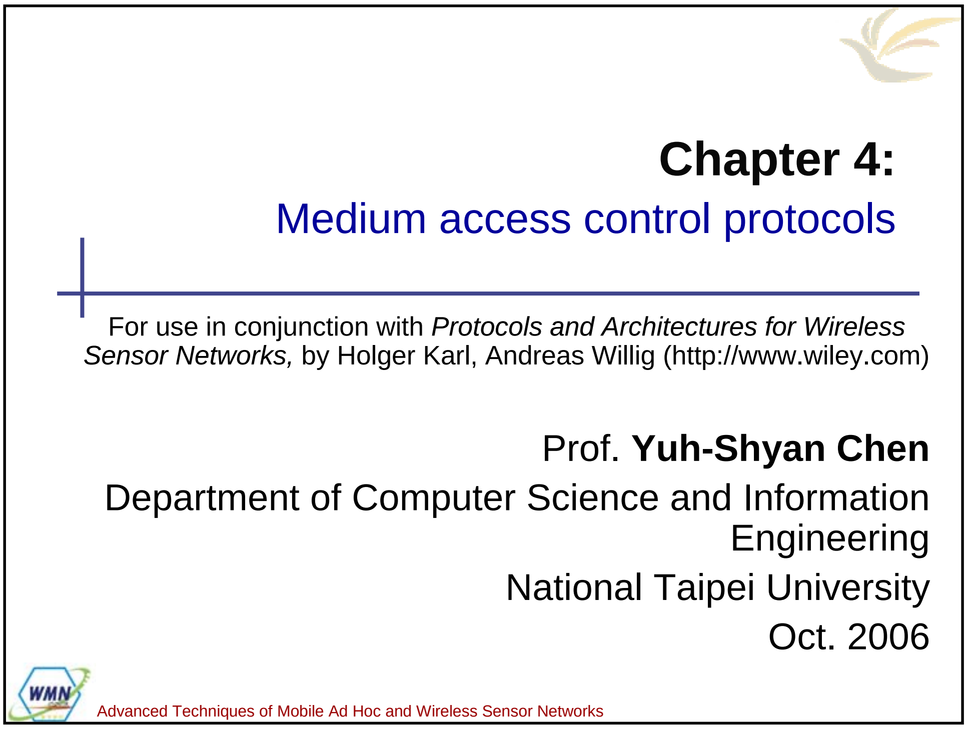

Chapter 4:

Medium access control protocols

For use in conjunction with *Protocols and Architectures for Wireless Sensor Networks,* by Holger Karl, Andreas Willig (http://www.wiley.com)

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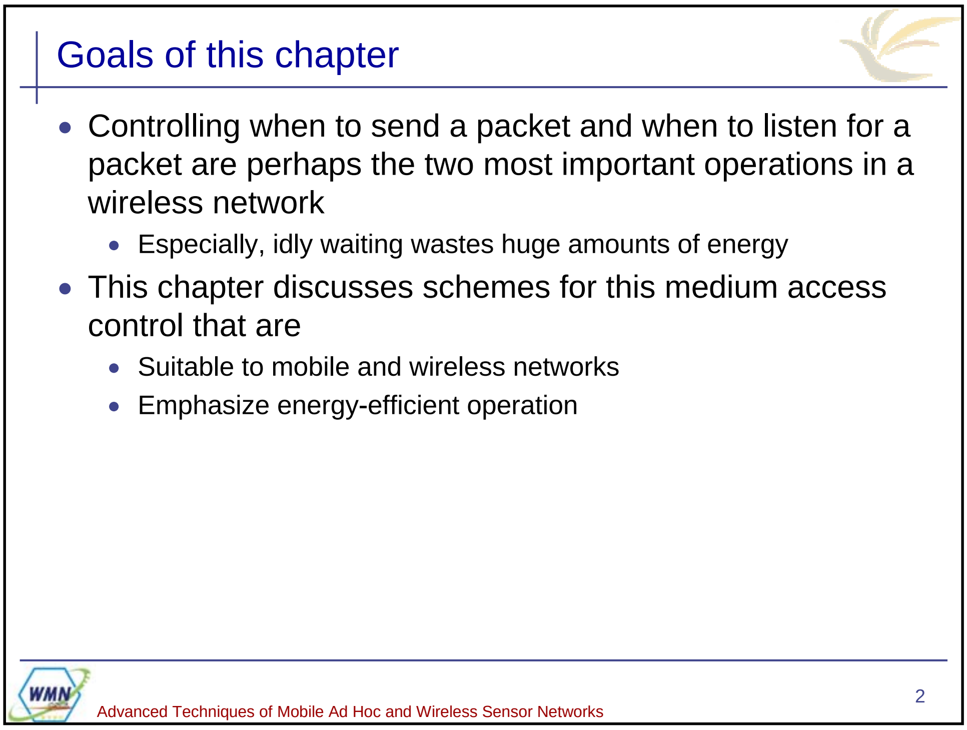
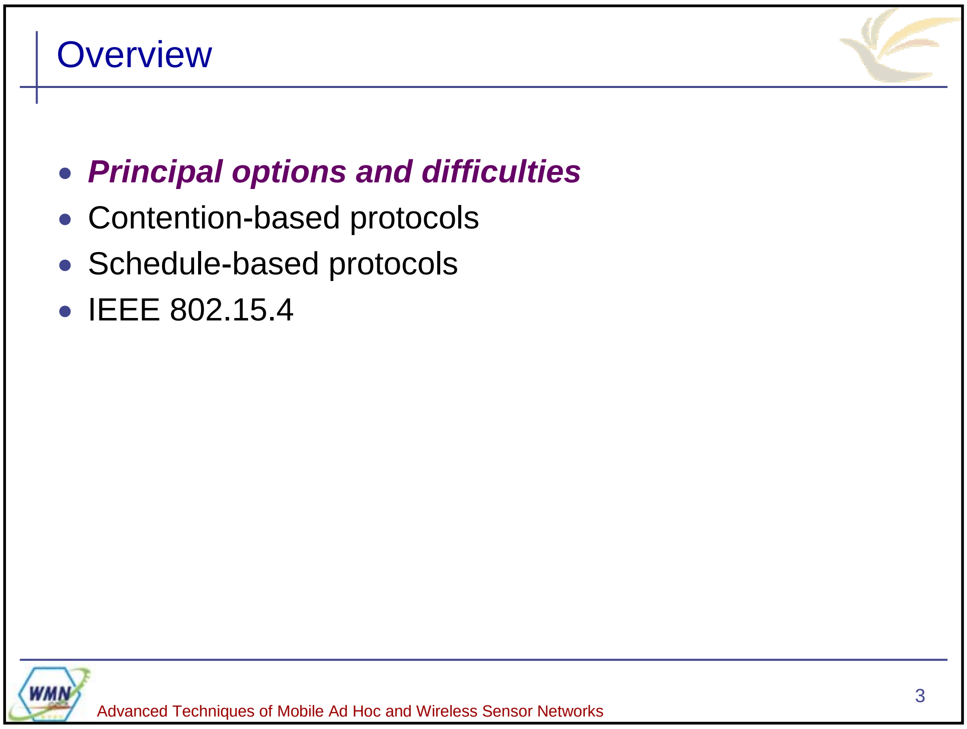
Oct. 2006



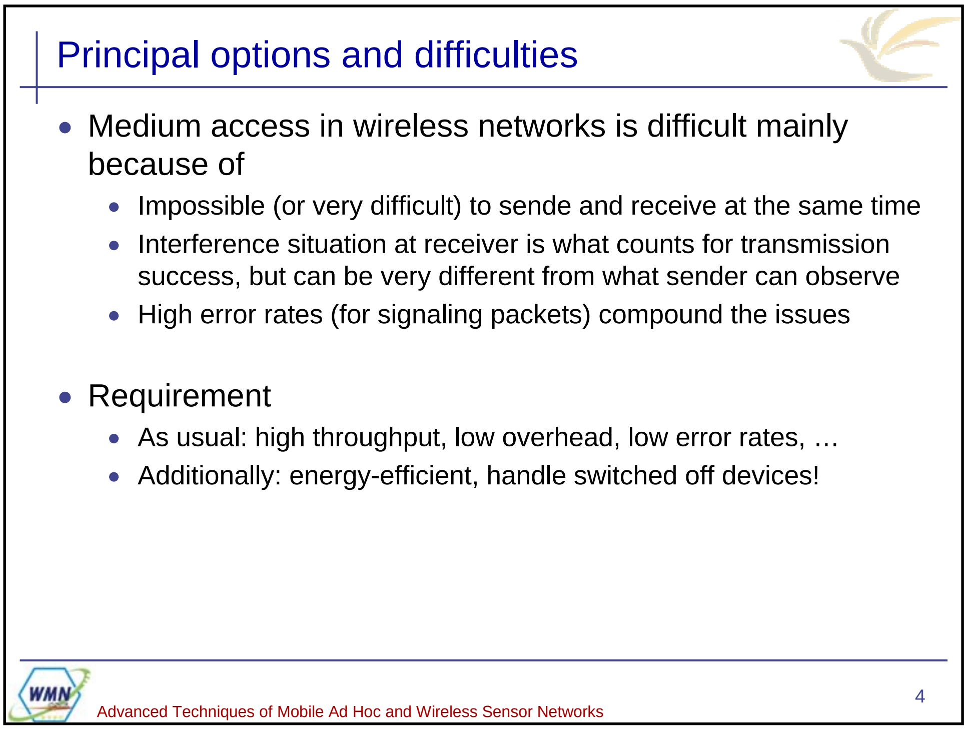
Goals of this chapter

- 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



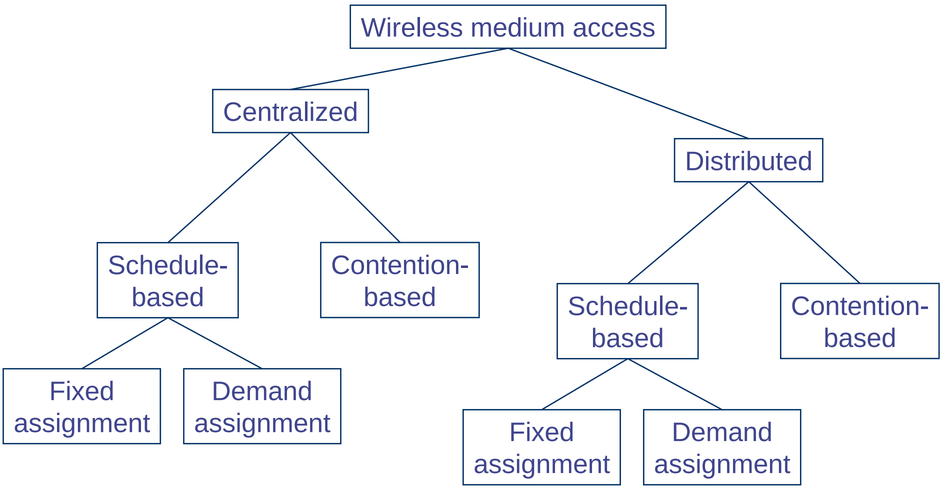
Principal options and difficulties

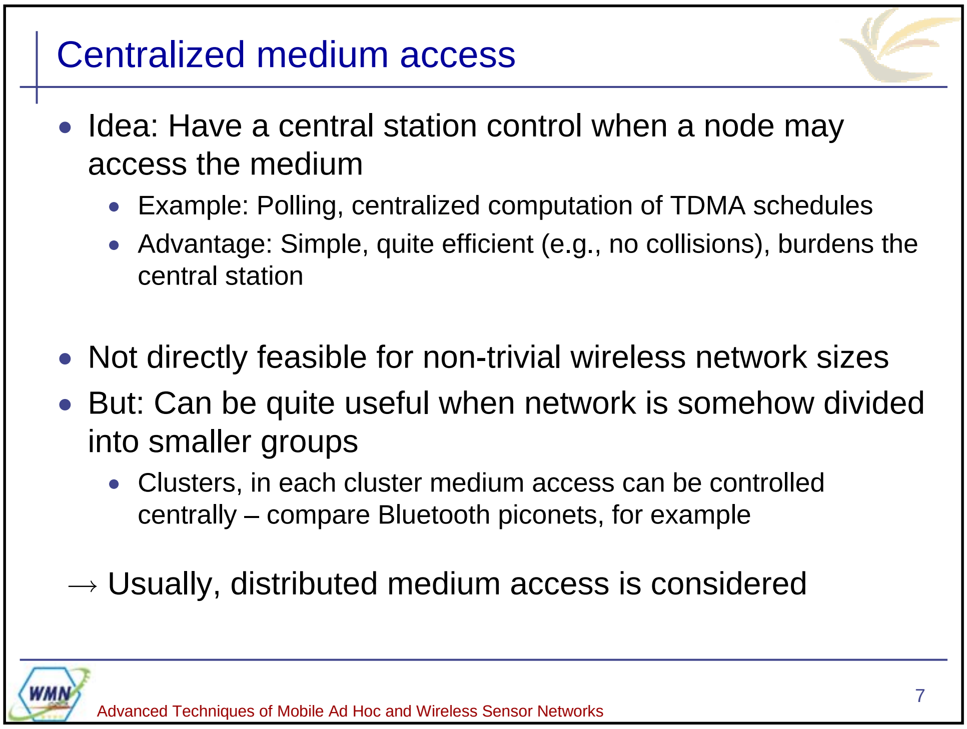
- Medium access in wireless networks is difficult mainly because of
  - Impossible (or very difficult) to sende and receive at the same time
  - Interference situation at receiver is what counts for transmission success, but can be very different from what sender can observe
  - High error rates (for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

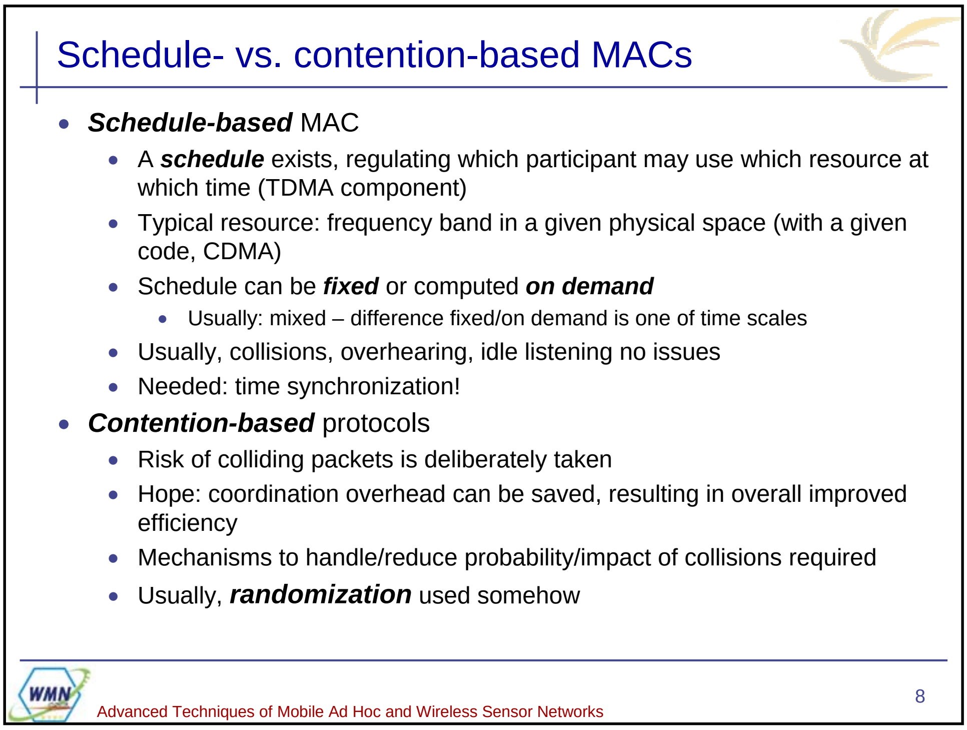




Centralized medium access

- 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)
  - Typical resource: frequency band in a given physical space (with a given code, CDMA)
  - Schedule can be ***fixed*** or computed ***on demand***
    - Usually: mixed – difference fixed/on demand is one of time scales
  - 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

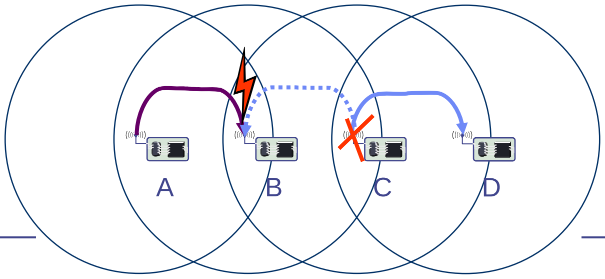
- Principal options and difficulties
- ***Contention-based protocols***
  - MACA
  - S-MAC, T-MAC
  - Preamble sampling, B-MAC
  - PAMAS
- Schedule-based protocols
- IEEE 802.15.4

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

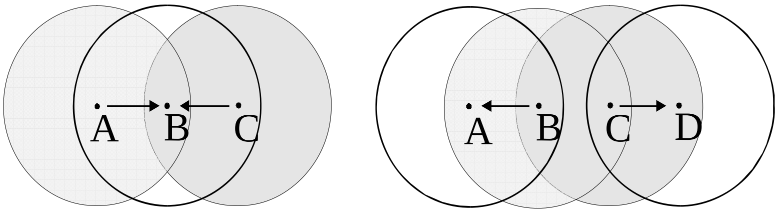
→ Receiver additionally needs some possibility to inform possible senders in its vicinity about impending transmission (to “shut them up” for this duration)

Hidden terminal scenario:



Also: recall exposed terminal scenario

Hidden-Terminal and Exposed-Terminal Problems



(a) (b)

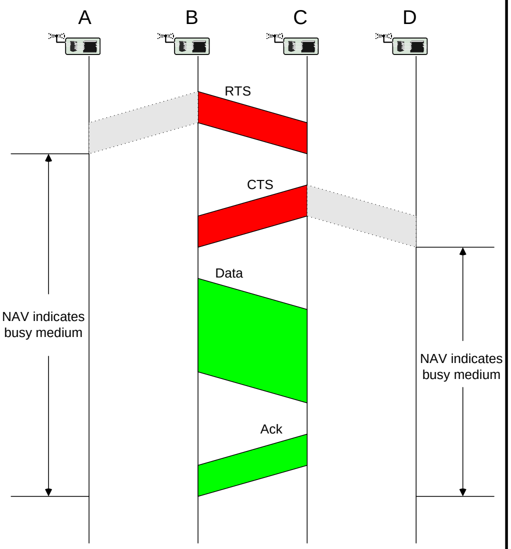
Fig. 1: (a) the hidden terminal problem,
(b) the exposed terminal problem

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

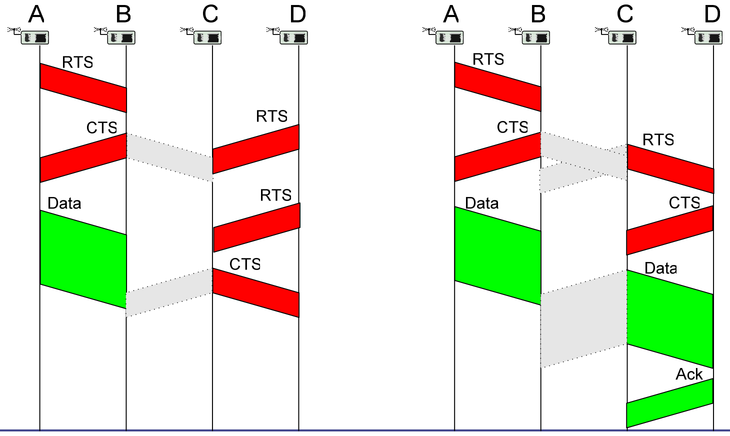
Receiver informs interferers before transmission – MACA

- 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***
- B sends, C acks
  → ***MACA protocol*** (used e.g. in ***IEEE 802.11***)



RTS/CTS

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

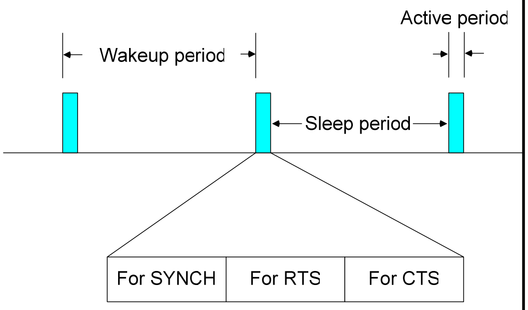


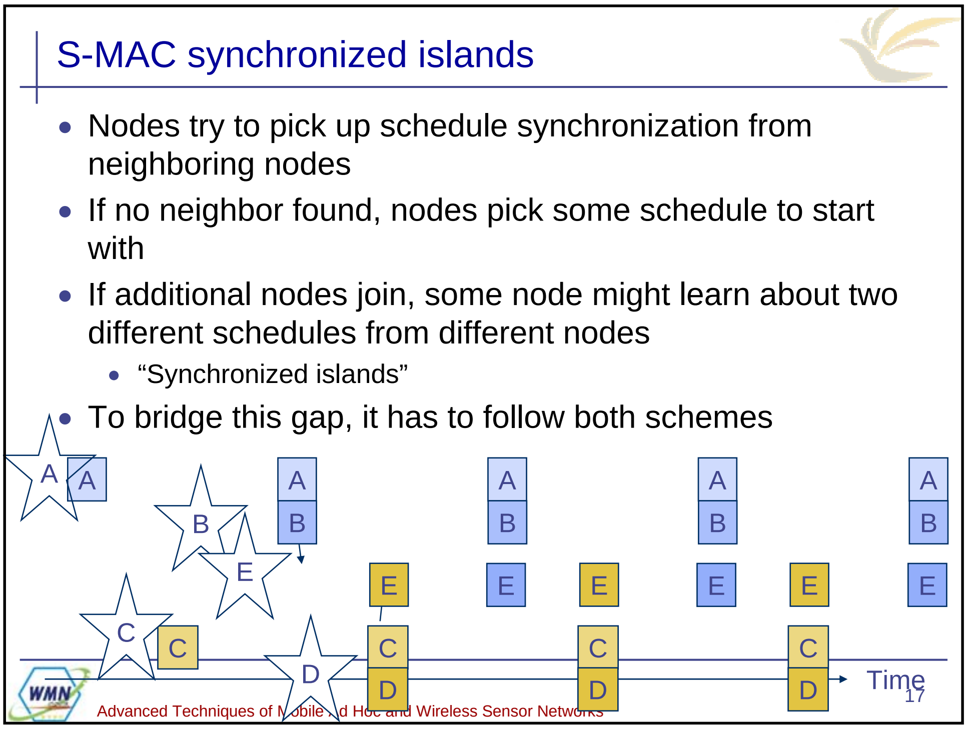
MACA Problem: Idle listening

- Need to sense carrier for RTS or CTS packets
  - In some form shared by many CSMA variants; but e.g. not by busy tones
  - Simple sleeping will break the protocol
- IEEE 802.11 solution: ATIM windows & sleeping
  - Basic idea: Nodes that have data buffered for receivers send ***traffic indicators*** at pre-arranged points in time
  - Receivers need to wake up at these points, but can sleep otherwise
- Parameters to adjust in MACA
  - Random delays – how long to wait between listen/transmission attempts?
  - Number of RTS/CTS/ACK re-trials?
  - …

Sensor-MAC (S-MAC)

- MACA's idle listening is particularly unsuitable if average data rate is low
  - Most of the time, nothing happens
- Idea: Switch nodes off, ensure that neighboring nodes turn on simultaneously to allow packet exchange (rendez-vous)
  - 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

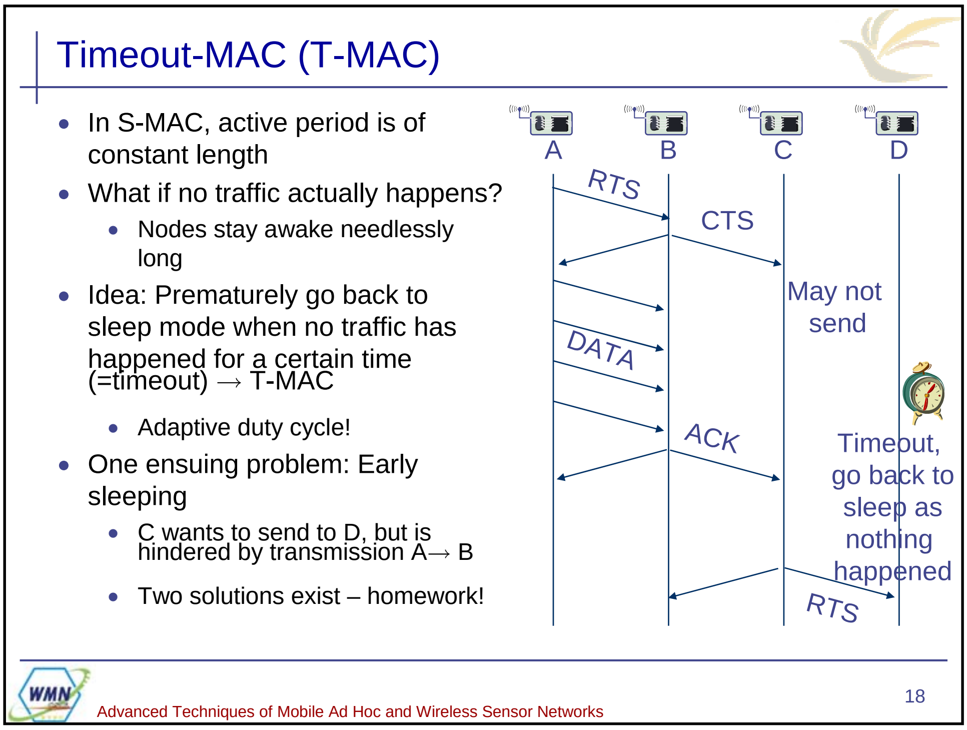




S-MAC synchronized islands

- 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

A
A
B
A
B
E
C
C
D
E
C
D
A
B
E
E
C
D
A
B
E
E
C
D
A
B
E
Time

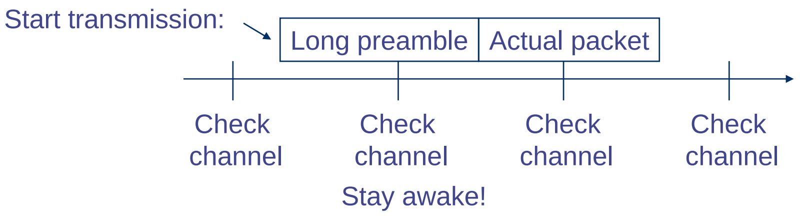


Timeout-MAC (T-MAC)

- 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
  - Two solutions exist – homework!

Preamble Sampling

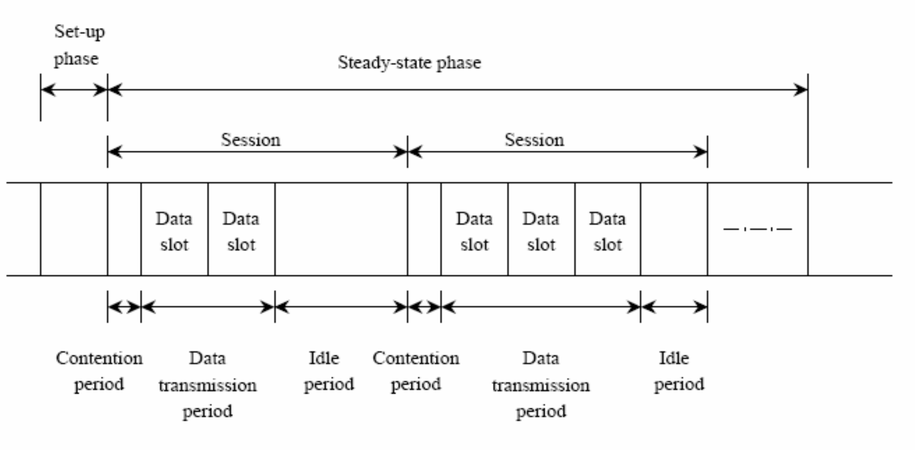
- So far: Periodic sleeping supported by some means to synchronize wake up of nodes to ensure rendez-vous between sender and receiver
- Alternative option: Don’t try to explicitly synchronize nodes
  - Have receiver sleep and only periodically sample the channel
- Use ***long preambles*** to ensure that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



B-MAC

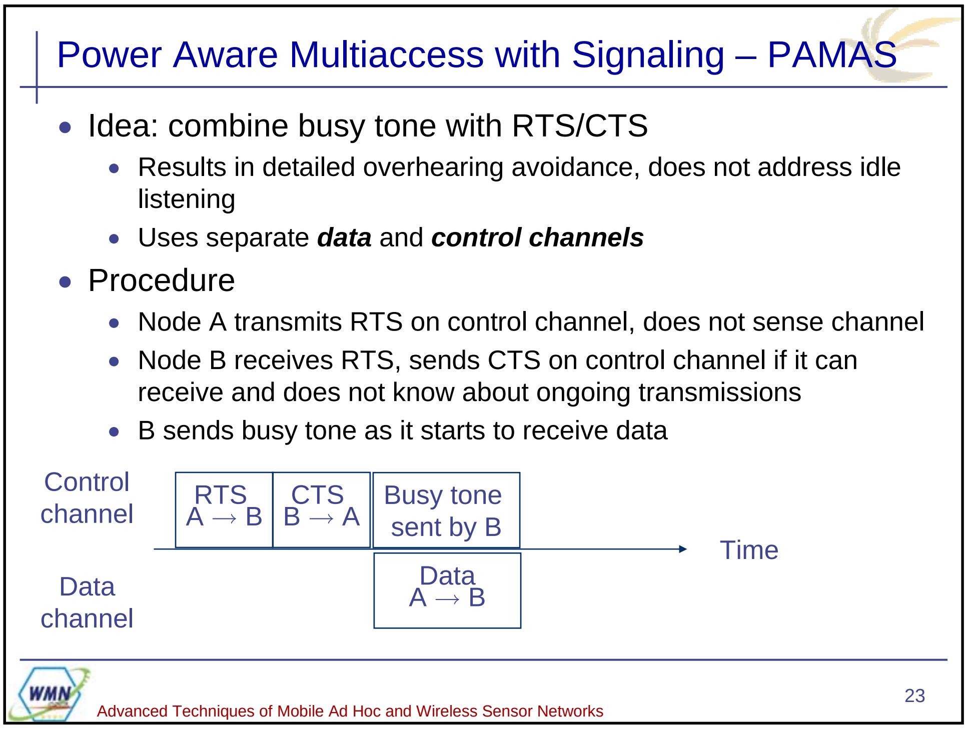
- Combines several of the above discussed ideas
  - Takes care to provide practically relevant solutions
- Clear Channel Assessment
  - Adapts to noise floor by sampling channel when it is assumed to be free
  - Samples are exponentially averaged, result used in gain control
  - For actual assessment when sending a packet, look at five channel samples – channel is free if even a single one of them is significantly below noise
  - Optional: random backoff if channel is found busy
- Optional: Immediate link layer acknowledgements for received packets

Illustration of single round of B-MAC



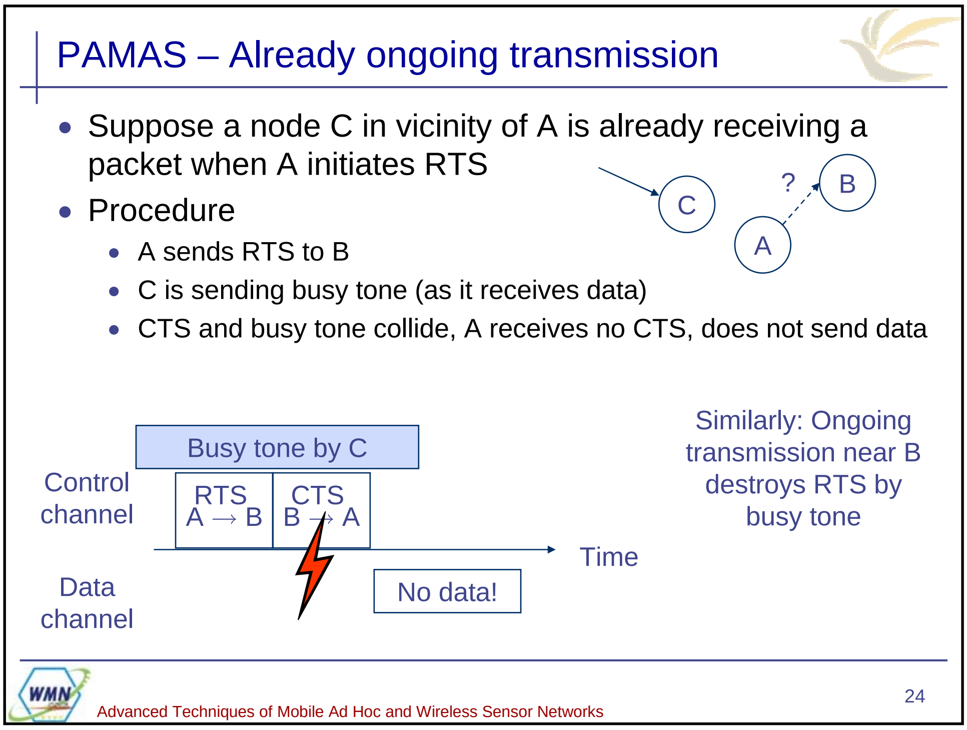
B-MAC II

- Low Power Listening (= preamble sampling)
  - Uses the clear channel assessment techniques to decide whether there is a packet arriving when node wakes up
  - Timeout puts node back to sleep if no packet arrived
- B-MAC does *not* have
  - Synchronization
  - RTS/CTS
  - Results in simpler, leaner implementation
  - Clean and simple interface
- Currently: Often considered as the ***default WSN MAC*** protocol



Power Aware Multiaccess with Signaling – PAMAS

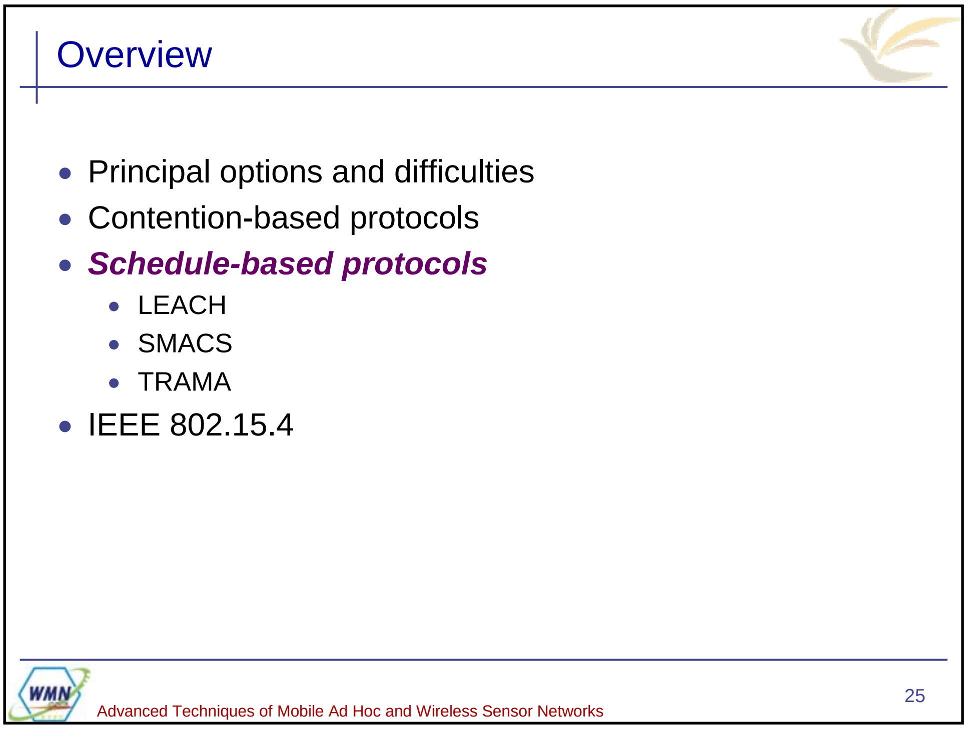
- Idea: combine busy tone with RTS/CTS
  - Results in detailed overhearing avoidance, does not address idle listening
  - Uses separate ***data*** and ***control channels***
- Procedure
  - Node A transmits RTS on control channel, does not sense channel
  - Node B receives RTS, sends CTS on control channel 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

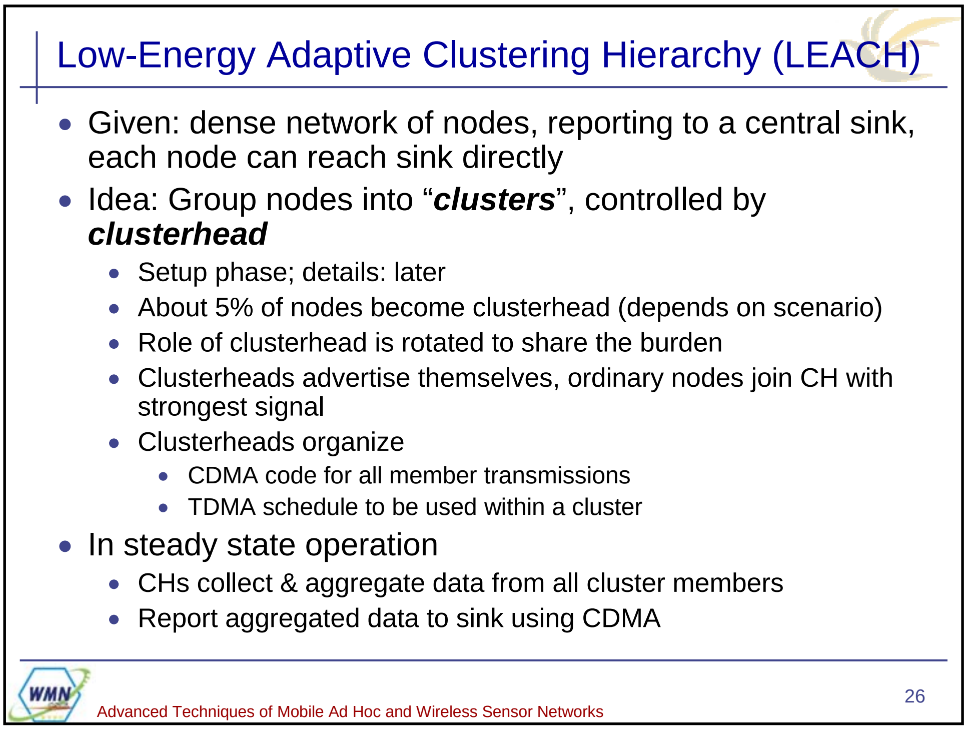
- Suppose a node C in vicinity of A is already receiving a packet when A initiates RTS
- Procedure
  - A sends RTS to B
  - C is sending busy tone (as it receives data)
  - CTS and busy tone collide, A receives no CTS, does not send data

Similarly: Ongoing transmission near B destroys RTS by busy tone



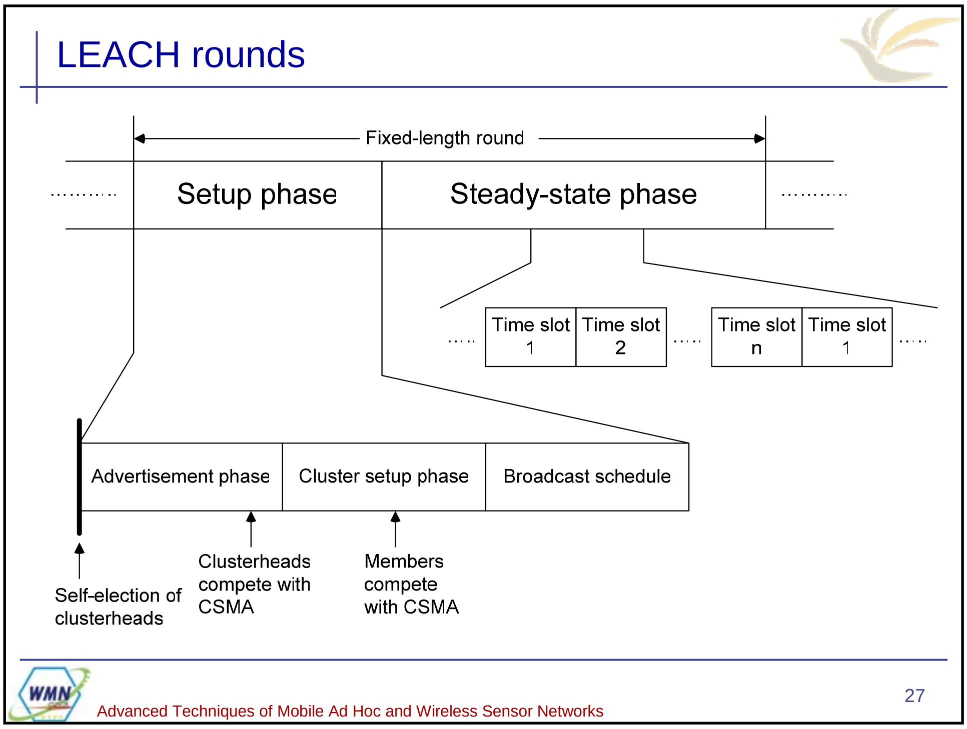
Overview

- 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

Fixed-length round

………. Setup phase | Steady-state phase ……….

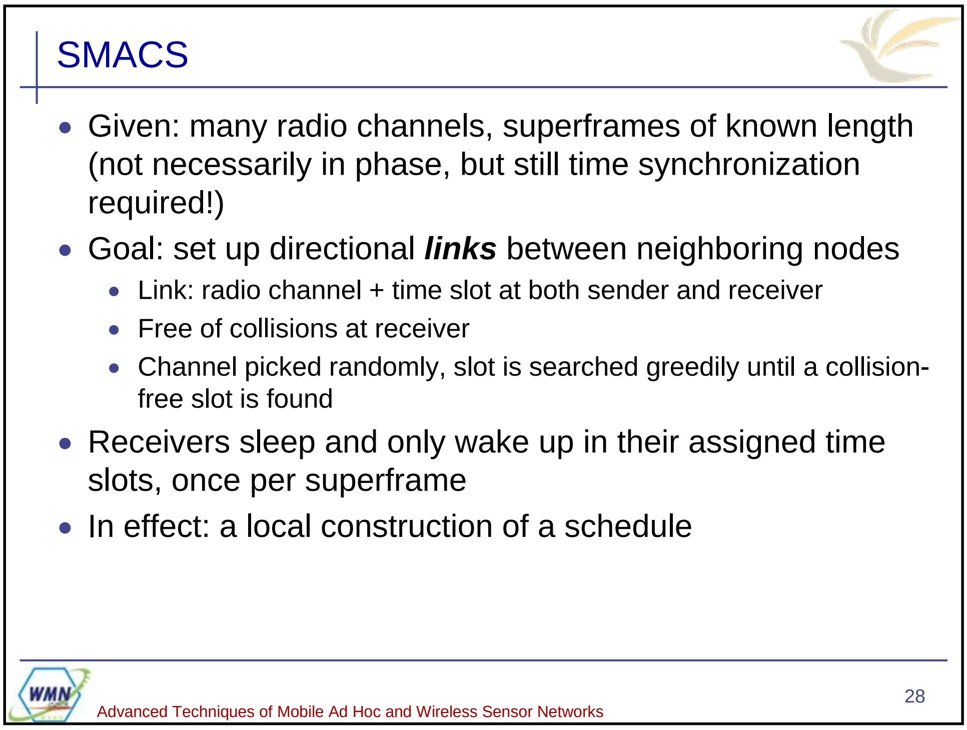
…. Time slot 1 | Time slot 2 …. Time slot n | Time slot 1 ….

Advertisement phase | Cluster setup phase | Broadcast schedule

Self-election of clusterheads

Clusterheads compete with CSMA

Members compete with CSMA

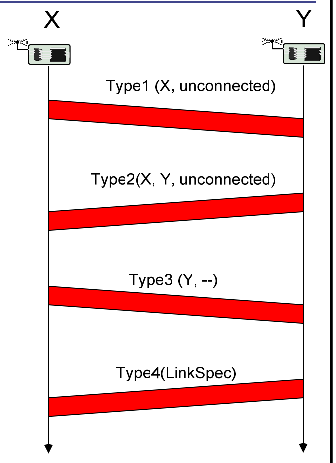


SMACS

- 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 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

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

TRAMA – adaptive election

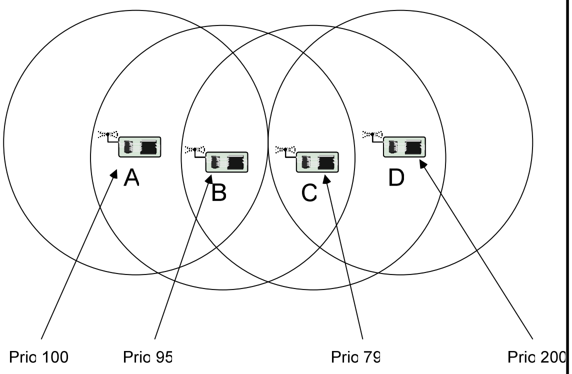
- Given: Each node knows its two-hop neighborhood and their current schedules
- How to decide which slot (in scheduled access period) a node can use?
  - Use ***node identifier*** x and globally known ***hash function*** h
  - For time slot t, compute ***priority*** p = h (x ⊕ t)
  - Compute this priority 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

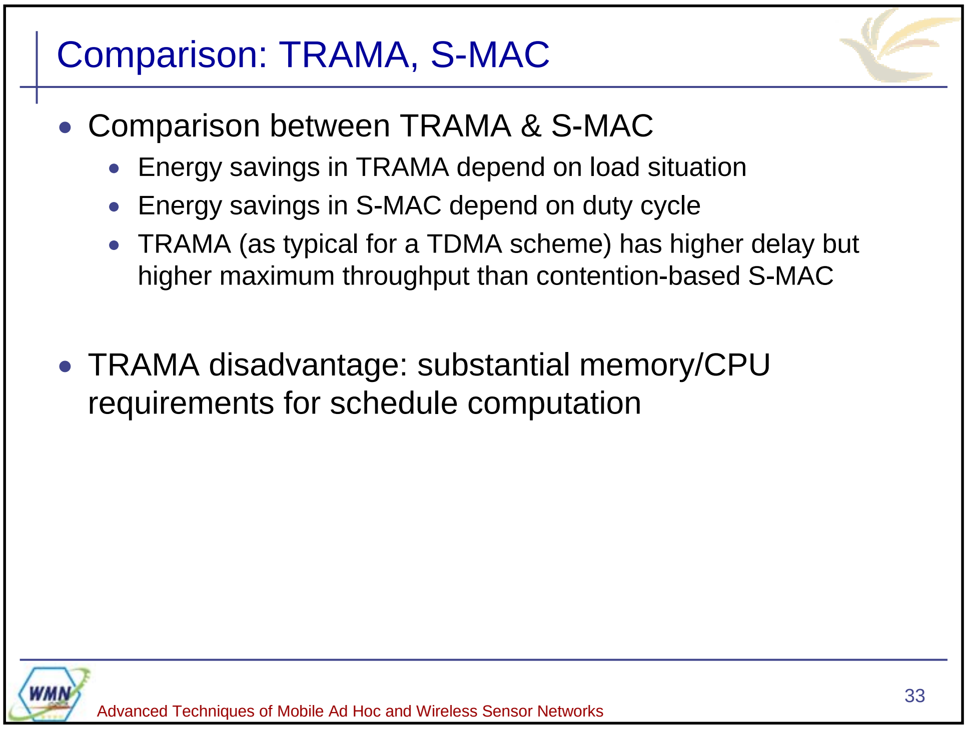
Priorities of node A and its two neighbors B & C

	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

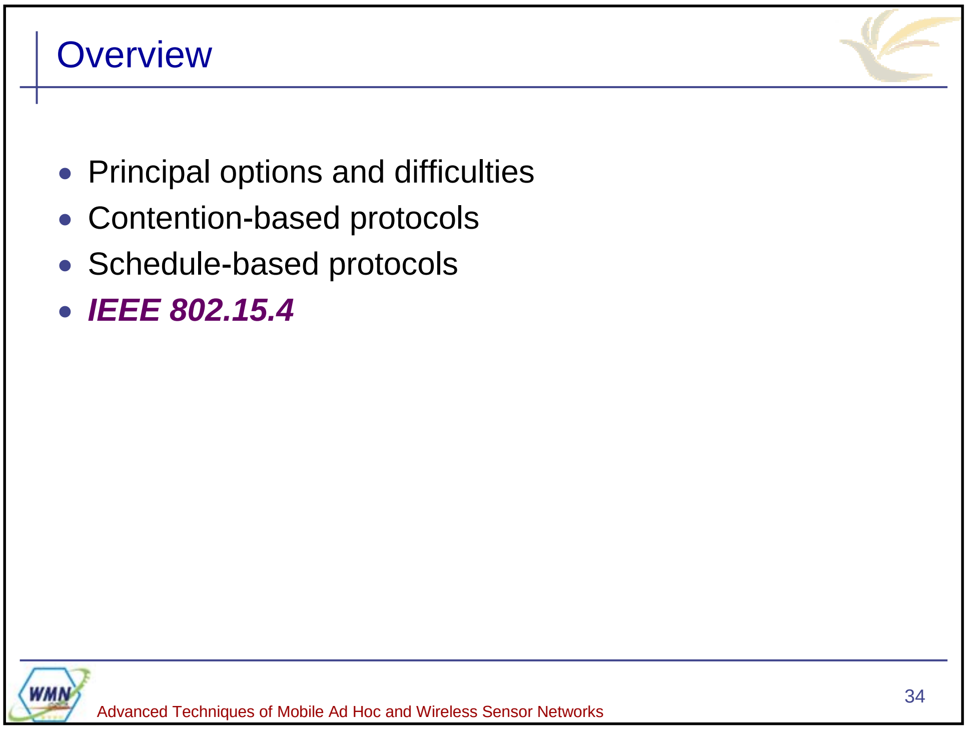
- When does a node have to receive?
  - Easy case: one-hop neighbor has won a time slot and announced a packet for it
  - But complications exist – compare example
- What does B believe?
  - A thinks it can send
  - B knows that D has higher priority in its 2-hop neighborhood!
- Rules for resolving such 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



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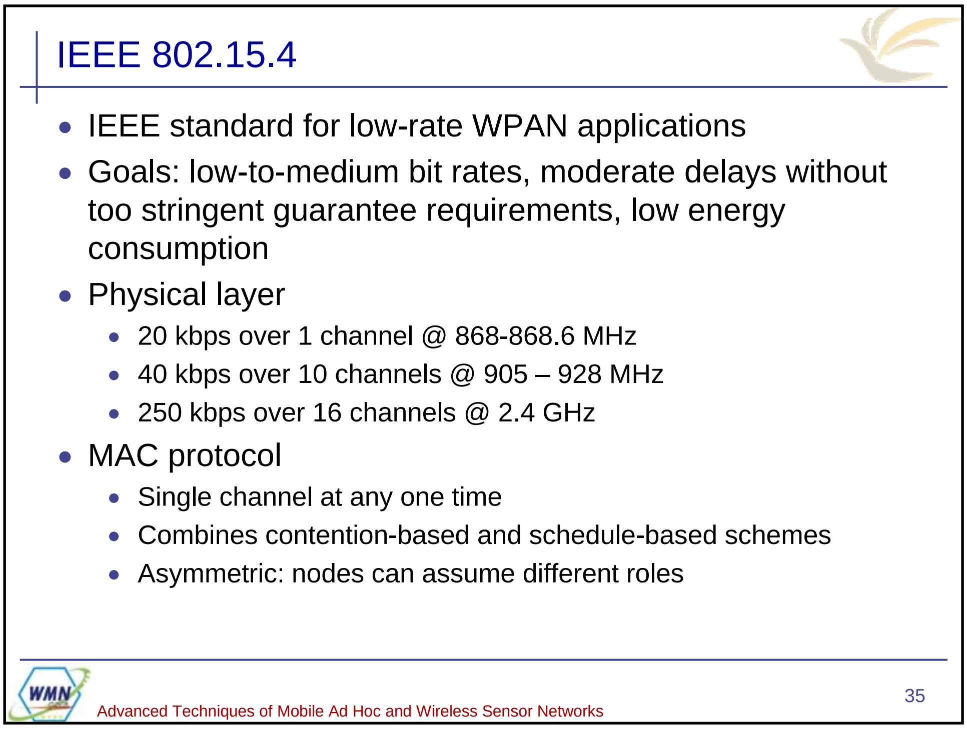
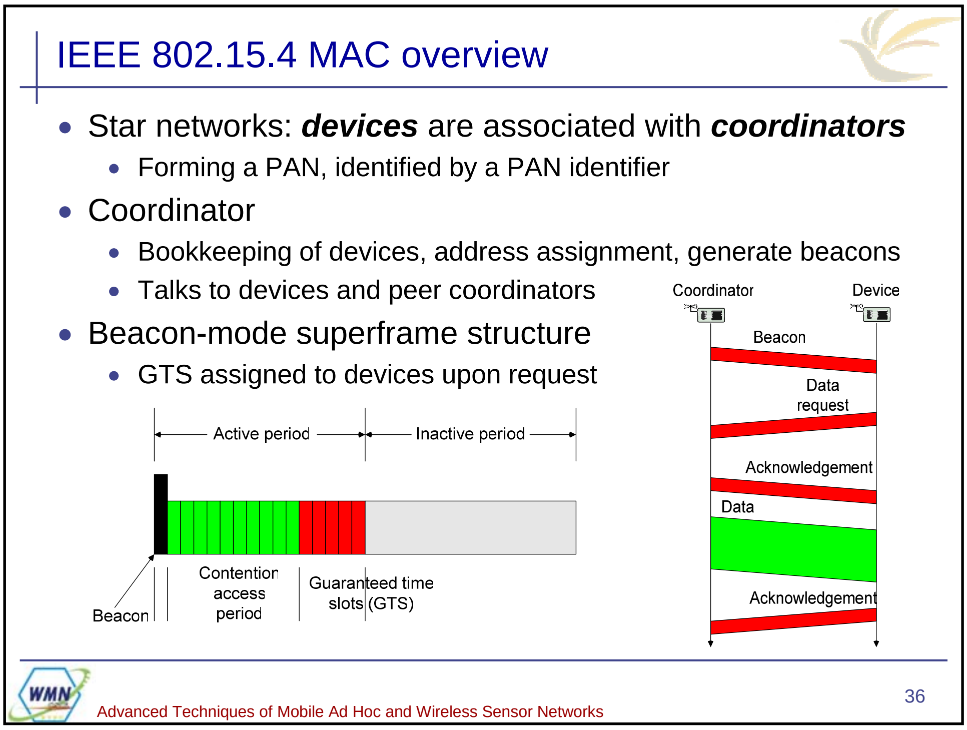


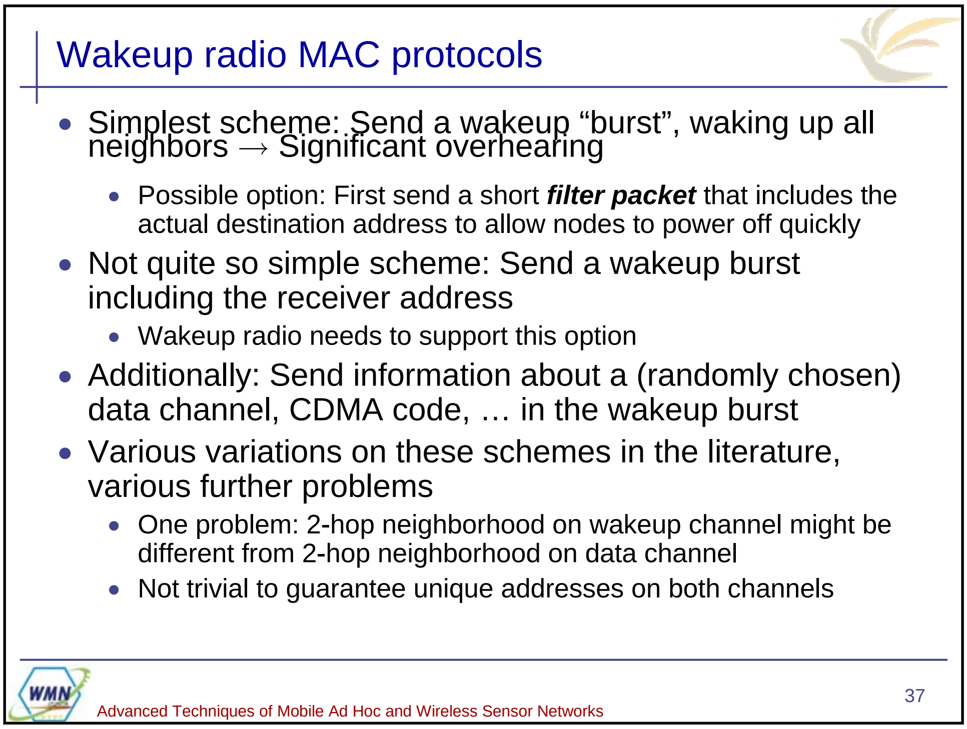
IEEE 802.15.4

- 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



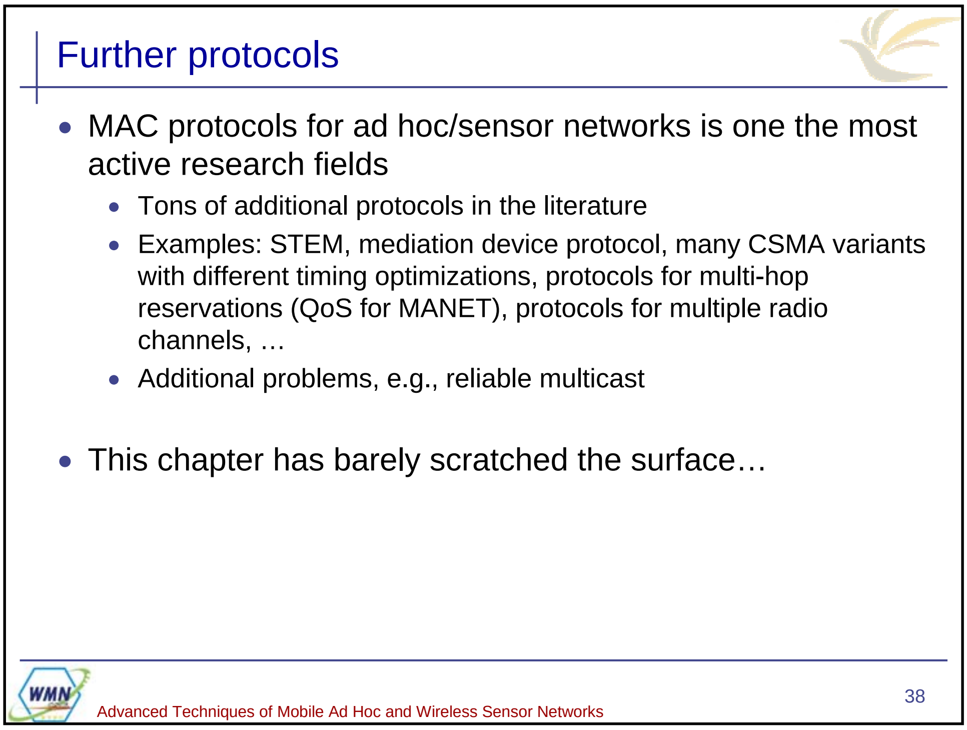
IEEE 802.15.4 MAC overview

- 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



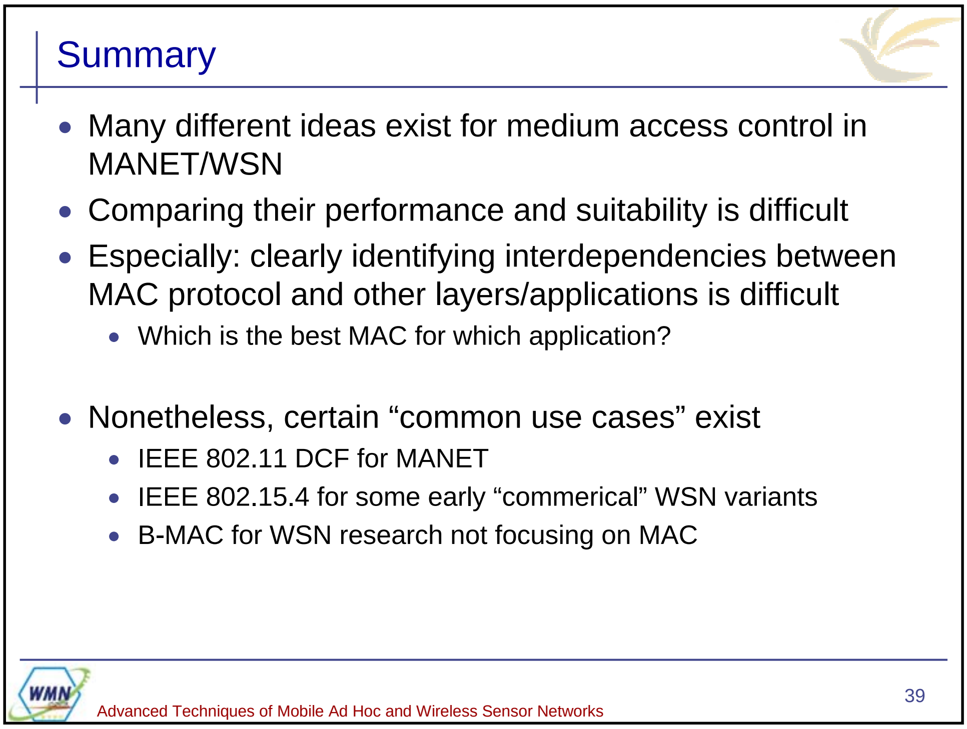
Wakeup radio MAC protocols

- Simplest scheme: Send a wakeup "burst", waking up all neighbors → Significant overhearing
  - Possible option: First send a short ***filter packet*** that includes the actual destination address to allow nodes to power off quickly
- Not quite so simple scheme: Send a wakeup burst including the receiver address
  - Wakeup radio needs to support this option
- Additionally: Send information about a (randomly chosen) data channel, CDMA code, … in the wakeup burst
- Various variations on these schemes in the literature, various further problems
  - One problem: 2-hop neighborhood on wakeup channel might be different from 2-hop neighborhood on data channel
  - Not trivial to guarantee unique addresses on both channels



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