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

Holger Karl, Andreas Willig, "Protocols and Architectures for Wireless Sensor Networks," Wiley 2005

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!

Why WSN MAC?

- Traditional MAC protocols **cannot** be applied directly to sensor networks without modification
- Unique characteristics of sensor networks
  - denser levels of node deployment
  - higher unreliability of sensor nodes
  - severe power, computation, and memory constraints.
- The primary concerns in traditional wireless networks, should also be considered, but are of secondary importance in WSN
  - delivery latency, network throughput, bandwidth utilization, and fairness

Unique Characteristics of WSNs

- A sensor network typically consists of a larger number of sensor nodes densely deployed in a geographical field
- Sensor nodes are usually powered by battery and thus are limited in power capacity. It is often difficult or impossible to change or recharge batteries for these nodes. The lifetime of a sensor network largely depends on the lifetime of its sensor nodes.
- Sensor nodes are often deployed in an ad hoc fashion without careful planning and engineering. Hence, they must be able to organize themselves into a communication network.
- The topology of a sensor network changes more frequently due to both node failure and mobility. Sensor nodes are prone to failures. Most sensor nodes are stationery after deployment. But in some applications, some sensor nodes can also be mobile.
- Sensor nodes have very limited computational capacity and memory.

Objectives of WSN MAC Design (Important)

- Energy Efficiency
  - to maximize not only the lifetime of individual sensor nodes, but also the lifetime of the entire network
- Scalability
  - to accommodate the change in network size
- Adaptability
  - to the ability to accommodate the changes in node density and network topology
- Channel Utilization
  - should make use of the bandwidth as efficiently as possible

Objectives of WSN MAC Design (Less Important)

- Latency
  - not a critical factor for some applications but critical to many others
- Throughput
  - the amount of data successfully transferred in a given time
- Fairness
  - the ability of different sensor nodes to equally share a common transmission channel
  - What is important is not to achieve per - node fairness, but to ensure the quality of service for the whole task.

Requirements for energy-efficient MAC protocols

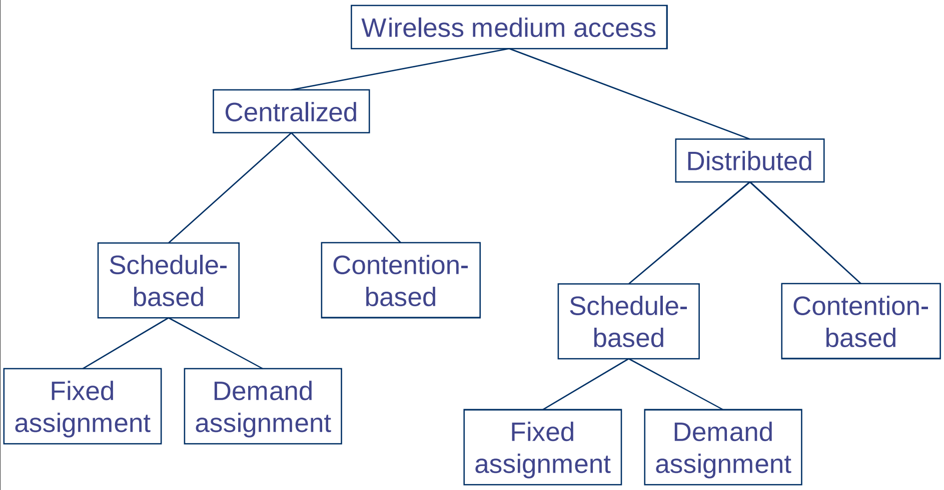
- Recall
  - Transmissions are costly
  - Receiving about as expensive as transmitting
  - Idling can be cheaper but is still expensive
- Energy problems
  - ***Collisions*** – wasted effort when two packets collide
  - ***Overhearing*** – waste effort in receiving a packet destined for another node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

- Always nice: Low complexity solution

Energy Efficiency in WSN MAC Design

- Energy waste 4 major sources
  - *Collision*
    - Collision occurs when two sensor nodes transmit their packets at the same time. Retransmissions of the packets increase both energy consumption and delivery latency.
  - *Overhearing*
    - Overhearing occurs when a sensor node receives packets that are destined for other nodes. Overhearing such packets results in unnecessary waste of energy and such waste can be very large when traffic load is heavy and node density is high.
  - *Idle Listening*
    - The node will stay in an idle state for a long time, which results in a large amount of energy waste. There are reports that idle listening consumes 50 – 100% of the energy required for receiving data traffic .
  - *Control Overhead*
    - A MAC protocol requires sending, receiving, and listening to a certain necessary control packets, which also consumes energy not for data communication.

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

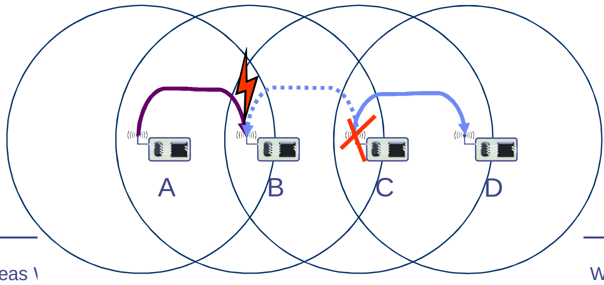
- Principal options and difficulties
- ***Contention-based protocols***
  - MACA
  - S-MAC, T-MAC
  - Preamble sampling, B-MAC
  - PAMAS
- Schedule-based protocols
- IEEE 802.15.4

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

Main options to shut up senders

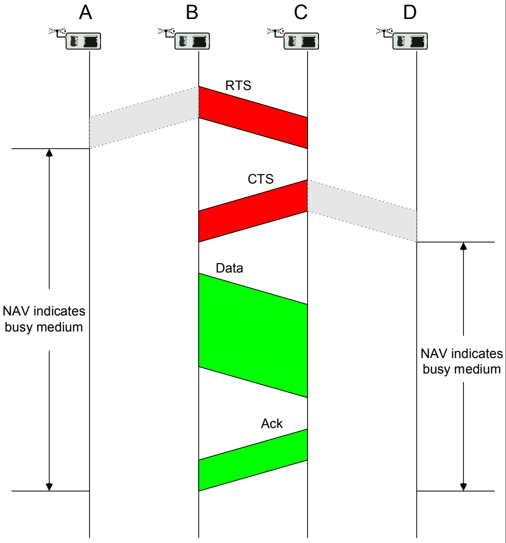
- Receiver informs potential interferers ***while*** a reception is on-going
  - By sending out a signal indicating just that
  - Problem: Cannot use same channel on which actual reception takes place

  ! 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

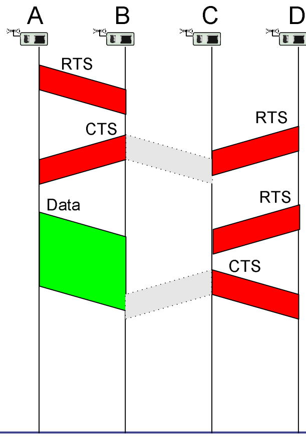
- Sender B asks receiver C whether C is able to receive a transmission
  Request to Send (RTS)
- Receiver C agrees, sends out a ***Clear to Send*** (***CTS***)
- Potential interferers overhear either RTS or CTS and know about impending transmission and for how long it will last
  - Store this information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

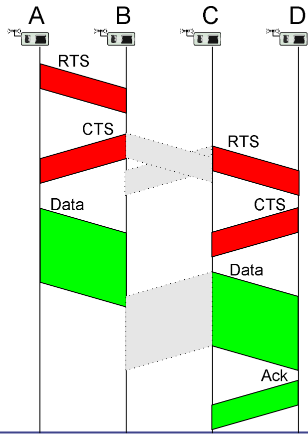
! ***MACA protocol*** (used e.g. in ***IEEE 802.11***)



RTS/CTS

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



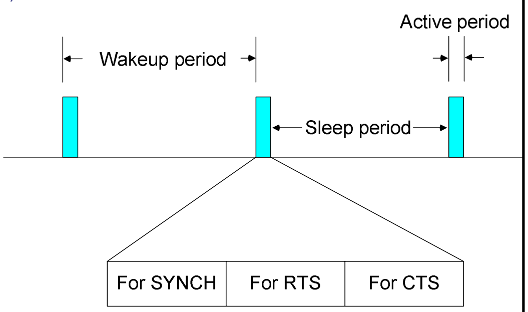


MACA Problem: Idle listening

- 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



Sensor-MAC (S-MAC)

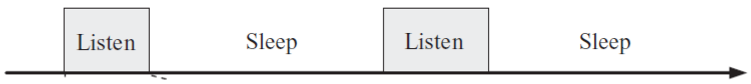
- S - MAC considers
  - a sensor network scenario in which communication occurs between nodes as peers, rather than to a single base station
  - its applications have long idle periods and can tolerate latency on the order of network messaging time.
- The primary goal of the S - MAC design is to improve energy efficiency while maintaining good scalability and collision avoidance.
- In exchange, it allows some performance degradation in both per - hop fairness and latency.
- This is implemented by integrating several effective control mechanisms into a contention - based MAC protocol built on top of the IEEE 802.11 standard.

Sensor-MAC (S-MAC)

- To achieve its goals, S - MAC tries to reduce energy consumption from all the major sources that cause inefficient use of energy
  - Periodic listen and sleep
  - collision avoidance
  - coordinated synchronization
  - message passing.

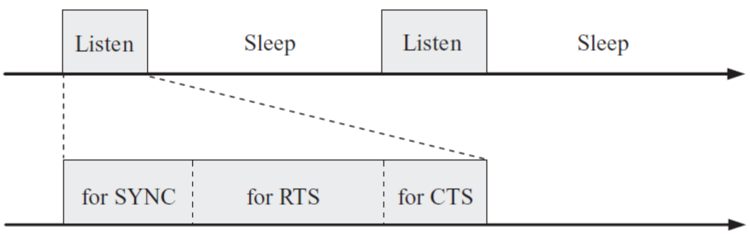
S-MAC Periodic Listen and Sleep Mechanism

- To reduce idle listening
- Establish a low-duty-cycle operation on each node
  - Ratio of listen time to whole frame time
- A complete cycle of listen and sleep periods is called a frame.



S-MAC Periodic Listen and Sleep Mechanism

- The listen period is further divided into smaller intervals for sending or receiving SYNC, RTS, and CTS packets.
- The duration of the listen period is normally fixed depending on physical - and MAC - layer parameters, e.g., the radio bandwidth and the contention window size.

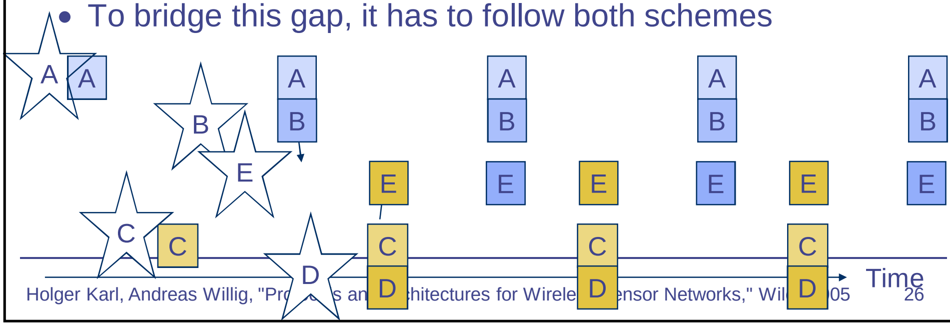


S-MAC Coordinated Synchronization

- To reduce control overhead
- However, neighboring nodes coordinate their sleep schedules and try to adopt the same schedules to listen and sleep, rather than randomly sleep on their own.
- To establish coordinated or synchronized sleep schedules, each node exchanges its schedule with other nodes by periodically (in SYNC)
- S - MAC allows a node to adopt multiple schedules to enable multihop operation in the network.
- S - MAC uses relative timestamps instead of absolute ones to avoid clock drifts

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



S-MAC Collision Avoidance

- The collision avoidance mechanism used in S - MAC is similar to that in the IEEE 802.11 DCF
- Awake time after SYNC part is further divided into many timeslots for senders to perform carrier sensing.

S-MAC Reduction of Overhearing

- If a node is unable to win the medium, it goes to sleep and wakes up when the receiver becomes free, and listens again.
  - Otherwise, the node stays awake to TX/RX packets
- Since DATA packets are normally much longer than control packets, this prevents neighboring nodes from overhearing long DATA packets and subsequent ACK packets

S-MAC Message Passing

- If a long message is transmitted as a single packet and only a few bits are corrupted, the whole packet needs to be retransmitted, which would result in a high transmission cost.

- On the other hand, if the long message is segmented into many independent small fragments, it would cause larger control overhead and longer delay because RTS and CTS packets are used in contention for each independent packet.

S-MAC Message Passing

- Only one RTS and one CTS are used to reserve the medium for transmitting all fragments.
- Each fragment is acknowledged separately and is retransmitted if the ACK packet is not received for the fragment.
- If a neighboring node hears an RTS or CTS packet, it will go to sleep for the time that is needed to transmit **all the fragments**.
- This is different from 802.11 ' s fragmentation mode, where each fragment only indicates the presence of an additional fragment rather than all of them.

S-MAC Shortcomings

- S - MAC is much more energy efficient than 802.11.
- However, due to the fixed sleep time/awake time ratio
  - some portion of the bandwidth is always unusable
  - the delay is higher
- The main drawback of S-MAC is high message delivery latency as S-MAC is designed to sacrifice latency for energy savings .

Dynamic S-MAC (DS - MAC)

- DS - MAC is an S - MAC protocol with a dynamic duty cycle
- Aims to achieve a good tradeoff between energy consumption and latency without incurring much overhead
- Each node attempts to dynamically adjust its sleep – wakeup cycle time based on the current energy consumption level and the average latency it has experienced.

Dynamic S-MAC (DS - MAC)

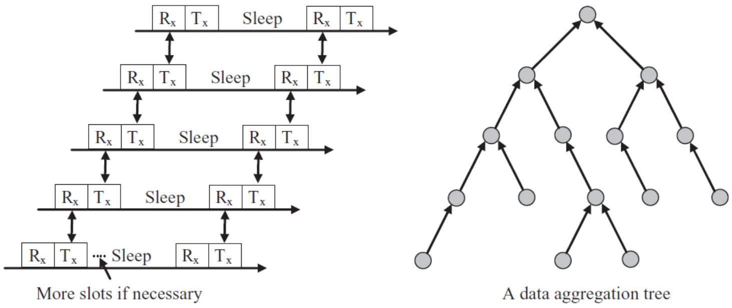
- If a receiver node finds that the latency becomes intolerable, it will double the original duty cycle by reducing the sleeping period accordingly without changing the listening period.
  - a node with an increased duty cycle can get more chances to receive packets from other senders
  - alleviates the high - latency problem with S-MAC under high traffic
- To implement DS - MAC, some additional protocol overhead needs to be introduced, including a “ duty cycle ” field and a “ delay ” field in each SYNC packet.

Mobility-aware MAC (MS-MAC)

- Before MS-MAC, most MAC protocols proposed for WSNs only consider stationery sensor nodes
- For a stationery scenario, MS–MAC operates similar to S-MAC in order to conserve energy.
- For a highly mobile scenario, it switches to an operating mode similar to IEEE 802.11.
- The protocol uses any change in the received signal levels of periodical SYNC messages as an indication of mobility and if necessary triggers a mobility handling mechanism.

D-MAC

- D - MAC is an energy-efficient and low-latency MAC
- Proposed to address the data forwarding interruption problem in multihop data delivery



D-MAC

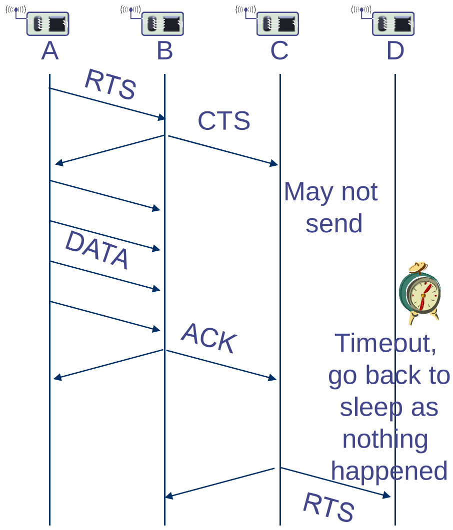
- To enable continuous data forwarding on a multihop path, D - MAC staggers the schedule of the nodes on the multihop path and allows the nodes to wake up sequentially like a chain reaction
- In the schedule, an interval is divided into three periods (or states): receiving, sending, and sleeping.
- The receiving and sending periods have the same length of μ , which is long enough for transmitting and receiving one packet. Depending on its depth d in the data gathering tree, a node sets its wake - up schedule $d\ \mu$ ahead from the schedule of the sink.

Timeout-MAC (T-MAC)

- The basic idea of T-MAC is to reduce idle listening by introducing
  - a dynamic duty cycle
  - transmitting all messages in bursts of variable size in active periods and sleeping between active periods
- To maintain an optimal active period under variable traffic load, T-MAC dynamically determines the length of an active period by simply timing out if nothing is heard.
- An active period will end and the node will go to sleep if no activation event occurred such as
  - (1) the timing out of a periodic frame timer
  - (2) the reception of a data packet on the radio
  - (3) the sensing of communication on the radio
  - (4) the end of transmission of a node's own data packet or acknowledgment
  - (5) the end of transmission of a neighbor's data packet.

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!



T-MAC Vs S-MAC

- The simulation results show that T - MAC and S - MAC achieve similar energy consumption reductions (up to 98%) compared to CSMA.
- However, T–MAC outperforms S-MAC by a factor of 5 in a sample scenario with variable traffic load.

SIFT

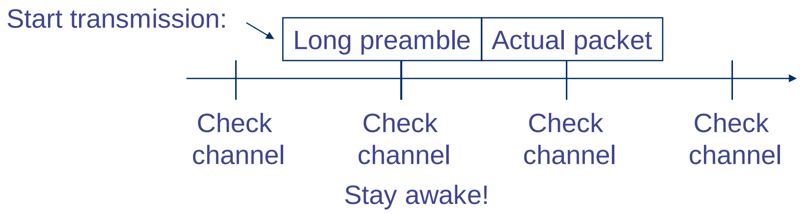
- SIFT is a CSMA based MAC protocol for handling spatially correlated contention in event - driven WSNs
- Motivated by the observations that sensor networks are usually event driven and have spatially correlated contention
  - not all the sensing nodes that observe an event need to report the event
  - the number of contending nodes changes over time
- For a shared medium with N nodes observing an event and contending for transmission at the same time, a MAC protocol should be designed with the objective to minimize the time taken to send R of N messages without collisions.

SIFT

- If R = N, this problem becomes the throughput optimization problem in classical MAC protocol design.
- If R < N, the objective is to allow the first R winners in the contention to send their messages through as quickly as possible, with the remaining nodes backing off their transmissions.
  - it uses a small and fixed contention window of 32 slots
  - geometrically increasing non - uniform probability distribution for picking a transmission slot in the contention window
  - based on a shared *belief:*
    - This belief starts with some large value and a correspondingly small probability for per node transmission. If no node transmits in the first slot, each node will reduce its belief of the number of competing nodes by multiplicatively increasing its transmission probability for the second slot.
- SIFT can offer up to a sevenfold latency reduction compared to IEEE 802.11 as the size of the network scales up to 512.

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

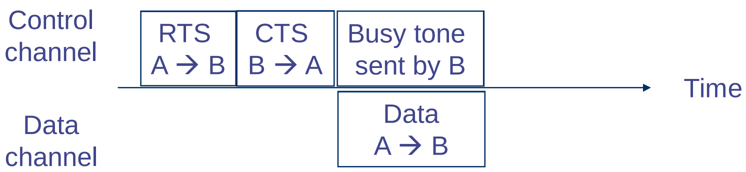
- Combines several of the above discussed ideas
  - Takes care to provide practically relevant solutions
- Clear Channel Assessment
  - Adapts to noise floor by sampling channel when it is assumed to be free
  - Samples are exponentially averaged, result used in gain control
  - For actual assessment 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

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

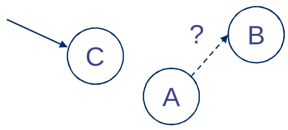
Power Aware Multiaccess with Signaling – PAMAS

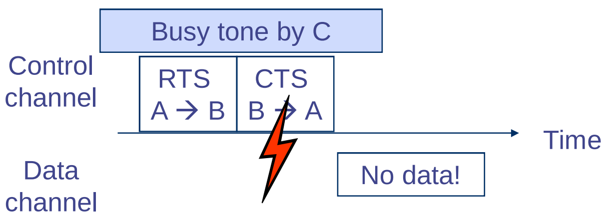
- Idea: combine busy tone with RTS/CTS
  - Results in detailed overhearing avoidance, does not address idle listening
  - Uses separate ***data*** and ***control channels***
- Procedure
  - Node A transmits RTS on control channel, does not sense channel
  - Node B receives RTS, sends CTS on control channel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

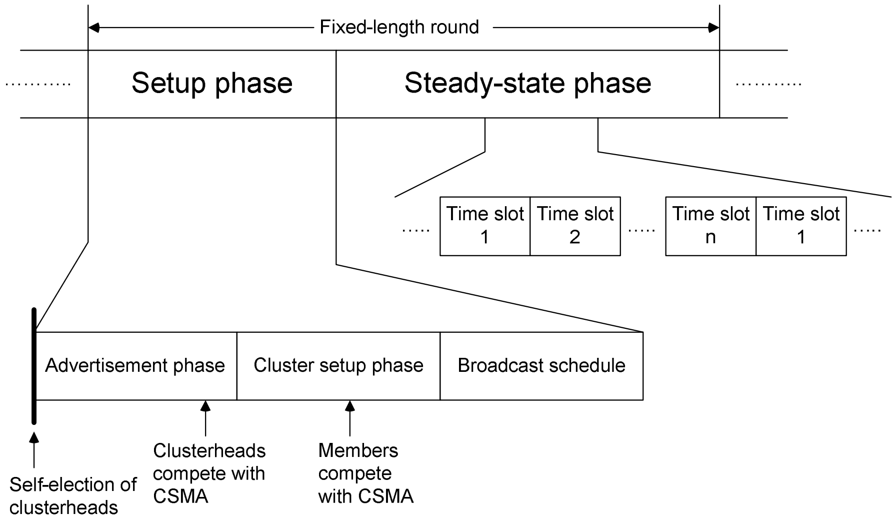
Overview

- 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



Self–organizing Medium Access Control for Sensor Networks (SMACS)

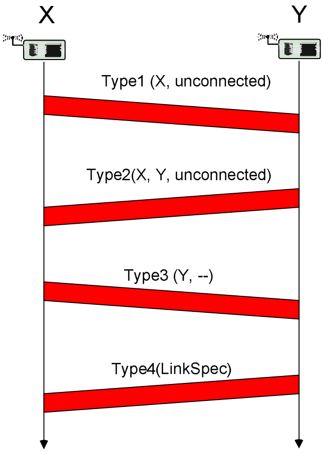
- Enables a collection of nodes to discover their neighbors and establish schedules for communicating with them without the need for any local or global master nodes.
- Multi-channel MAC
  - The number of available bands is relatively large.
- Neighbor discovery and channel assignment phases are combined.
- The drawback of SMACS is its low bandwidth utilization.
  - For example, if a node only has packets to be sent to one neighbor, it cannot reuse the timeslots scheduled for other neighbors

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



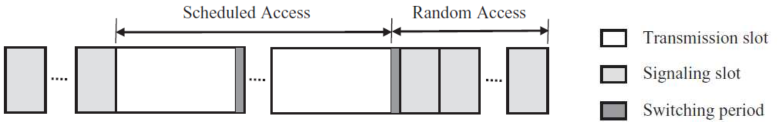
Message exchanges protected by randomized backoff

Traffic-Adaptive Medium Access (TRAMA)

- TDMA based MAC protocol
  - provide energy-efficient collision-free channel access
  - while maintaining good throughput, acceptable latency, and fairness
- Energy efficiency is achieved by ensuring collision - free data transmissions and allowing nodes to switch to a low - power idle state when they are not transmitting or receiving.
- To maintain throughput and fairness, TRAMA uses a transmitter - election algorithm that is inherently fair

TRAMA System Model

- A single time-slotted channel for both data and signaling transmissions.
- Time is divided into a series of random-access periods and scheduled-access periods, which alternate with each other.
  - A random-access period, also referred to as a signaling slot, is further divided into smaller signaling slots
  - A scheduled-access period, also referred to as a transmission slot, into smaller transmission slots.
- Slot synchronization can be implemented by using a simple timestamp mechanism or a technique, e.g., GPS.



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 Protocol

- The TRAMA protocol consists of three components:
  - Neighbor Protocol (NP)
  - Schedule Exchange Protocol (SEP)
  - Adaptive Election Algorithm (AEA)
- Both the NP and the SEP allow nodes to exchange 2 - hop neighborhood information and their schedules.
- The AEA uses the neighbor and schedule information to select transmitters and receivers for the current timeslot, allowing all other nodes to switch to a low - power mode.

TRAMA NP Protocol

- The NP collects 2-hop neighborhood information by exchanging small signaling packets among neighboring nodes during the random access periods.
- A signaling packet carries incremental neighborhood updates.
  - If there are no updates, it is sent as a " keep alive " beacon.
  - Each node sends incremental updates about its 1-hop neighborhood.
  - A node times out a neighbor if it does not hear from that neighbor for a certain period of time.
- Since a node knows the 1-hop neighbors of its 1-hop neighbors, consistent 2-hop neighborhood information can eventually be obtained.

TRAMA – adaptive election

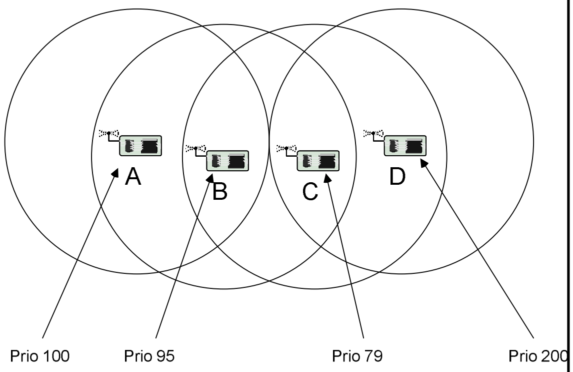
- Given: Each node knows its two-hop neighborhood and their current schedules
- How to decide which slot (in scheduled access period) a node can use?
  - Use ***node identifier*** x and globally known ***hash function*** h
  - For time slot t, compute ***priority*** p = h (x © t)
  - Compute this priority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

Overview

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

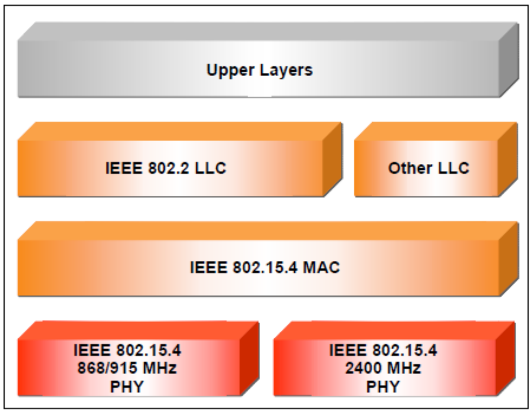
IEEE 802.15.4 Main Characteristics

- Data rates of 250 kb/s, 40 kb/s and 20 kb/s
- Star or peer-to-peer operation
- Support for low latency devices
- CSMA-CA channel access
- Dynamic device addressing

IEEE 802.15.4 Main Characteristics

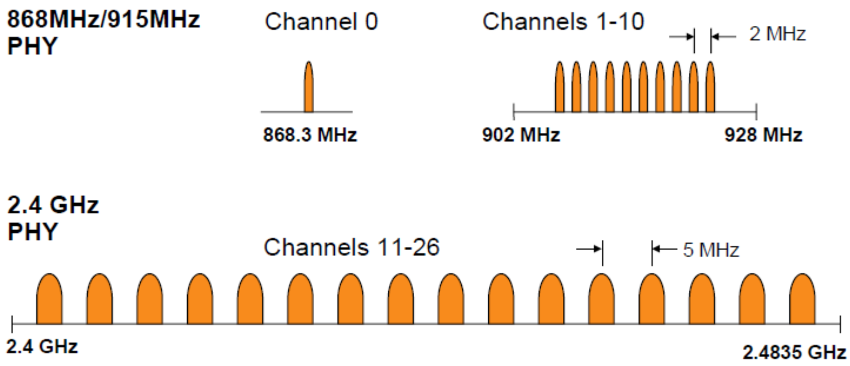
- Fully handshake protocol for transfer reliability
- Low power consumption
- Frequency bands of operation
  - 16 channels in the 2.4GHz ISM band
  - 10 channels in the 915MHz ISM band
  - 1 channel in the European 868MHz band

IEEE 802.15.4 Protocol Architecture



IEEE 802.15.4 Physical Layer

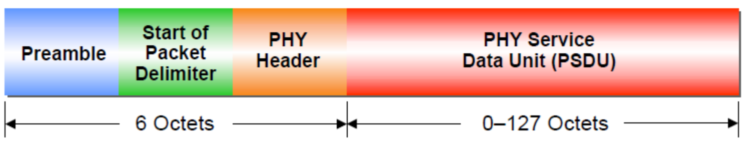
Operating Frequency Bands



802.15.4 Packet Structure

PHY Packet Fields

- Preamble (32 bits) – synchronization
- Start of Packet Delimiter (8 bits)
- PHY Header (8 bits) – PSDU length
- PSDU (0 to 1016 bits) – Data field



IEEE 802.15.4 Modulation Scheme

2.4 GHz PHY
- 250 kb/s (4 bits/symbol, 62.5 kBaud)
- Data modulation is 16-ary orthogonal modulation
- 16 symbols are ~orthogonal set of 32-chip PN codes
- Chip modulation is MSK at 2.0 Mchips/s

868MHz/915MHz PHY
- Symbol rate
  - 868 MHz Band: 20 kb/s (1 bit/symbol, 20 kBaud)
  - 915 MHz Band: 40 kb/s (1 bit/symbol, 40 kBaud)
- Data modulation is BPSK with differential encoding
- Spreading code is a 15-chip m-sequence
- Chip modulation is BPSK at
  - 868 MHz Band: 300 kchips/s
  - 915 MHz Band: 600 kchips/s

IEEE 802.15.4 Common Parameters

Transmit Power
- Capable of at least 1 mW

Transmit Center Frequency Tolerance
- ± 40 ppm

Receiver Sensitivity (packet error rate <1%)
- –85 dBm @ 2.4 GHz band
- –92 dBm @ 868/915 MHz band

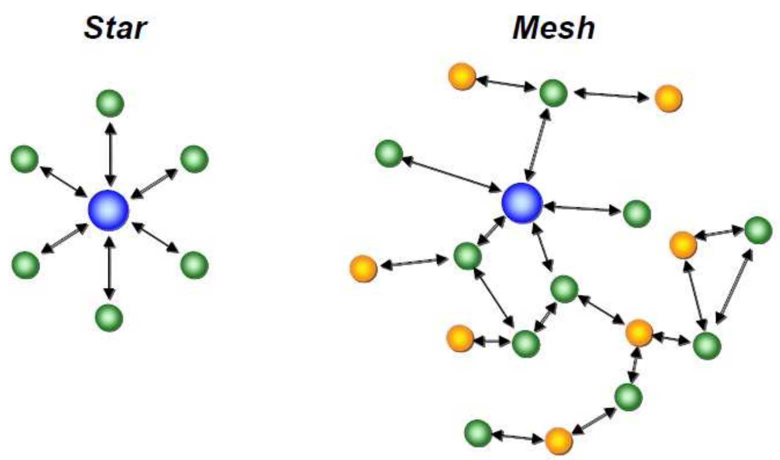
RSSI Measurements
- Packet strength indication
- Clear channel assessment

IEEE 802.15.4 MAC Design Drivers

- Extremely low cost
- Ease of implementation
- Reliable data transfer
- Short range operation
- Very low power consumption

Simple but flexible protocol!

IEEE 802.15.4 Network Topologies



IEEE 802.15.4 Device Classes

- Full function device (FFD)
  - Any topology
  - PAN coordinator capable
  - Talks to any other device
- Reduced function device (RFD)
  - Limited to star topology
  - Cannot become a network coordinator
  - Talks only to a network coordinator
  - Very simple implementation

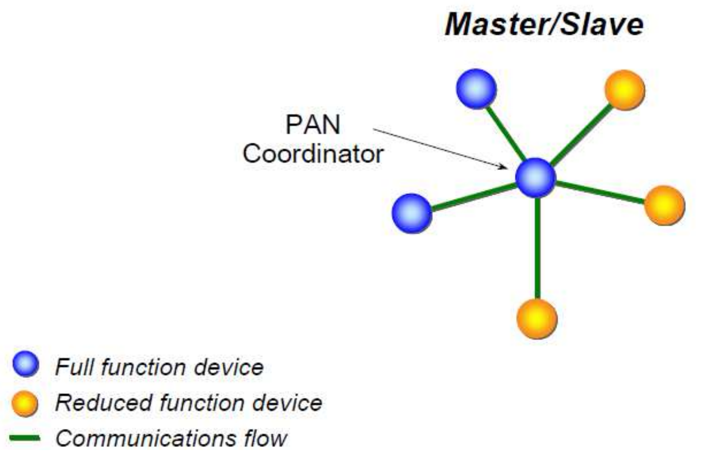
IEEE 802.15.4 Definitions

Coordinator
- An FFD with network device functionality that provides coordination and other services to the network.

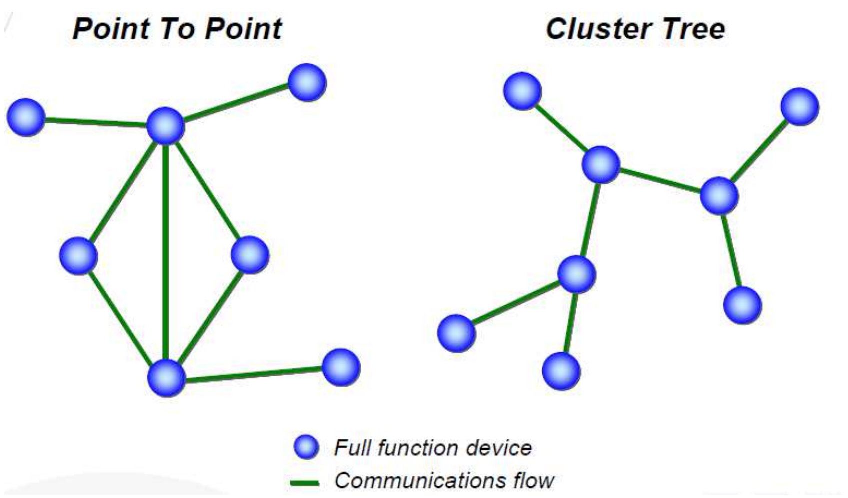
PAN Coordinator
- A coordinator that is the principal controller of the PAN. A network has exactly one PAN coordinator.

Network Device
- An RFD or FFD implementation containing an IEEE 802.15.4 medium access control and physical interface to the wireless medium.

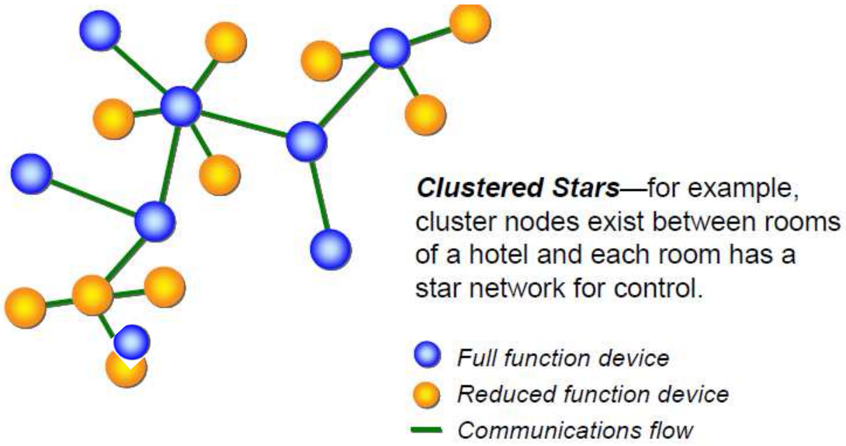
IEEE 802.15.4 MAC Star Topology



IEEE 802.15.4 MAC Peer-to-Peer



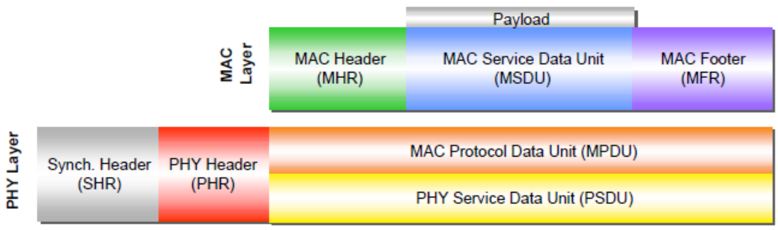
IEEE 802.15.4 MAC Combined Topology



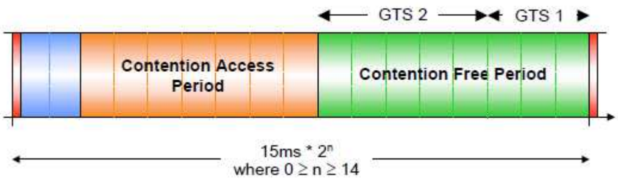
IEEE 802.15.4 MAC Frame Structure

4 Types of MAC Frames:

- Data frame
- Beacon frame
- Acknowledgment frame
- MAC command frame



IEEE 802.15.4 MAC Superframe Structure



Network Beacon—Transmitted by network coordinator. Contains network information, frame structure and notification of pending node messages.

Beacon Extension Period—Space reserved for beacon growth due to pending node messages

Contention Period—Access by any node using CSMA-CA

Guaranteed Time Slot—Reserved for nodes requiring guaranteed bandwidth [n = 0]

IEEE 802.15.4 MAC Traffic Types

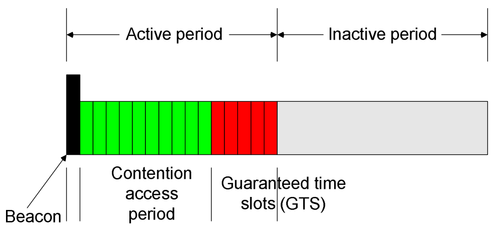
- Periodic data
  - Application defined rate (e.g., ***sensors***)
- Intermittent data
  - Application/external stimulus defined rate (e.g., ***light switch***)
- Repetitive low latency data
  - Allocation of time slots (e.g., ***mouse***)

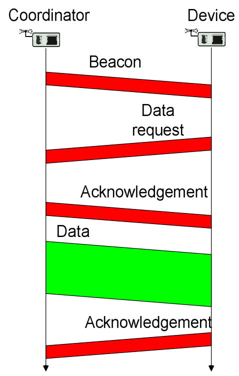
IEEE 802.15.4

- 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