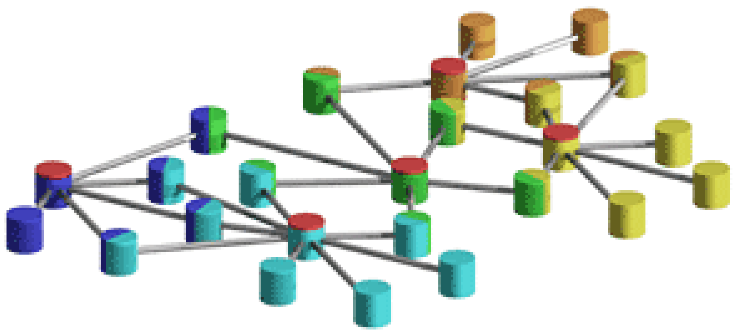
*Πανεπιστήμιο Θεσσαλίας*
*Τμήμα Μηχανικών Η/Υ, Τηλεπικοινωνιών και Δικτύων*

# Ασύρματα Δίκτυα Αισθητήρων

## *Link Layer και MAC Πρωτόκολλα*



# Overview

- ***Error control***
- Framing
- Link management

# Link layer tasks in general

- Framing – group bit sequence into packets/frames
  - Important: format, size
- Error control – make sure that the sent bits arrive and no other
  - Forward and backward error control
- Flow control – ensure that a fast sender does not overrun its slow(er) receiver
- Link management – discovery and manage links to neighbors
  - Do not use a neighbor at any cost, only if link is good enough

# Error control

- Error control has to ensure that data transport is
  - Error-free – deliver exactly the sent bits/packets
  - In-sequence – deliver them in the original order
  - Duplicate-free – and at most once
  - Loss-free – and at least once
- Causes: fading, interference, loss of bit synchronization, …
  - Results in bit errors, bursty, sometimes heavy-tailed runs (see physical layer chapter)
  - In wireless, sometimes quite high average bit error rates – $10^{-2}$ … $10^{-4}$ possible!
- Approaches
  - Backward error control – ARQ
  - Forward error control – FEC

# Backward error control – ARQ

- Basic procedure (a quick recap)
  - Put header information around the payload
  - Compute a checksum and add it to the packet
    - Typically: Cyclic redundancy check (CRC), quick, low overhead, low residual error rate
  - Provide feedback from receiver to sender
    - Send ***positive*** or ***negative acknowledgement***
  - Sender uses timer to detect that acknowledgements have not arrived
    - Assumes packet has not arrived
    - Optimal timer setting?
  - If sender infers that a packet has not been received correctly, sender can retransmit it
    - What is maximum number of retransmission attempts? If bounded, at best a semi-reliable protocols results

# Standard ARQ protocols

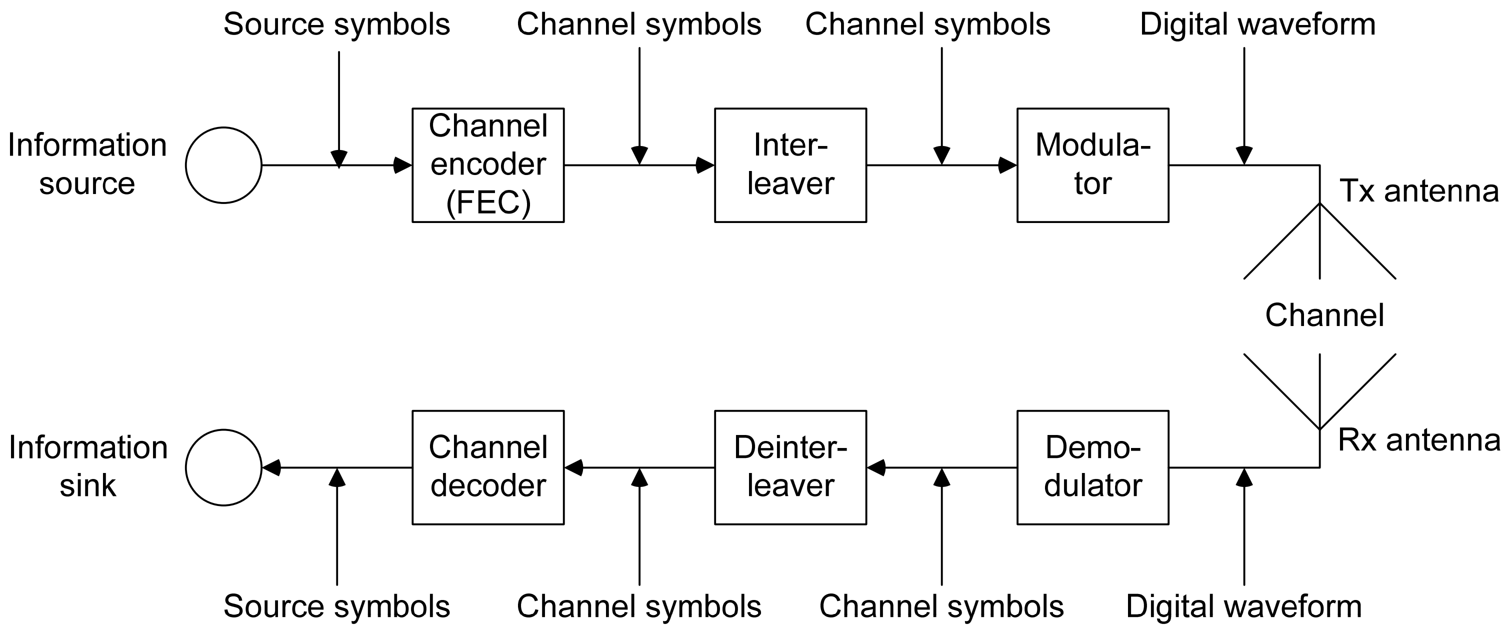
- Alternating bit – at most one packet outstanding, single bit sequence number
- Go-back N – send up to N packets, if a packet has not been acknowledged when timer goes off, retransmit all unacknowledged packets
- Selective Repeat – when timer goes off, only send that particular packet

# How to use acknowledgements

- Be careful about ACKs from different layers
  - A MAC ACK (e.g., S-MAC) does not necessarily imply buffer space in the link layer
  - On the other hand, having both MAC and link layer ACKs is a waste
- Do not (necessarily) acknowledge every packet – use cumulative ACKs
  - Tradeoff against buffer space
  - Tradeoff against number of negative ACKs to send

# Forward error control

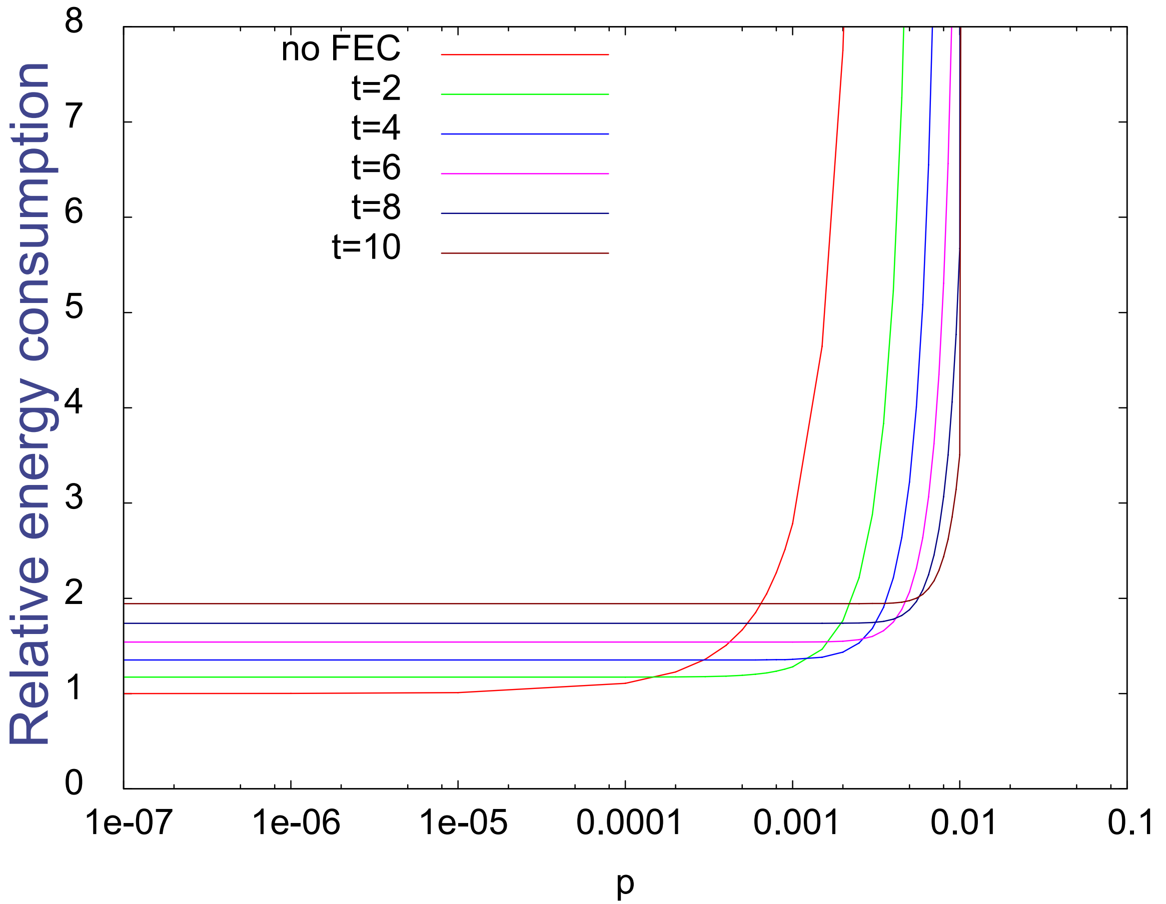
- Idea: Endow symbols in a packet with additional redundancy to withstand a limited amount of random permutations
  - Additionally: interleaving – change order of symbols to withstand burst errors



# Comparison: FEC vs. ARQ

- FEC
  - Constant overhead for each packet
  - Not (easily) possible to adapt to changing channel characteristics
- ARQ
  - Overhead only when errors occurred (expect for ACK, always needed)
- Both schemes have their uses ! ***hybrid schemes***

t: error correction capacity




BCH + unlimited number of retransmissions

# Power control on a link level

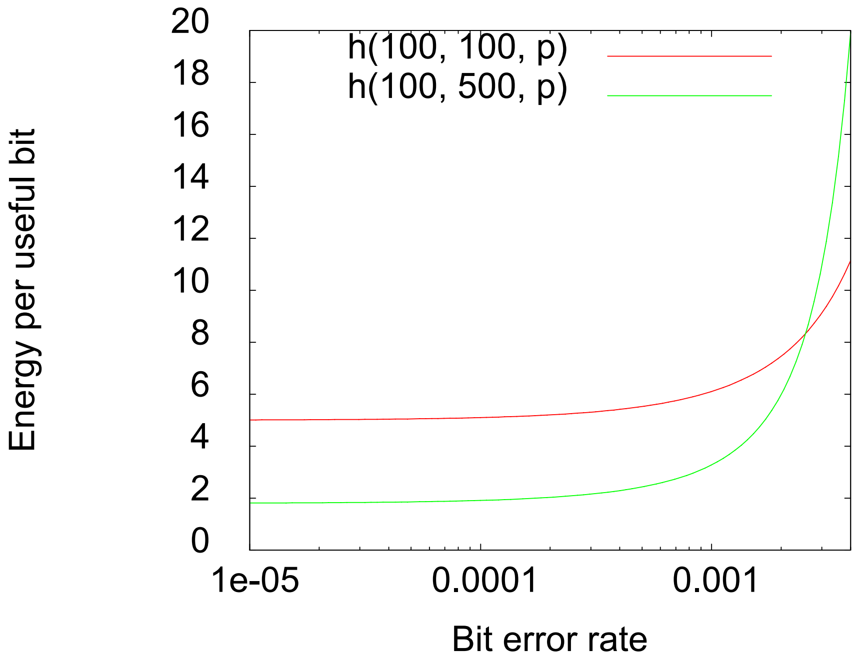
- Further controllable parameter: transmission power
  - Higher power, lower error rates – less FEC/ARQ necessary
  - Lower power, higher error rates – higher FEC necessary
- Tradeoff!

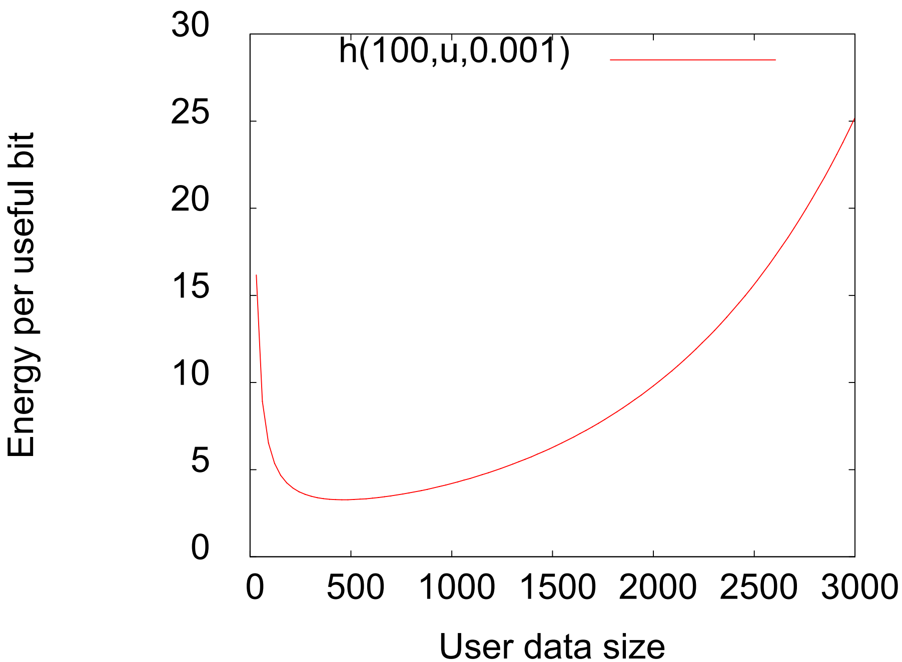
# Overview

- Error control
- ***Framing***
- Link management

# Frame, packet size

- Small packets: low packet error rate, high packetization overhead
- Large packets: high packet error rate, low overhead
- Depends on bit error rate, energy consumption per transmitted bit



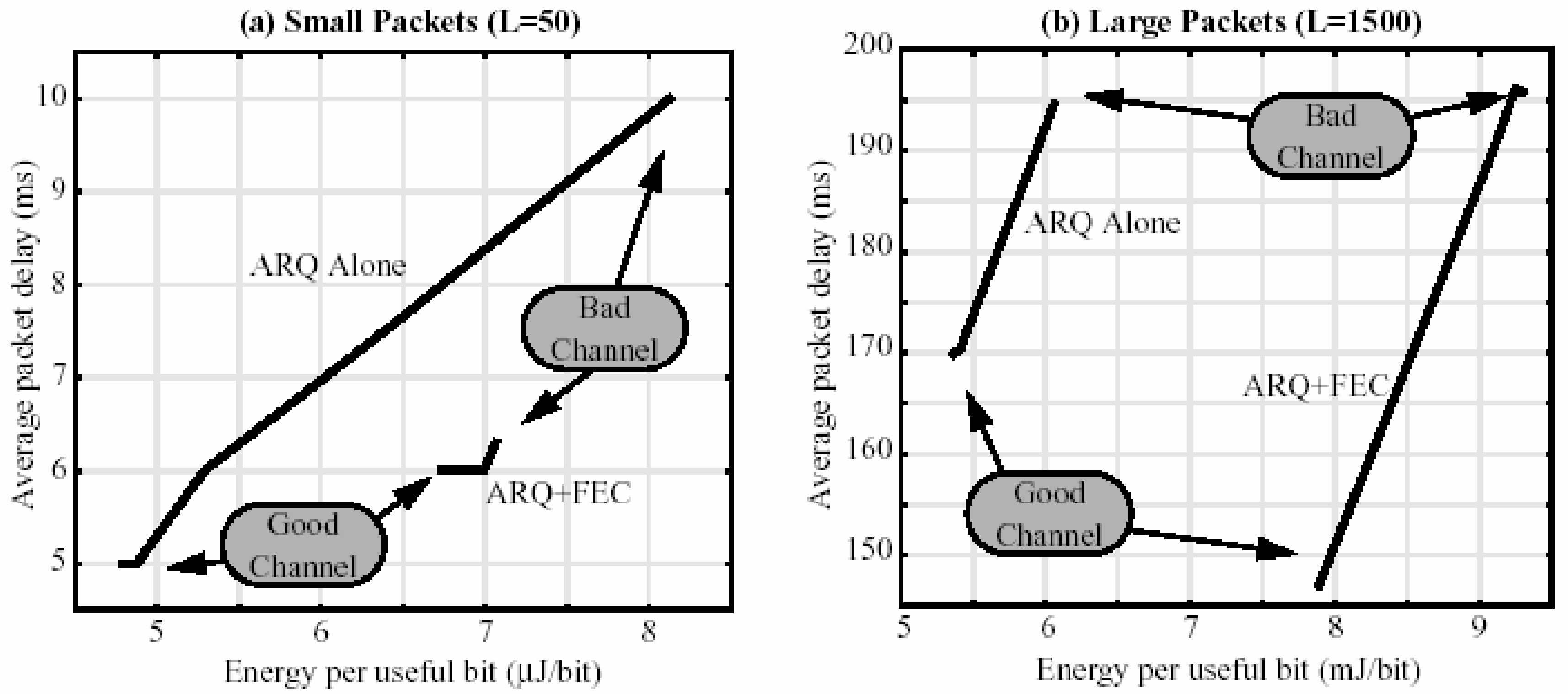



# Dynamically adapt frame length

- For known bit error rate (BER), optimal frame length is easy to determine
- Problem: how to estimate BER?
  - Collect channel state information at the receiver (RSSI, FEC decoder information, …)
  - Example: Use number of attempts T required to transmit the last M packets as an estimator of the packet error
  - Second problem: how long are observation valid/how should they be aged?
  - Only recent past is – if anything at all – somewhat credible

# Putting it together: ARQ, FEC, frame length optimization

- Applying ARQ, FEC (both block and convolutional codes), frame length optimization to a Rayleigh fading channel



# Overview

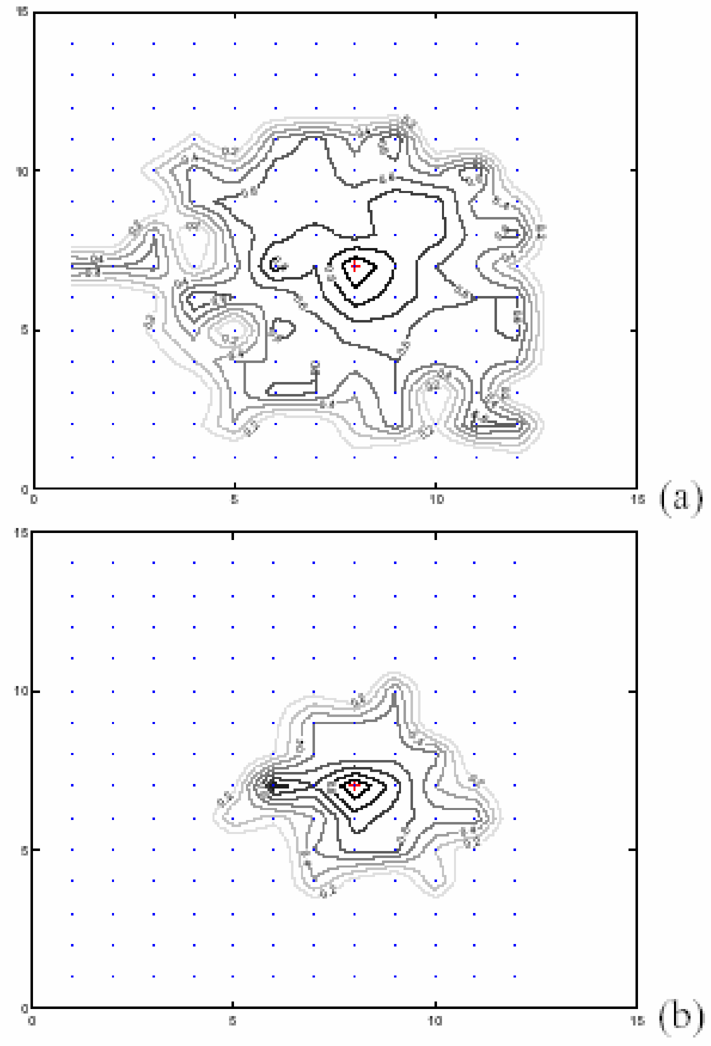
- Error control
- Framing
- ***Link management***

# Link management

- Goal: decide to which neighbors that are *more or less* reachable a link should be established
  - Problem: communication quality fluctuates, far away neighbors can be costly to talk to, error-prone, quality can only be estimated
- Establish a ***neighborhood table*** for each node
  - Partially automatically constructed by MAC protocols

# Link quality characteristics

- Expected: simple, circular shape of “region of communication” – not realistic
- Instead:
  - Correlation between distance and loss rate is weak; iso-loss-lines are not circular but irregular
  - Asymmetric links are relatively frequent (up to 15%)
  - Significant short-term PER variations even for stationary nodes



# Conclusion

- Link layer combines traditional mechanisms
  - Framing, packet synchronization, flow control

  with relatively specific issues
  - Careful choice of error control mechanisms – tradeoffs between FEC & ARQ & transmission power & packet size …
  - Link estimation and characterization

# Overview

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

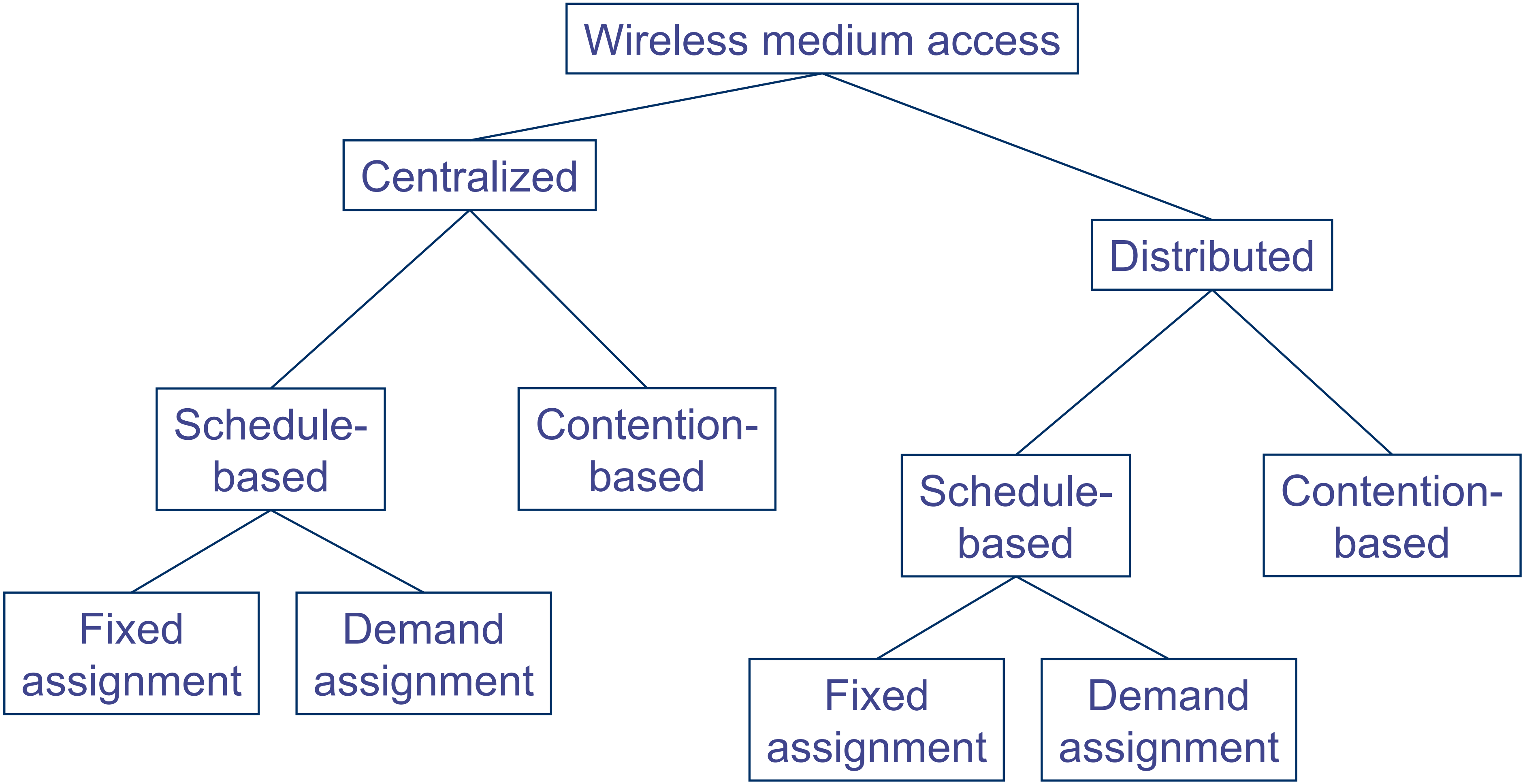
# Principal options and difficulties

- Medium access in wireless networks is difficult mainly because of
  - Impossible (or very difficult) to sender and receive at the same time
  - Interference situation at receiver is what counts for transmission success, but can be very different to 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,
  - Preamble sampling, B-MAC
  - PAMAS
- Schedule-based protocols
- IEEE 802.15.4

# Main options to shut up senders

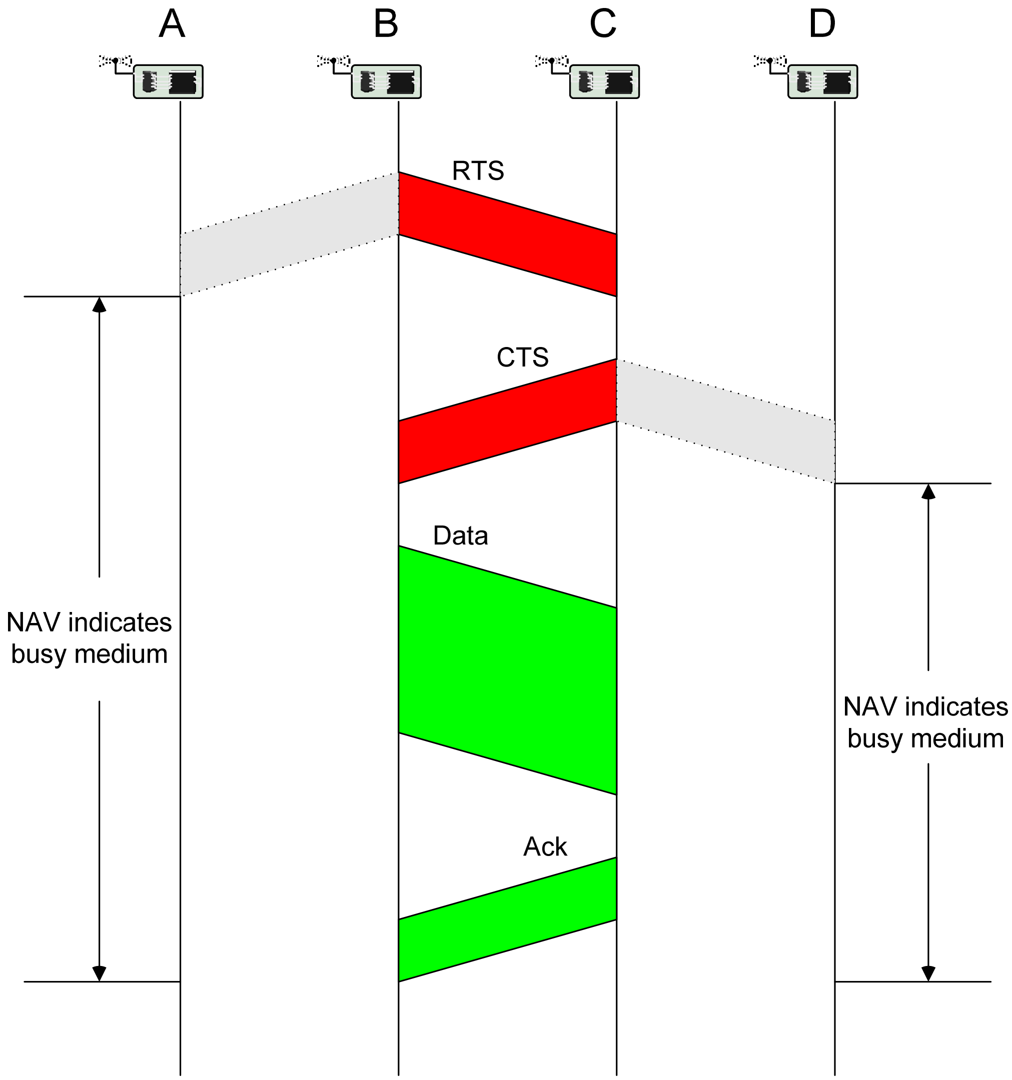
- Receiver informs potential interferers ***while*** a reception is on-going
  - By sending out a signal indicating just that
  - Problem: Cannot use same channel on which actual reception takes place

  ! 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 overhead 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***)

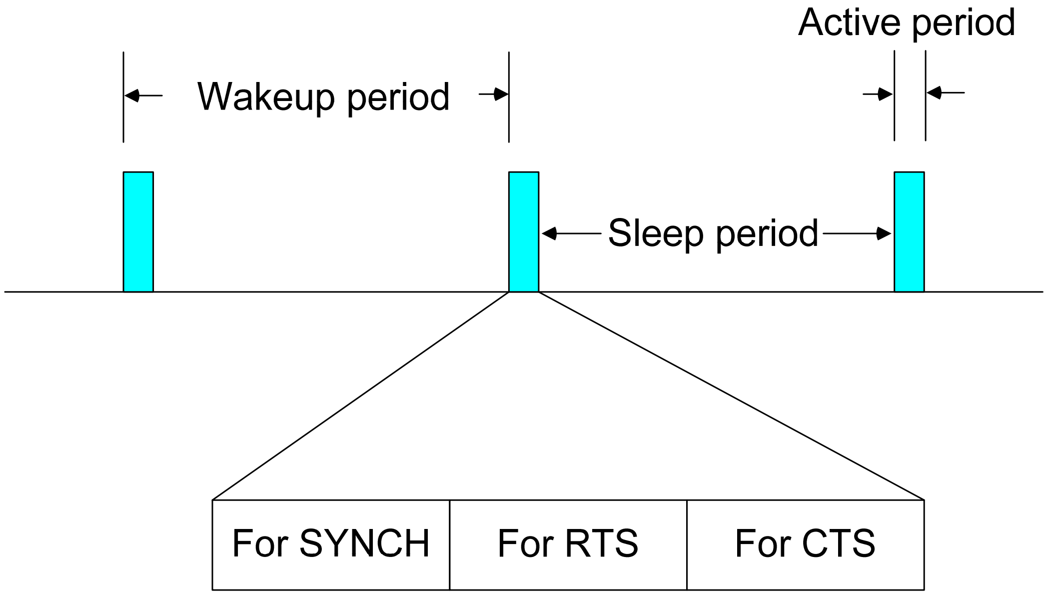


# MACA Problem: Idle listening

- 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?
  - …

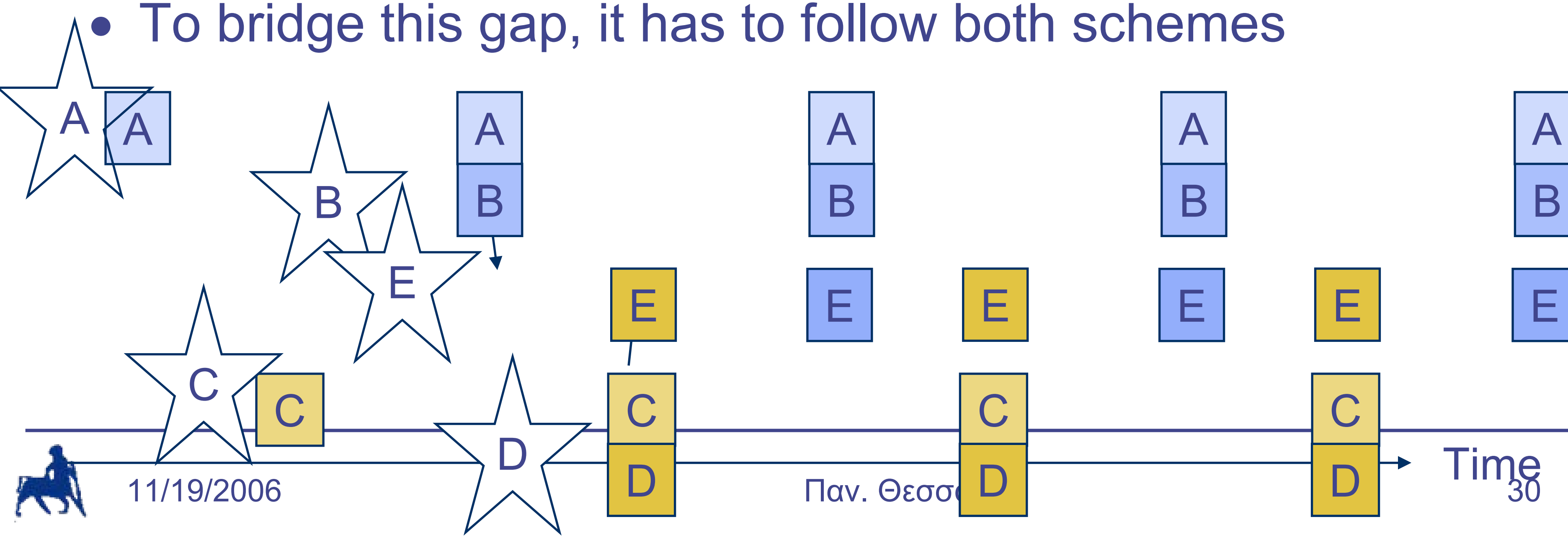
# Sensor-MAC (S-MAC)

- 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



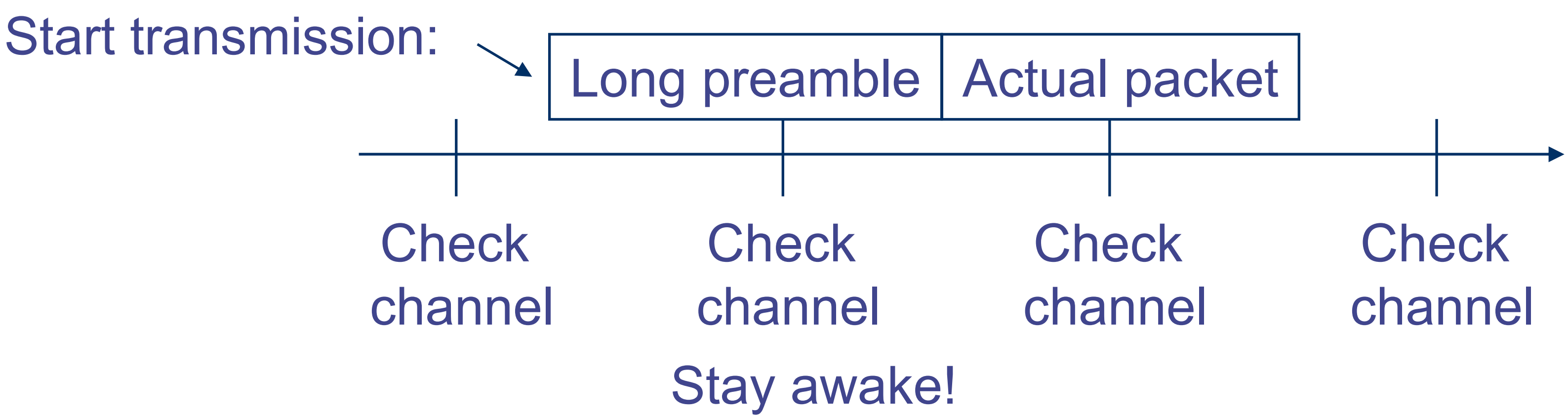
# S-MAC synchronized islands

- 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



# 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

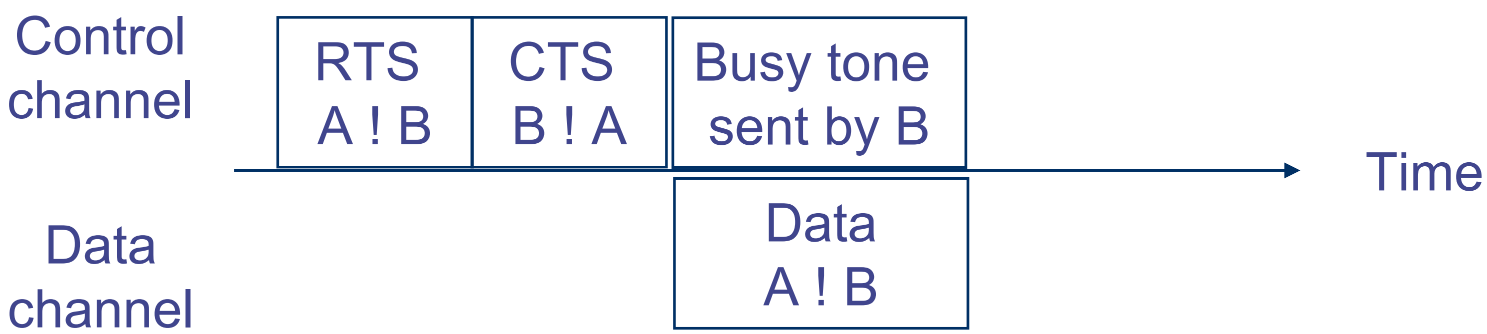
- Combines several of the above discussed ideas
  - Takes care to provide practically relevant solutions
- Clear Channel Assessment
  - Adapts to noise floor by sampling channel when it is assumed to be free
  - For actual assessment when sending a packet, look at five channel samples – channel is free 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

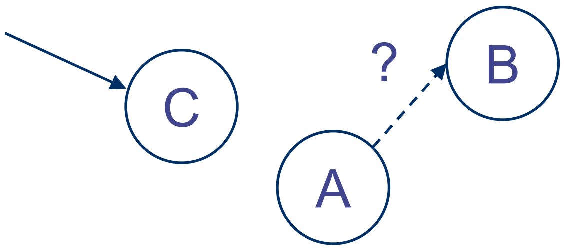
# Power Aware Multiaccess with Signaling – PAMAS

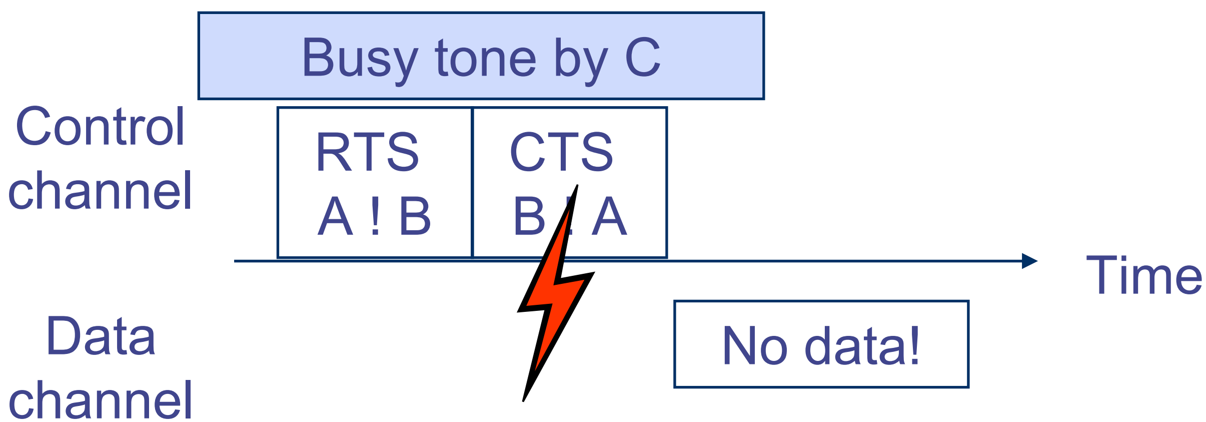
- Idea: combine busy tone with RTS/CTS
  - Results in detailed overhearing avoidance, does not address idle listening
  - Uses separate ***data*** and ***control channels***
- Procedure
  - Node A transmits RTS on control channel, does not sense channel
  - Node B receives RTS, sends CTS on control channel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

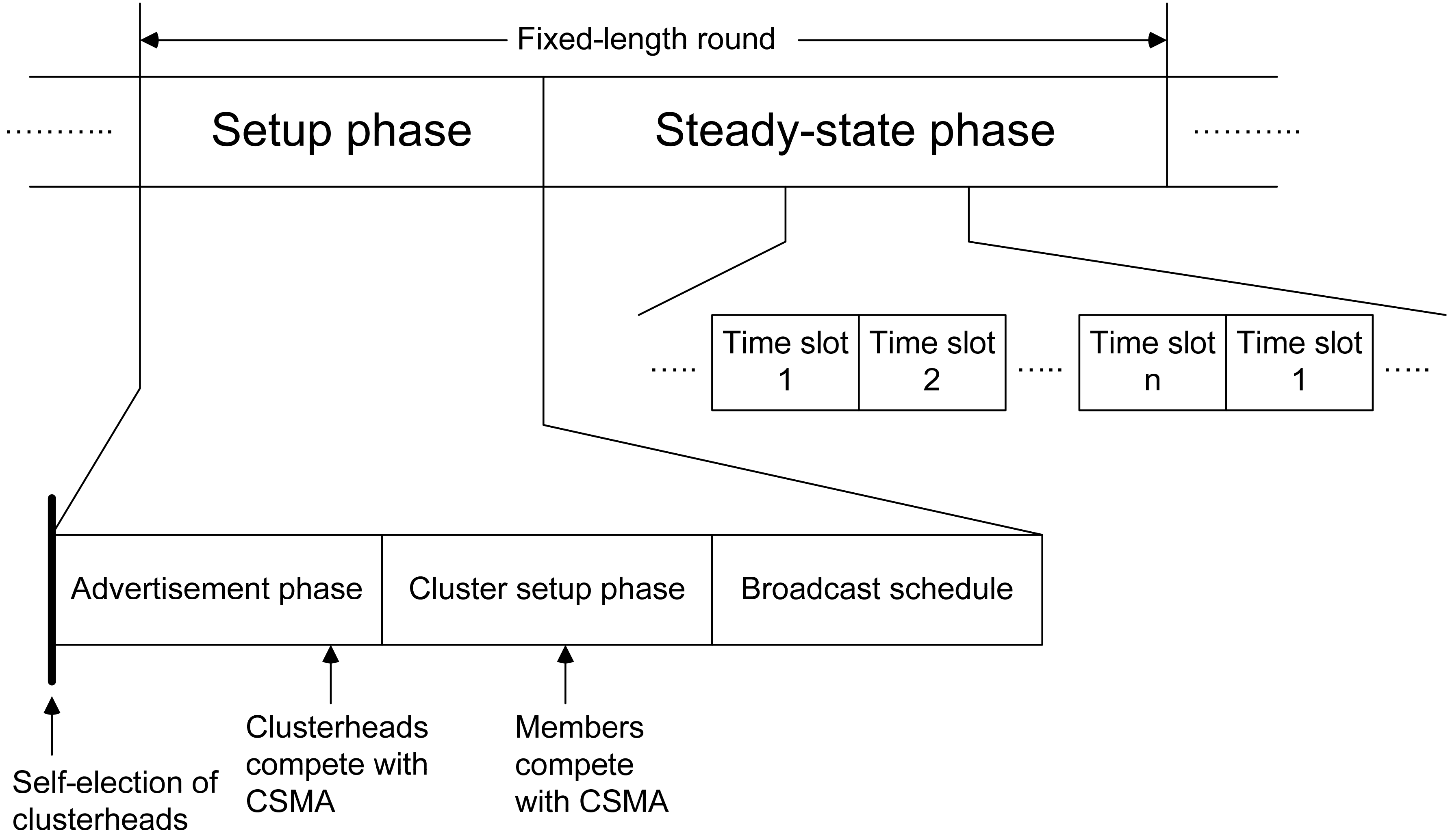
# Overview

- Principal options and difficulties
- Contention-based protocols
- ***Schedule-based protocols***
  - LEACH
  - 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



# Overview

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

# IEEE 802.15.4

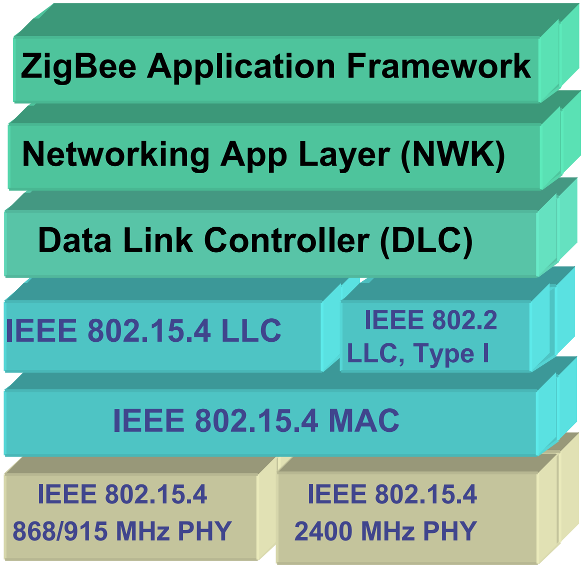
- IEEE standard for low-rate WPAN applications
- Goals: low-to-medium bit rates, moderate delays without too stringent guarantee requirements, low energy consumption
- Physical layer
  - 20 kbps over 1 channel @ 868-868.6 MHz
  - 40 kbps over 10 channels @ 905 – 928 MHz
  - 250 kbps over 16 channels @ 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 Basics

- 802.15.4 is a simple packet data protocol for lightweight wireless networks
  - Channel Access is via Carrier Sense Multiple Access with collision avoidance and optional time slotting
  - Message acknowledgement and an optional beacon structure
  - Multi-level security
  - Three bands, 27 channels specified
    - 2.4 GHz: 16 channels, 250 kbps
    - 868.3 MHz : 1 channel, 20 kbps
    - 902-928 MHz: 10 channels, 40 kbps
  - Works well for
    - Long battery life, selectable latency for controllers, sensors, remote monitoring and portable electronics
  - Configured for maximum battery life, has the potential to last as long as the shelf life of most batteries

# IEEE 802.15.4 standard

- Includes layers up to and including Link Layer Control
  - LLC is standardized in 802.1
- Supports multiple network topologies including Star, Cluster Tree and Mesh
- Features of the MAC: Association/dissociation, ACK, frame delivery, channel access mechanism, frame validation, guaranteed time slot management, beacon management, channel scan
  - Low complexity: 26 primitives versus 131 primitives for 802.15.1 (Bluetooth)

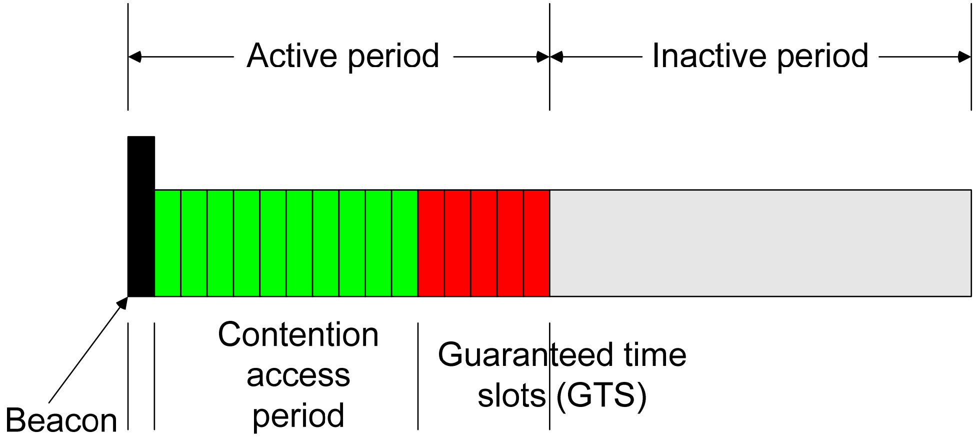


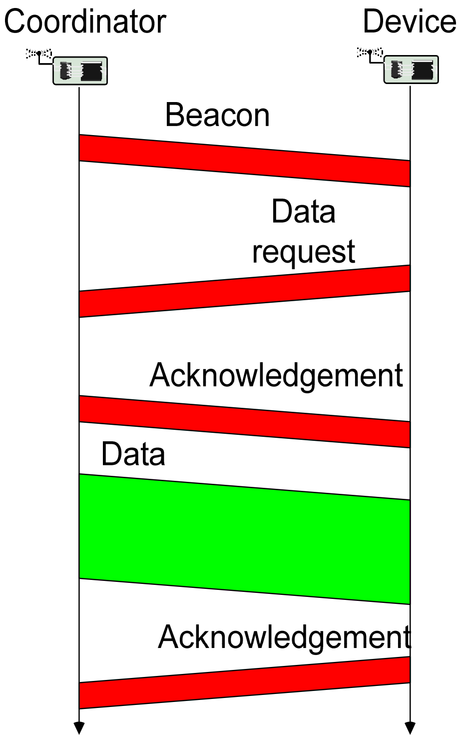
# IEEE 802.15.4 MAC Overview

- Employs 64-bit IEEE & 16-bit short addresses
  - Ultimate network size can reach $2^{64}$ nodes (more than we'll probably need…)
  - Using local addressing, simple networks of more than 65,000 (2^16) nodes can be configured, with reduced address overhead
- Three devices specified
  - Network Coordinator
  - Full Function Device (FFD)
  - Reduced Function Device (RFD)
- Simple frame structure
- Reliable delivery of data
- Association/disassociation
- AES-128 security
- CSMA-CA channel access
- Optional superframe structure with beacons
- GTS mechanism

# 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

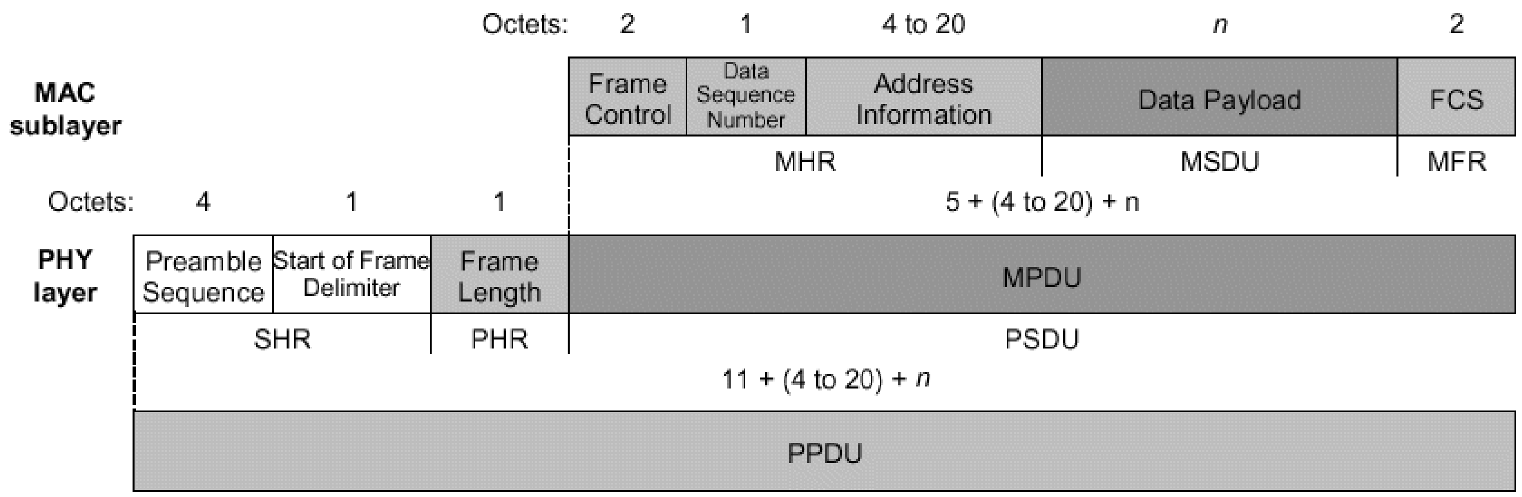


# MAC Options

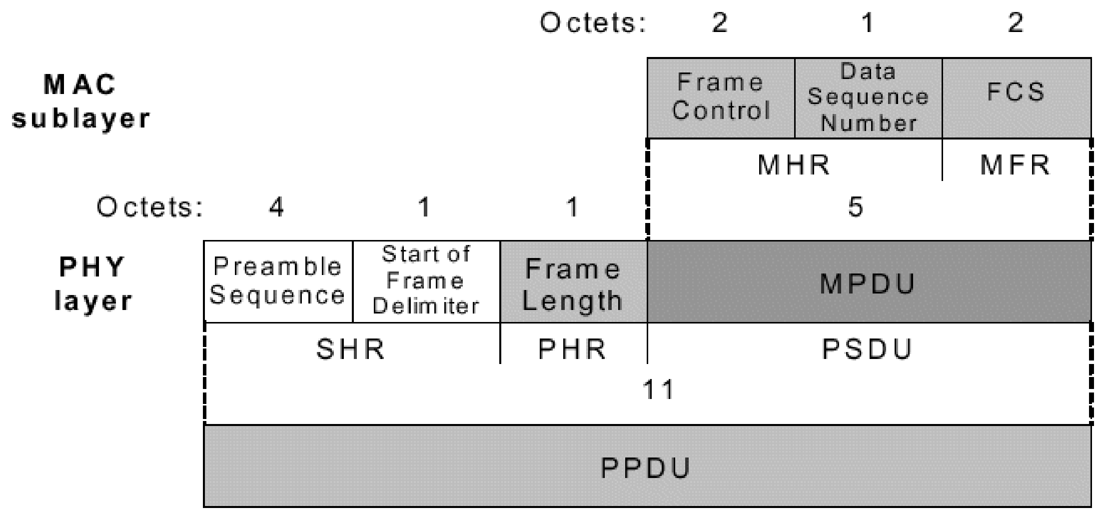
- Two channel access mechanisms
  - Non-beacon network
    - Standard ALOHA CSMA-CA communications
    - Positive acknowledgement for successfully received packets
  - Beacon-enabled network
    - Superframe structure
      - For dedicated bandwidth and low latency
      - Set up by network coordinator to transmit beacons at predetermined intervals
        - 15ms to 252sec (15.38ms*2n where $0 \leq n \leq 14$)
        - 16 equal-width time slots between beacons
        - Channel access in each time slot is contention free
  - Three security levels specified
    - None
    - Access control lists
    - Symmetric key employing AES-128

# Data Frame format




- One of two most basic and important structures in 15.4
- Provides up to 104 byte data payload capacity
- Data sequence numbering to ensure that all packets are tracked
- Robust frame structure improves reception in difficult conditions
- Frame Check Sequence (FCS) ensures that packets received are without error

# Acknowledgement Frame Format




- The other most important structure for 15.4
- Provides active feedback from receiver to sender that packet was received without error
- Short packet that takes advantage of standards-specified “quiet time” immediately after data packet transmission

# IEEE 802.15.4 Device Types

- Three device types
  - Network Coordinator
    - Maintains overall network knowledge; most sophisticated of the three types; most memory and computing power
  - Full Function Device
    - Carries full 802.15.4 functionality and all features specified by the standard
    - Additional memory, computing power make it ideal for a network router function
    - Could also be used in network edge devices (where the network touches the real world)
  - Reduced Function Device
    - Carriers limited (as specified by the standard) functionality to control cost and complexity
    - General usage will be in network edge devices
- All of these devices can be no more complicated than the transceiver, a simple 8-bit MCU and a pair of AAA batteries!

# Frequencies and Data Rates

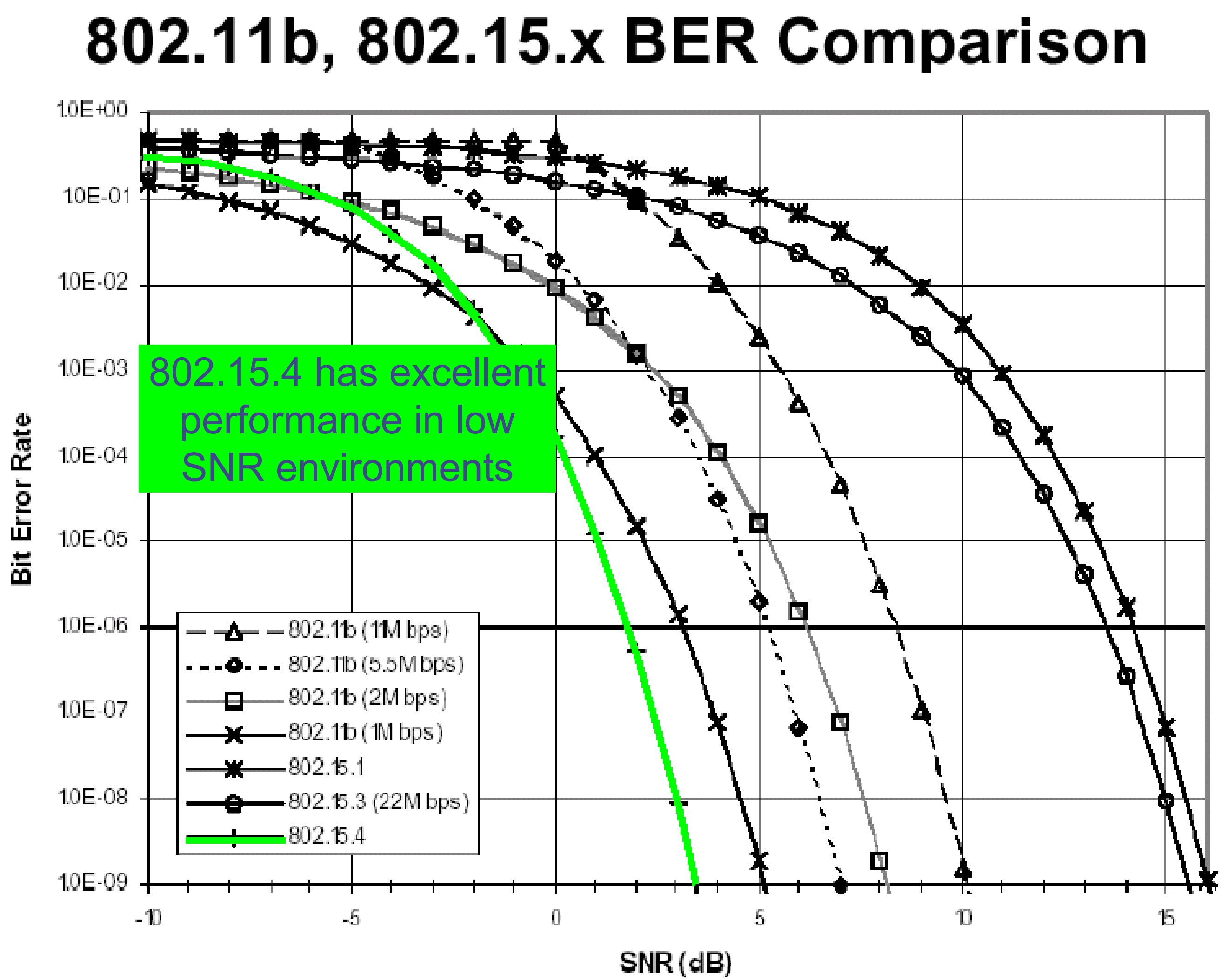
| PHY (MHz) | Frequency band (MHz) | Spreading parameters | | Data parameters | | |
|---|---|---|---|---|---|---|
| | | Chip rate (kchip/s) | Modulation | Bit rate (kb/s) | Symbol rate (ksymbols/s) | Symbols |
| 868/915 | 868-868.6 | 300 | BPSK | 20 | 20 | Binary |
| | 902-928 | 600 | BPSK | 40 | 40 | Binary |
| 2450 | 2400-2483.5 | 2000 | O-QPSK | 250 | 62.5 | 16-ary Orthogonal |

- The two PHY bands (UHF/Microwave) have different physical, protocol-based and geopolitical characteristics
  - Worldwide coverage available at 2.4GHz at 250kbps
  - 900MHz for Americas and some of the Pacific
  - 868MHz for European-specific markets

# ISM Band Interference and Coexistence

- Potential for interference exists in every ISM band, not just 2.4GHz
- IEEE 802.11 and 802.15.2 committees are addressing coexistence issues
- ZigBee/802.15.4 Protocol is very robust
  - Clear channel checking before transmission
  - Backoff and retry if no acknowledgement received
  - Duty cycle of a ZigBee-compliant device is usually extremely low
  - It's the "cockroach that survives the nuclear war"
    - Waits for an opening in otherwise busy RF spectrum
    - Waits for acknowledgements to verify packet reception at other end

# PHY Performance



# 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, CDAM 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

# Questions ?