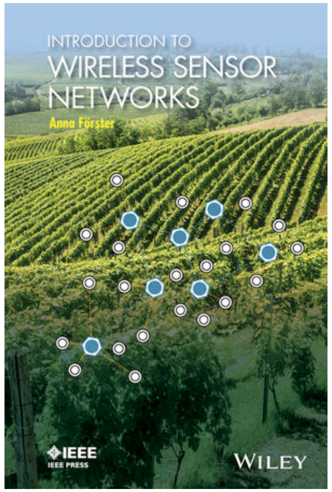


INTRODUCTION TO WIRELESS SENSOR NETWORKS

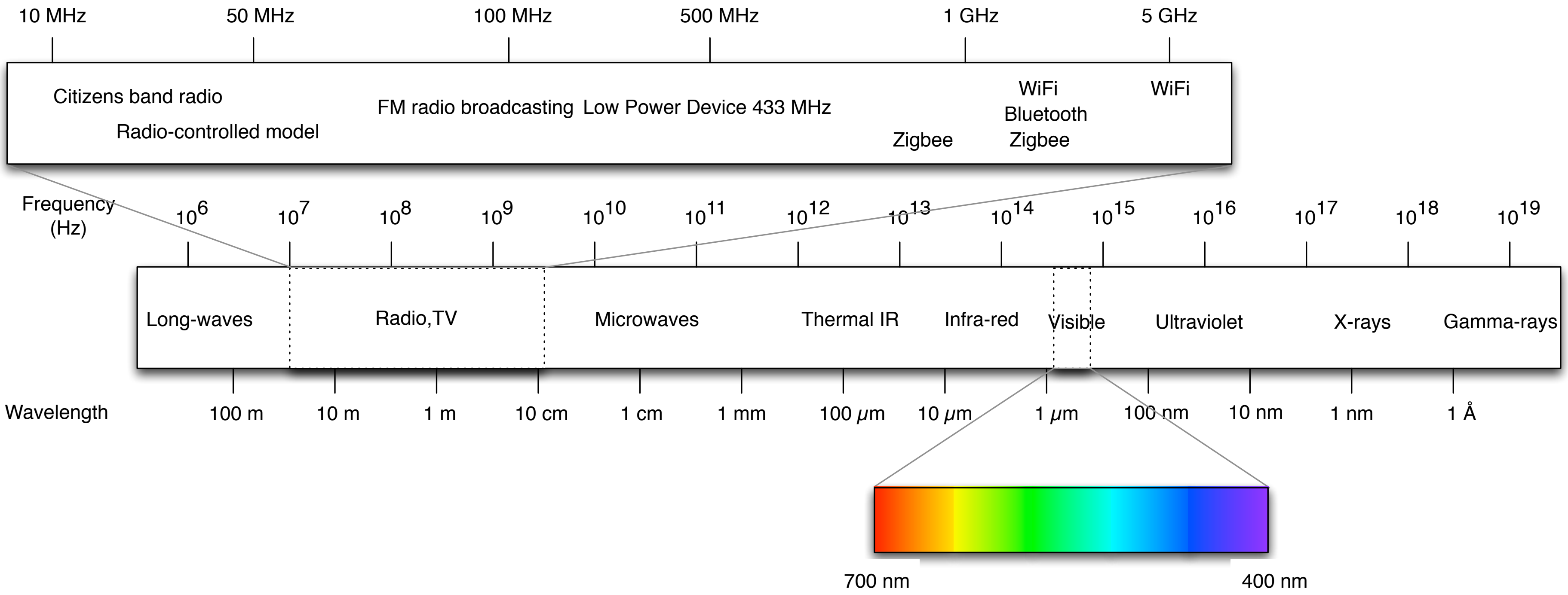
CHAPTER 3: RADIO COMMUNICATIONS

Anna Förster

OVERVIEW

1. Radio Waves and Modulation/Demodulation
2. Properties of Wireless Communications
    1. Interference and noise
    2. Hidden Terminal Problem
    3. Exposed Terminal Problem
3. Medium Access Protocols
    1. Design Criteria for Medium Access Protocols
    2. Time Division Multiple Access
    3. Carrier Sense Multiple Access
    4. Sensor MAC
    5. Berkeley MAC
    6. Optimizations of B-MAC
    7. Other Protocols and Trends

RADIO WAVES



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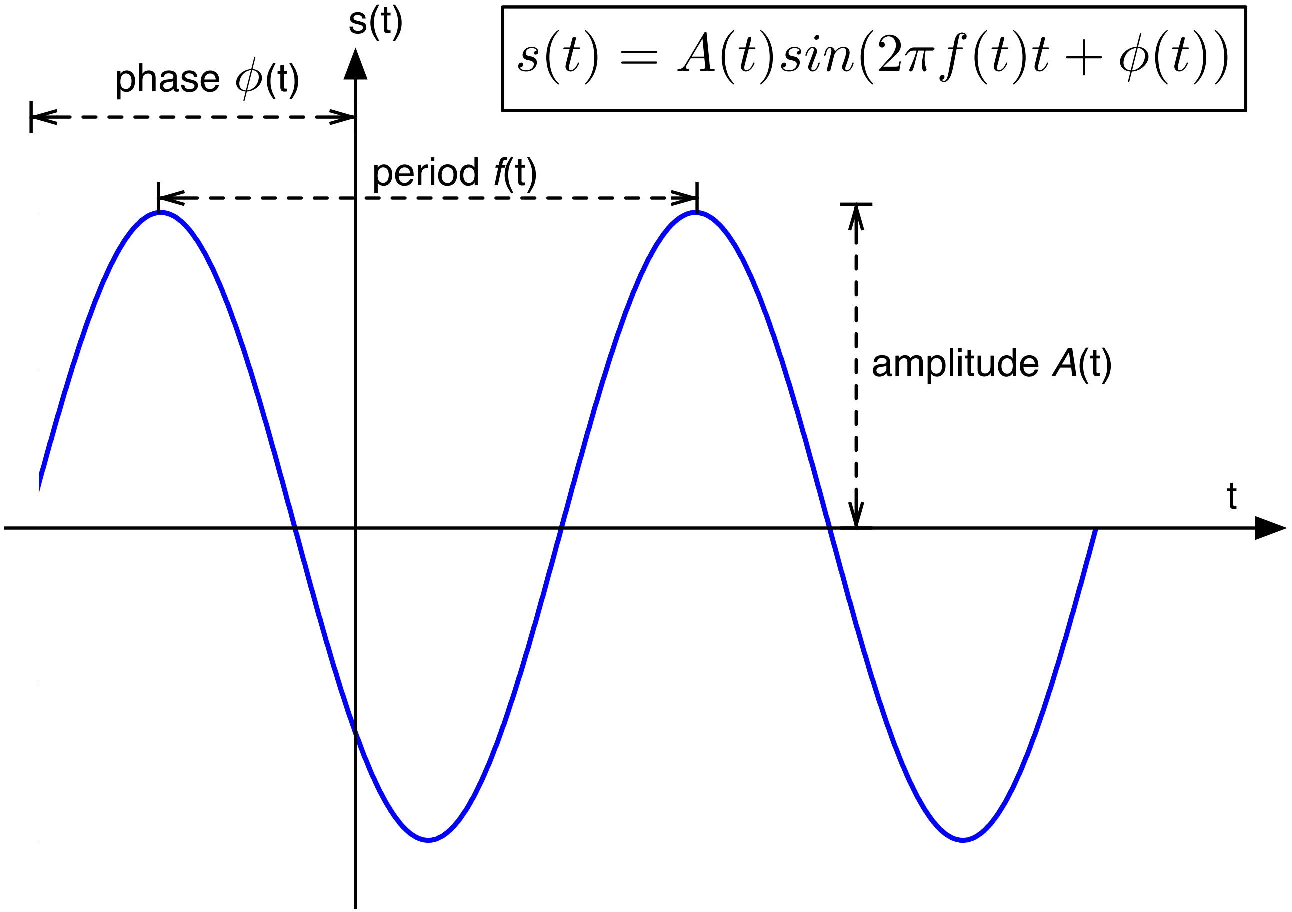
RADIO WAVES



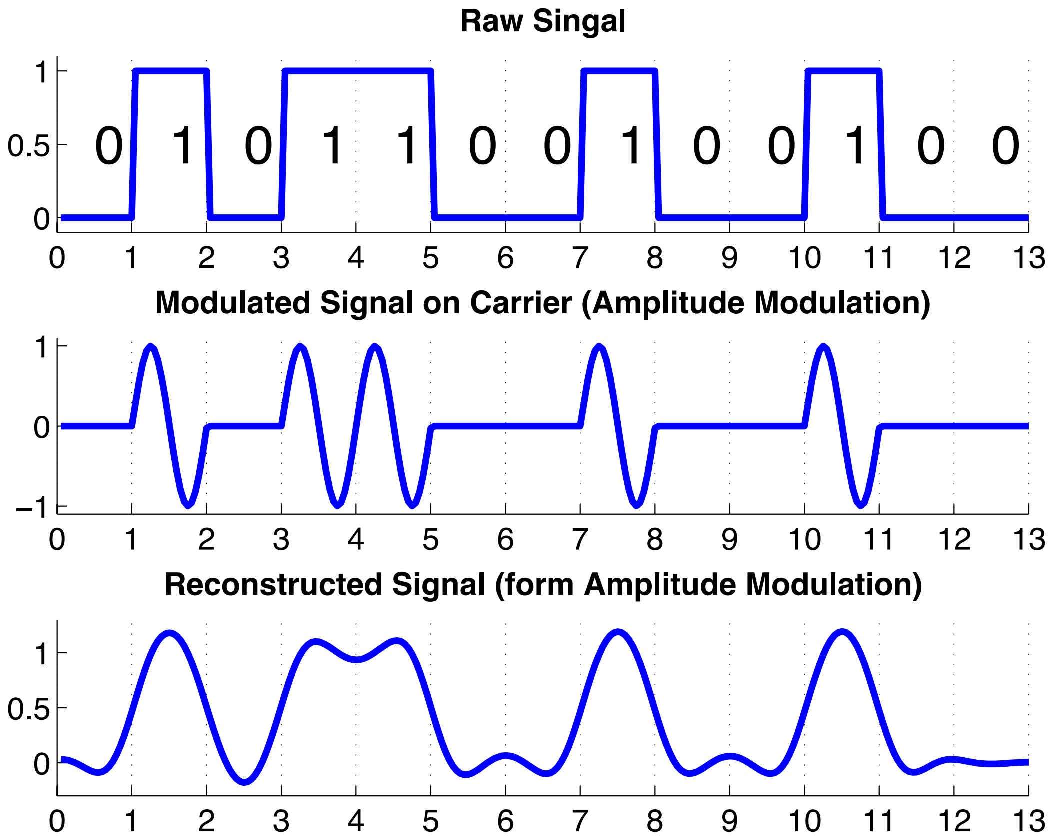
$$s(t) = A(t)sin(2\pi f(t)t + \phi(t))$$

MODULATION/DEMODULATION

- Waves do not carry information by themselves.
- By changing one or more of the parameters of a wave, we can encode information into it.

> ***Signal modulation/demodulation.*** *This is the process of changing radio wave parameters in a well-defined way to encode/decode information into/from the wave.*

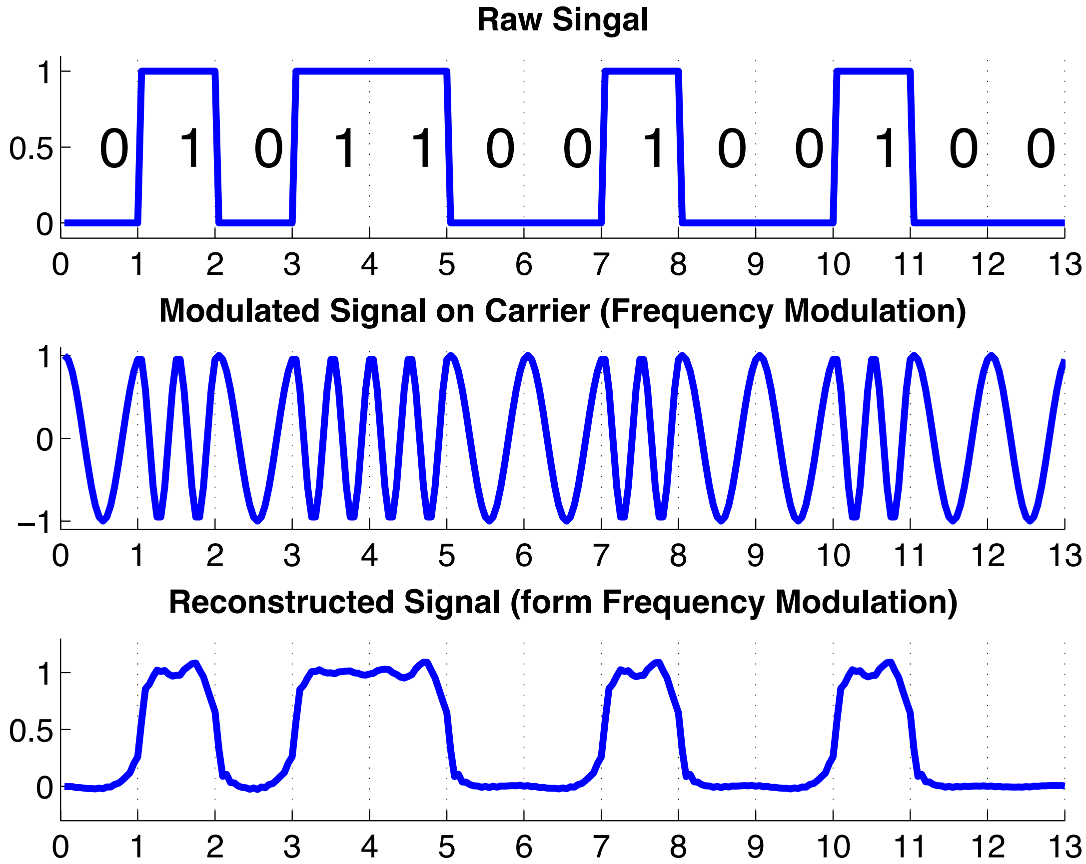
AMPLITUDE MODULATION



$$s(t) = A(t)\sin(2\pi f(t)t + \phi(t))$$

Amplitude A(t): *This parameter gives how high the wave is. To encode information, you can change the amplitude from very small (encoding a 0) to very high (encoding a 1).*

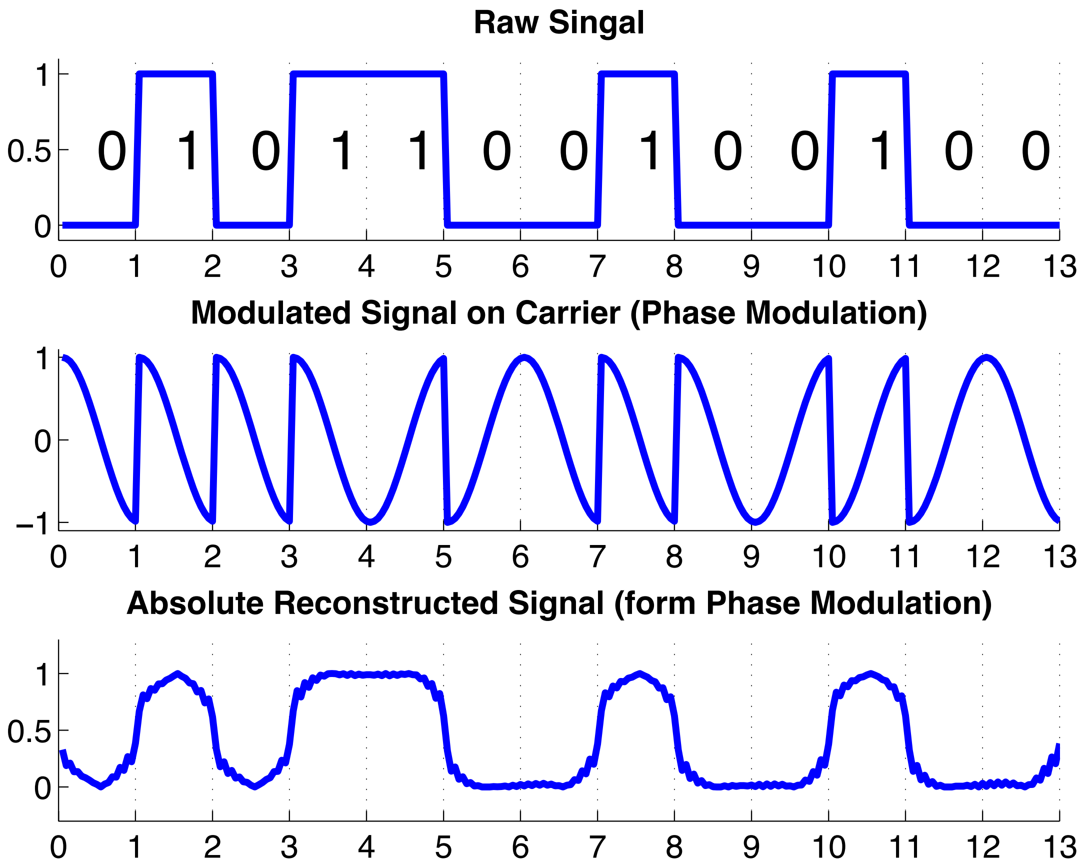
FREQUENCY MODULATION



$$s(t) = A(t)\sin(2\pi f(t)t + \phi(t))$$

***Frequency or period f(t)**. This parameter dictates how often the wave form is repeated over time. The frequency of the signal can be changed to indicate different codes.*

PHASE MODULATION



$$s(t) = A(t)\sin(2\pi f(t)t + \phi(t))$$

Displacement or phase ϕ(t). *This parameter identifies the displacement of the wave in respect to the beginning of the axes. You can displace the wave to indicate change of codes.*

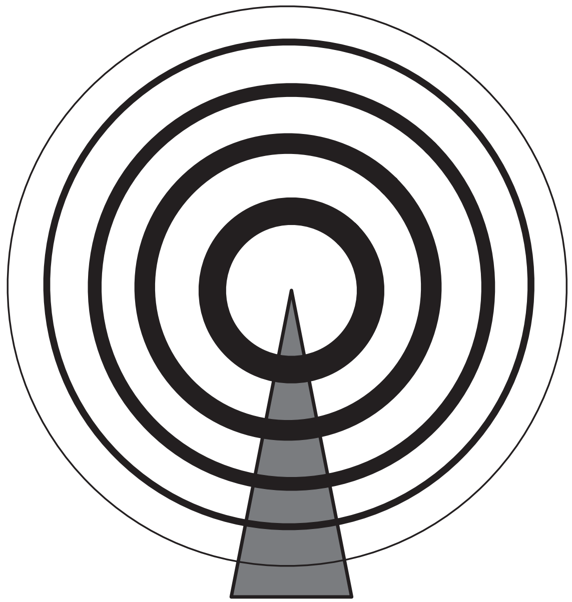
Properties of Wireless Communications

While traveling through the environment (we talk about *wave propagation*), the electromagnetic wave experiences multiple distortions:

- Attenuation
- Reflection/Refraction
- Diffraction/Distortion
- Doppler Effect

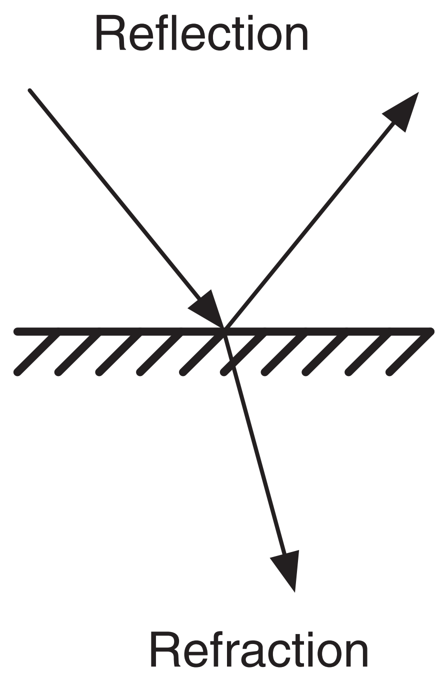
Attenuation

This process spreads the energy of the wave to larger space. It is similar to a balloon, which is a dark red color before filling it with air, but then becomes almost transparent once filled. Thus, with growing distance from the sender, the wave becomes less and less powerful and harder to detect



Reflection / Refraction

This process changes the direction of the wave when it meets a surface. Part of the wave gets reflected and travels a new trajectory, another part of the wave gets refracted into the material and changes its properties. Both processes create new, secondary waves, which also reach the receiver at some point in time, slightly after the primary wave.



Diffraction / Scattering

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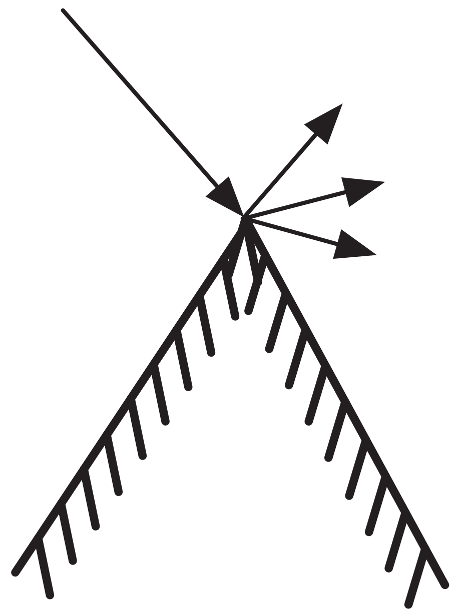
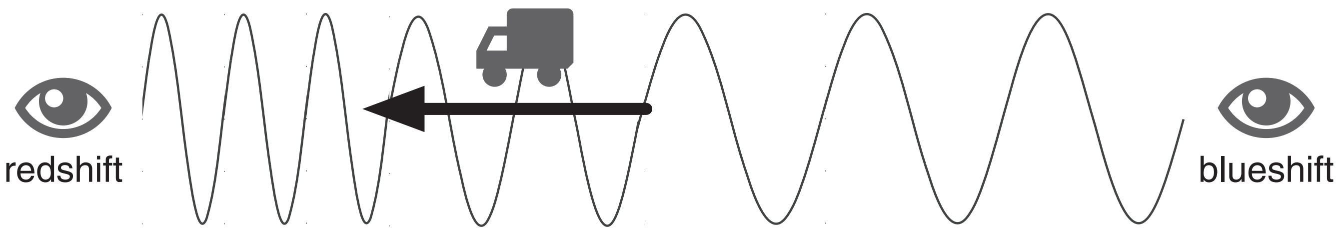
Sharp edges and uneven surfaces in the environment can break the wave into several secondary waves



Doppler Effect

The frequency of the signal changes with its relative velocity to the receiver. The Doppler effect is well known for its impact on the police siren, which sounds different to the observer depending on whether the police car is approaching or moving away. The same happens with the radio waves when their frequencies get shifted in one or the other direction which results in a loss of center.



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Path Loss

All these properties lead to:

Path loss *is the reduction in power density of an electromagnetic wave as it propagates through space.*

Interference

> ***Electromagnetic interference*** *is the disturbance of an electromagnetic signal due to an external source. It is typically measured with the signal-to-interference ratio (SIR) or with signal-to-noise plus interference ratio (SNIR).*

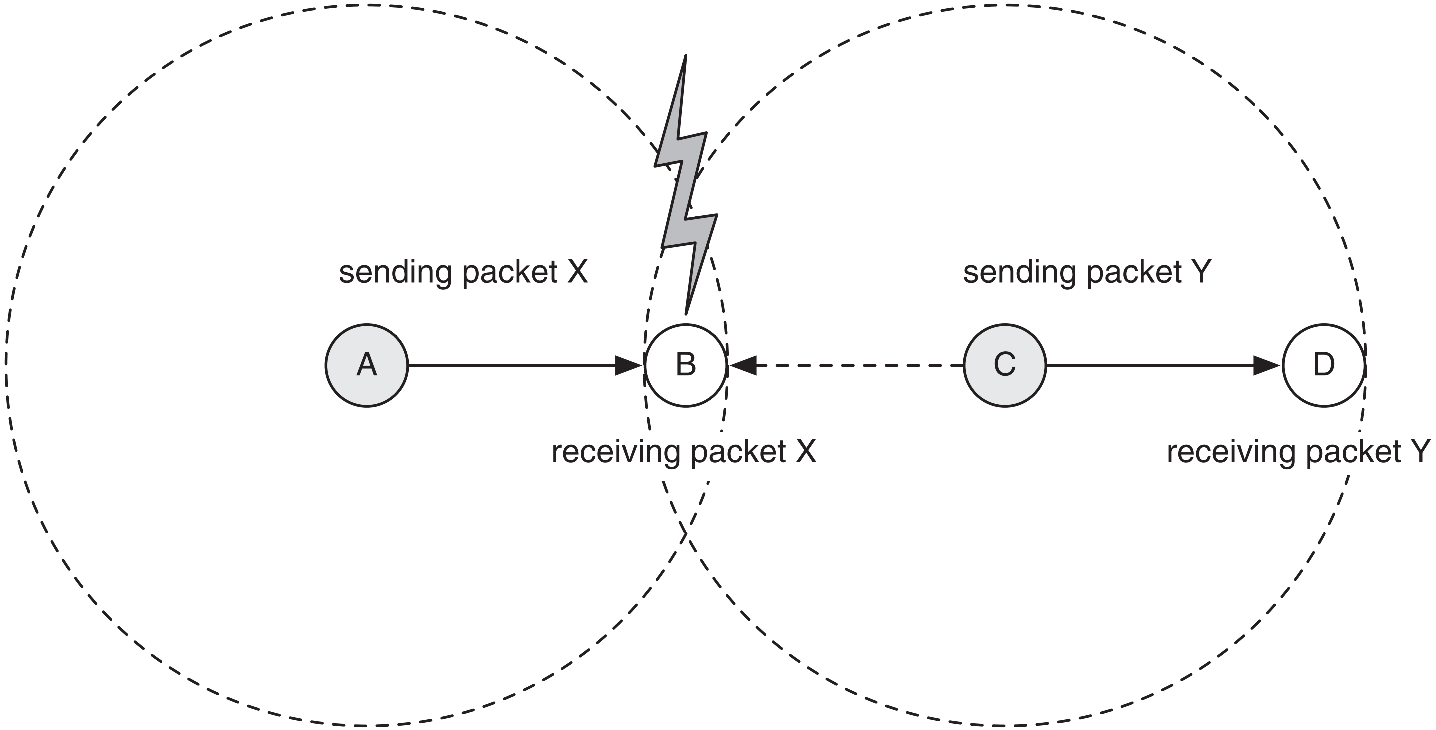
Caused by:

- Other sensor networks
- Bluetooth
- WiFi
- Microwaves, etc.

Noise

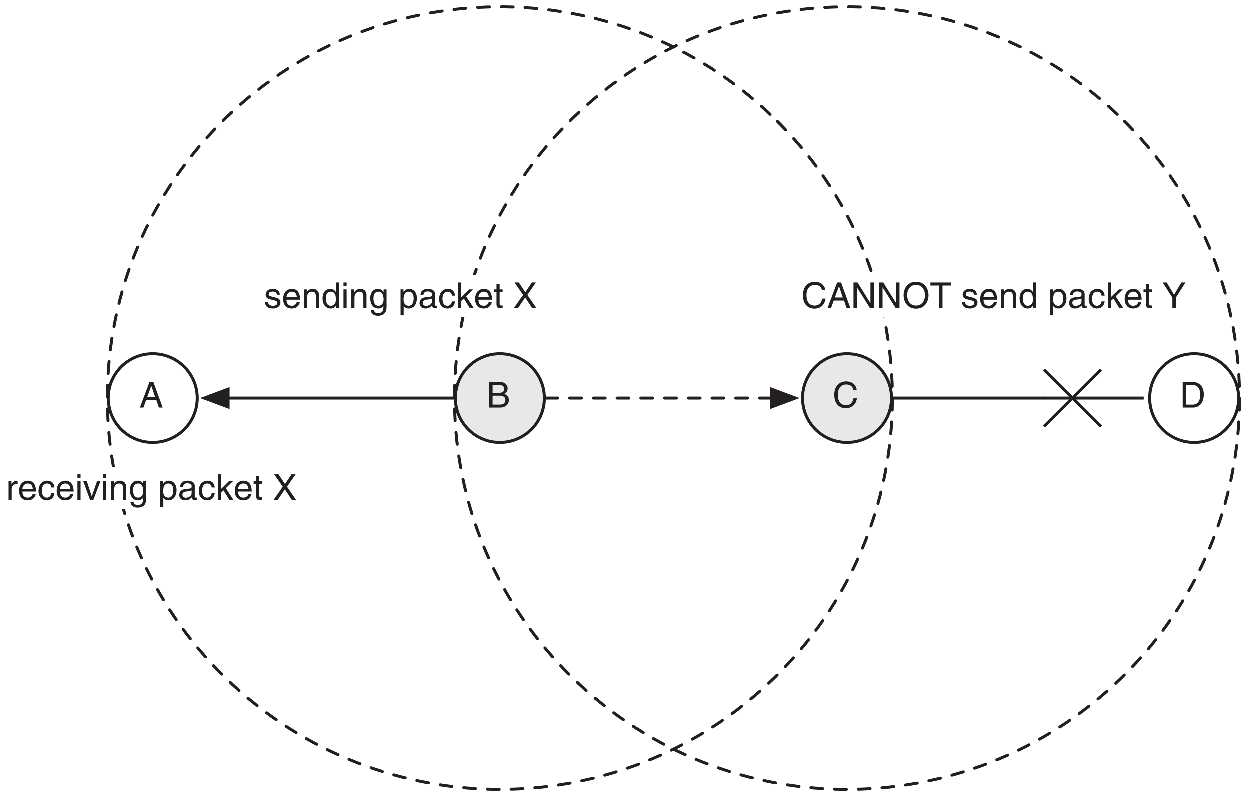
Electromagnetic noise *is the unwanted fluctuation of a signal or energy from natural sources such as the sun. It is generally distinguished from interference or from systematic alteration of the signal such as in the Doppler Effect. It is typically measured with signal-to-noise ratio (SNR) to identify the strength of the useful signal compared to the overall environmental noise.*

Hidden Terminal Problem



Collision at Node B! A is hidden from C.

Exposed Terminal Problem



B and C could send their data simultaneously, but believe to interfere with each other.

Medium Access Protocol (MAC)

- The role of Medium Access Protocols is to regulate the access of the sensor nodes to
the shared wireless medium, this is, to the "air"
- Metrics used to optimize its behavior:
  - **Throughput**: *number of bits or bytes successfully transmitted per time unit*
  - **Delay**: *amount of time between sending a packet and receiving the packet*
- The main goal of medium access protocols is to *prevent* interference and corrupted packets, while *maximizing* the throughput of the wireless medium and *minimizing* the energy spent.

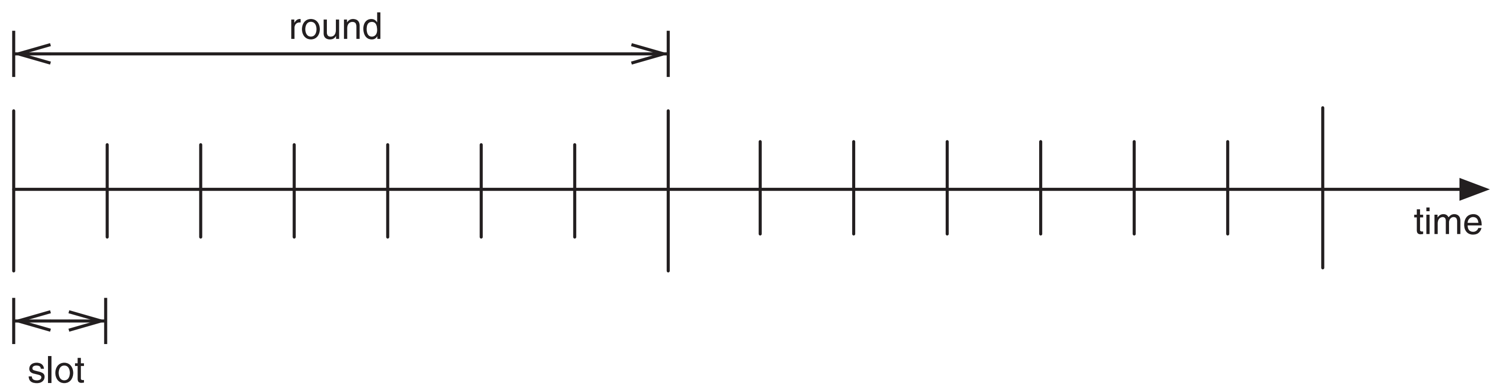
Design Criteria for MAC Protocols

- Minimize Collisions
- Minimize Overhearing
- Minimize Idle Listening
- Minimize Overhead

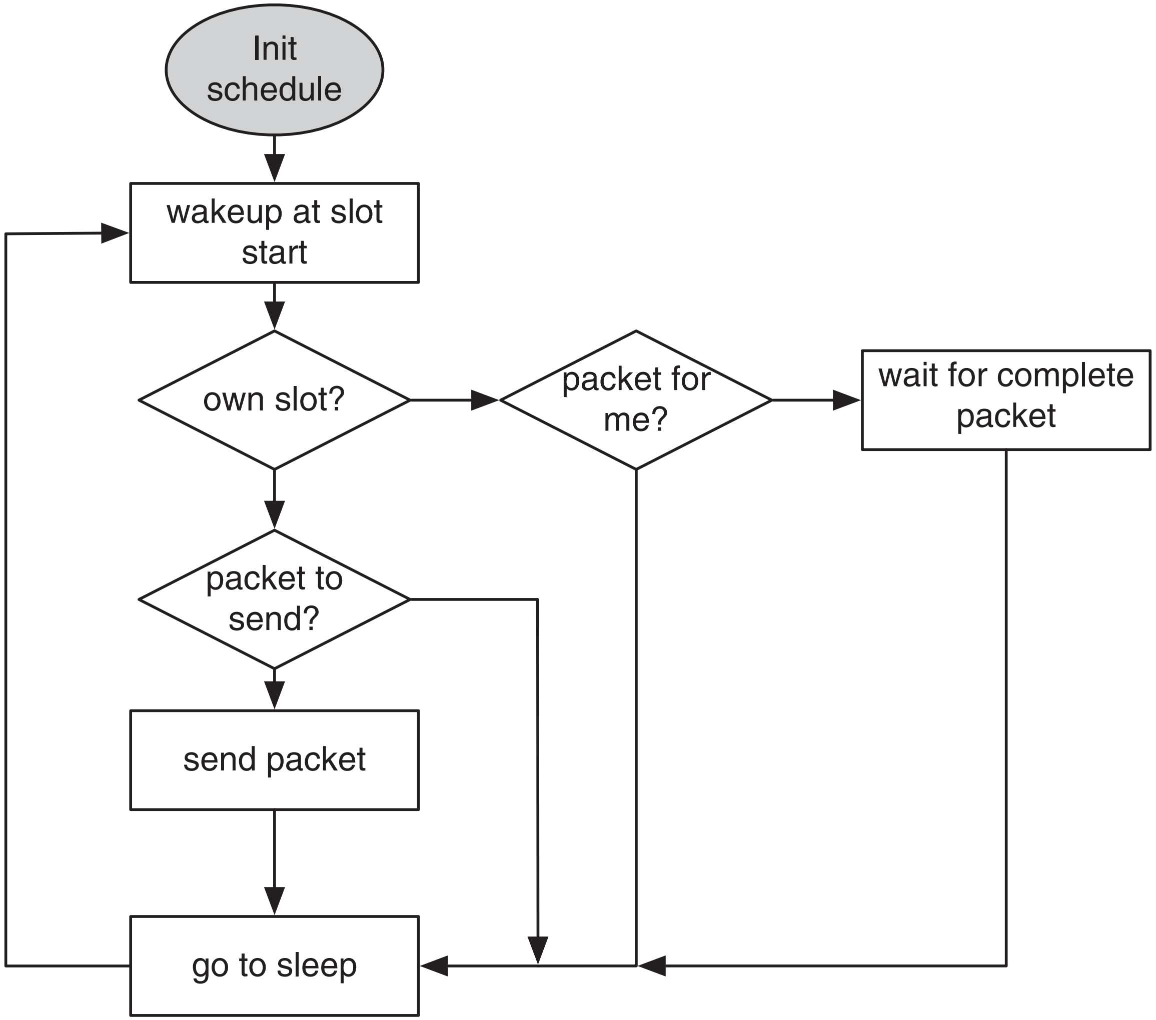
No single optimal solution, always a tradeoff!

Time Division Multiple Access (TDMA)

- Organize communications in a network is by time
- Divide the time available across the nodes into slots and give the nodes full control over their slots



General TDMA Algorithm



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Centralized TDMA

- Schedule is calculated offline:
  - If no information about topology is known, then reserve N slots for N nodes.
    - PRO: simple and robust
    - CON: slow
  - With additional information available, reuse as many slots as possible to minimize duration of rounds.
    - PRO: faster
    - CON: very sensitive to changes in the network
- Provided to sensor nodes at startup

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Distributed TDMA

- Nodes attempt to find a good schedule by cooperation
- Start by competing for access (all together)
- Exchange neighbor information in terms of link quality
- Compete for the slots by trying to reserve them then release them again if interference occurs
- PRO: Efficient and does not need a central decision point
- CON: Initialization long and needs to be repeated in case of changes

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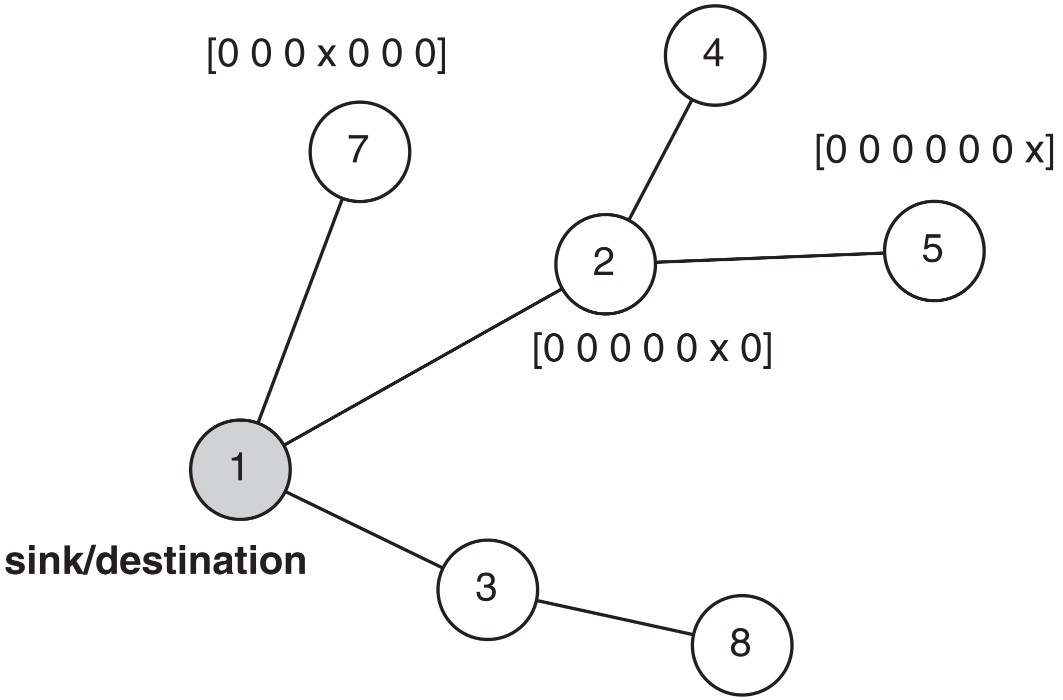
Discussion of TDMA

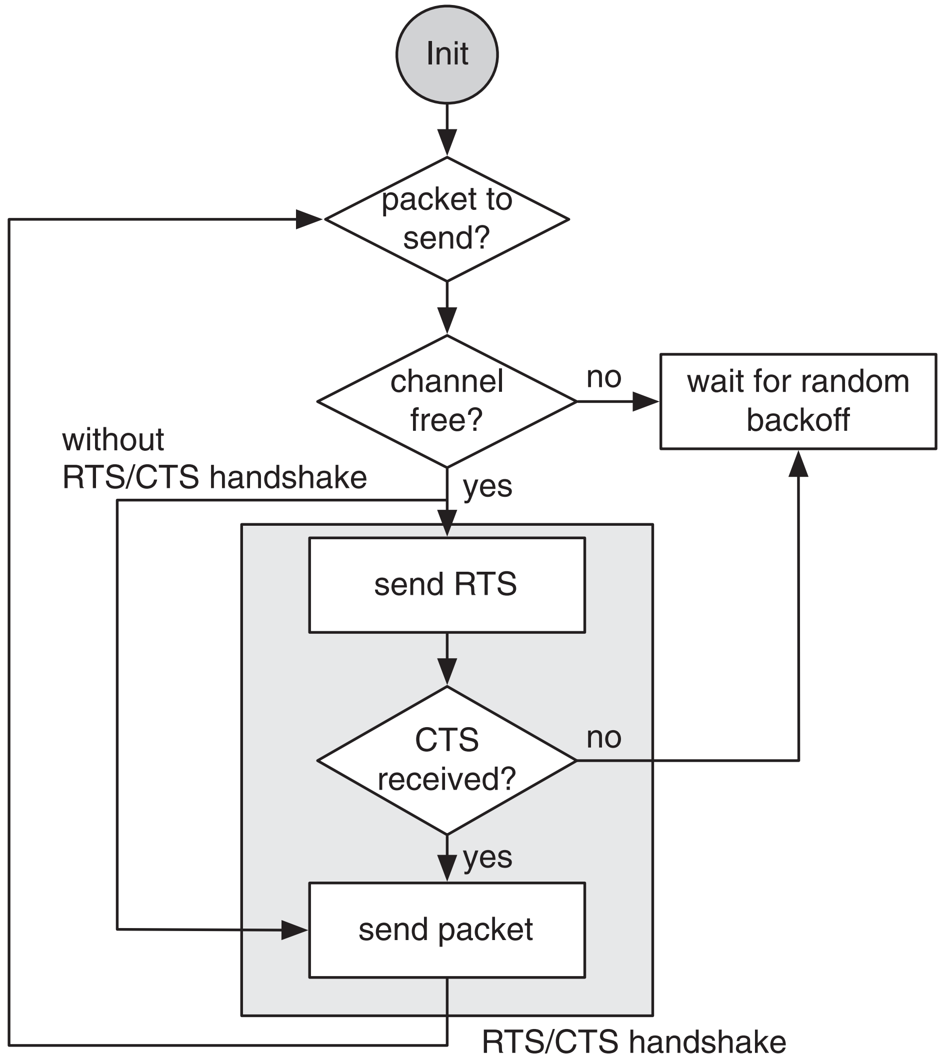
- Not efficient in case of very low traffic
- Nodes with more traffic do not get more slots
- In multi-hop networks, TDMA schedule affects greatly end-to-end delay:



Carrier Sense Multiple Access (CSMA)

- "Listen before Talk"
- Listen to channel first
- If free, send
- If not, re-try later
- Two main variants:
  - CSMA-CA: with collision avoidance (used more often)
  - CSMA-CD: with collision detection

CSMA-CA General Algorithm



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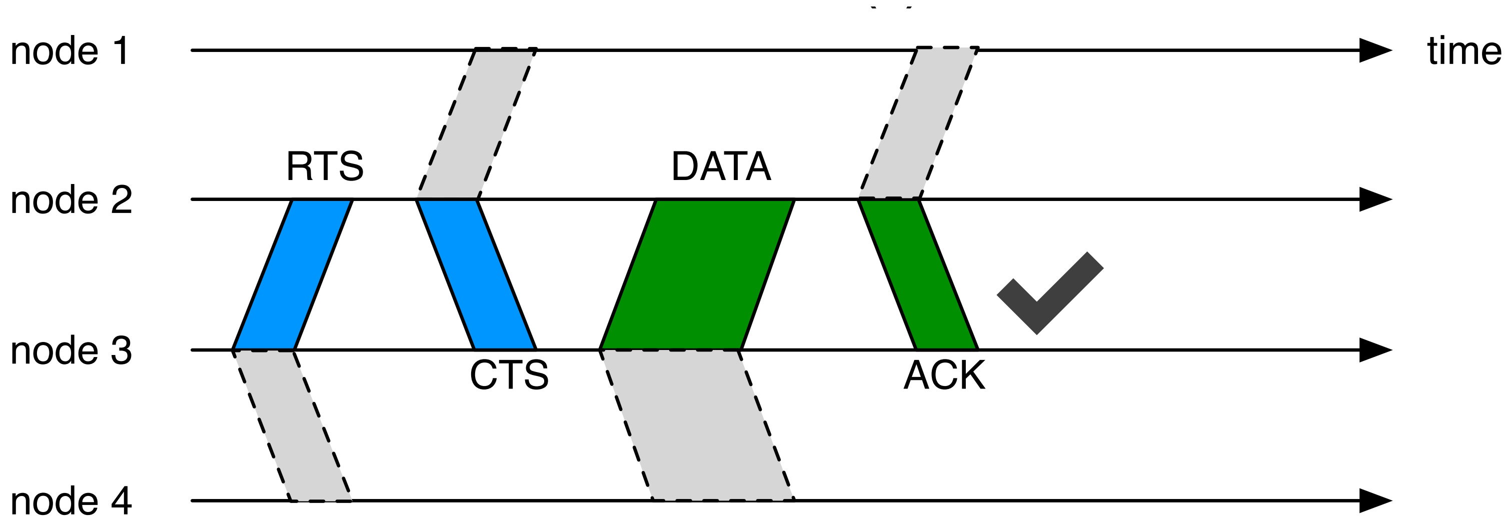
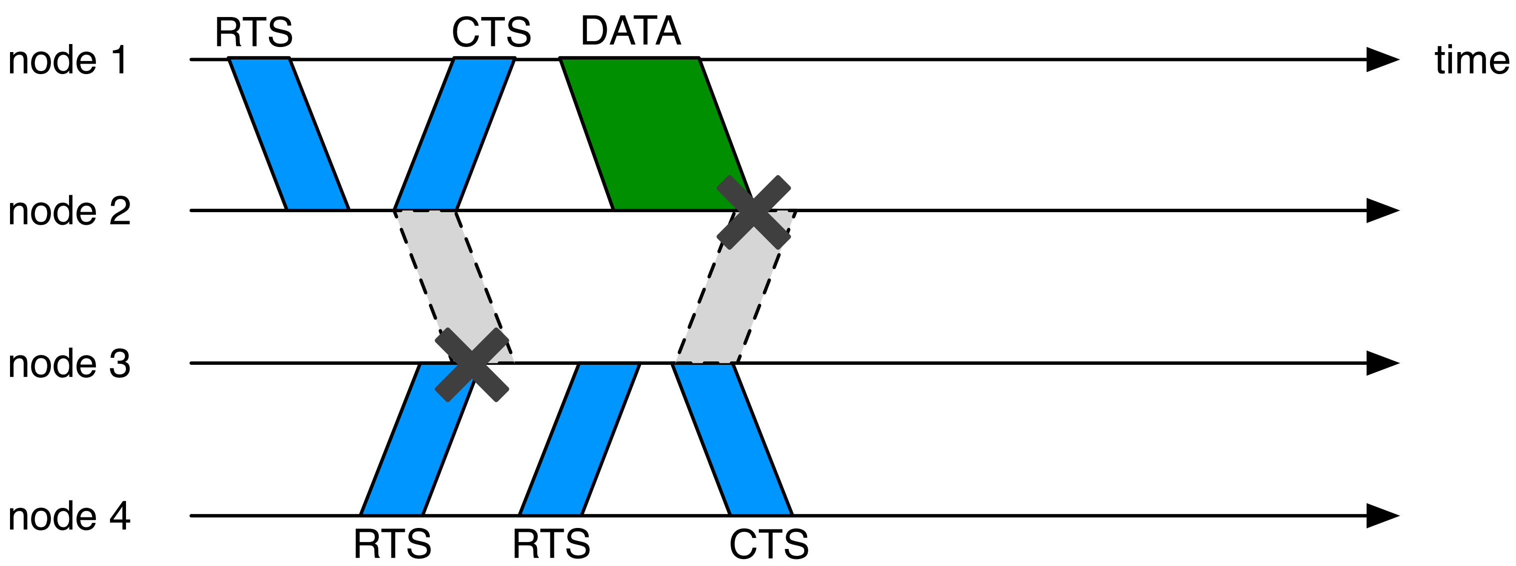
RTS/CTS Handshake

- Ready-to-send, clear-to-send short messages
- Designed to avoid the hidden terminal problem



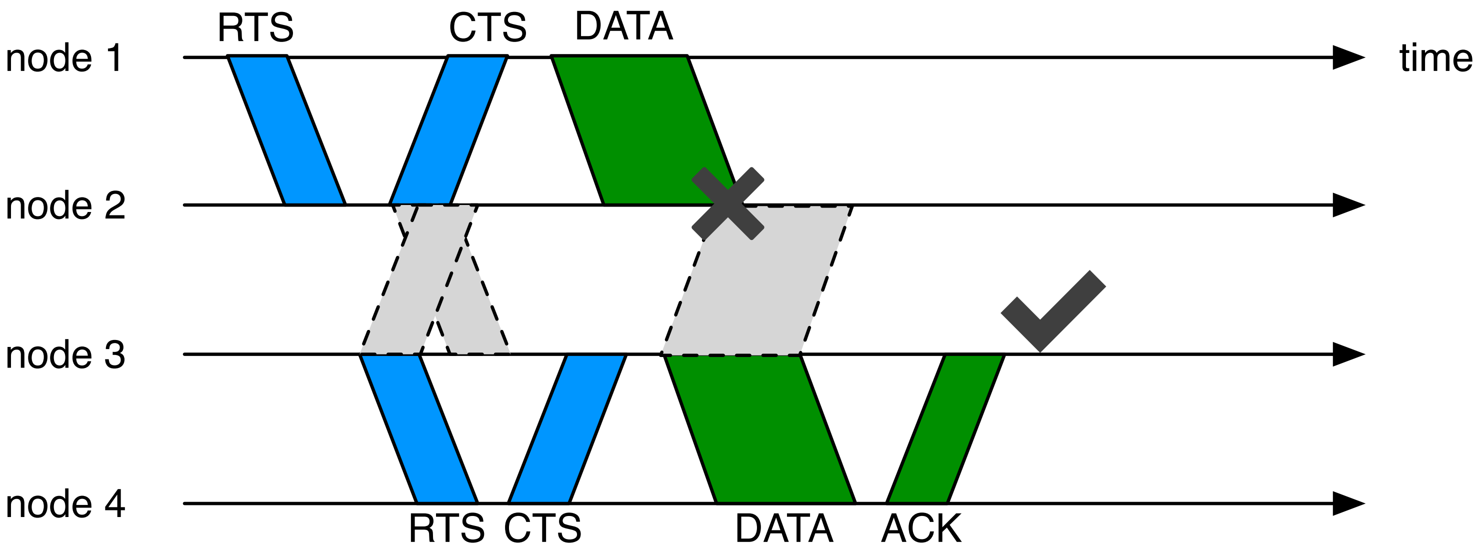
RTS/CTS in Hidden Terminal

- Successfully solves the problem:



RTS/CTS - Problems

- Another problematic case:



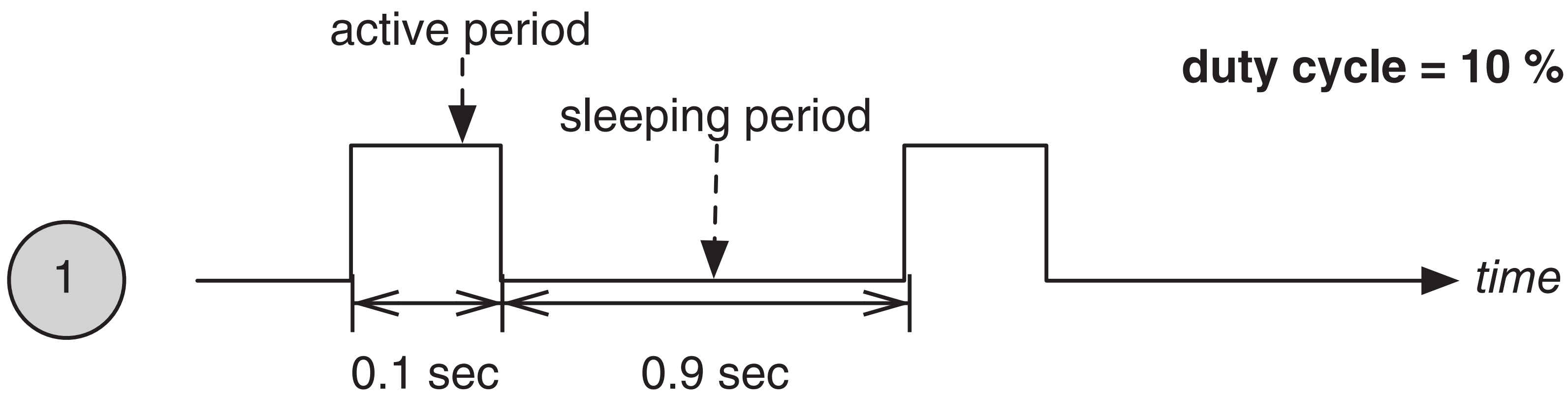
Variants of CSMA

- 1-persistent CSMA
- Non persistent CSMA
- P-persistent CSMA (implemented in IEEE802.15.4, lower layer of Zigbee)
- O-persistent CSMA

Sensor Node Duty Cycle

Duty cycle *is the relation between the length of the active and sleeping cycles of a sensor node and is measured in percent. It is defined as:*

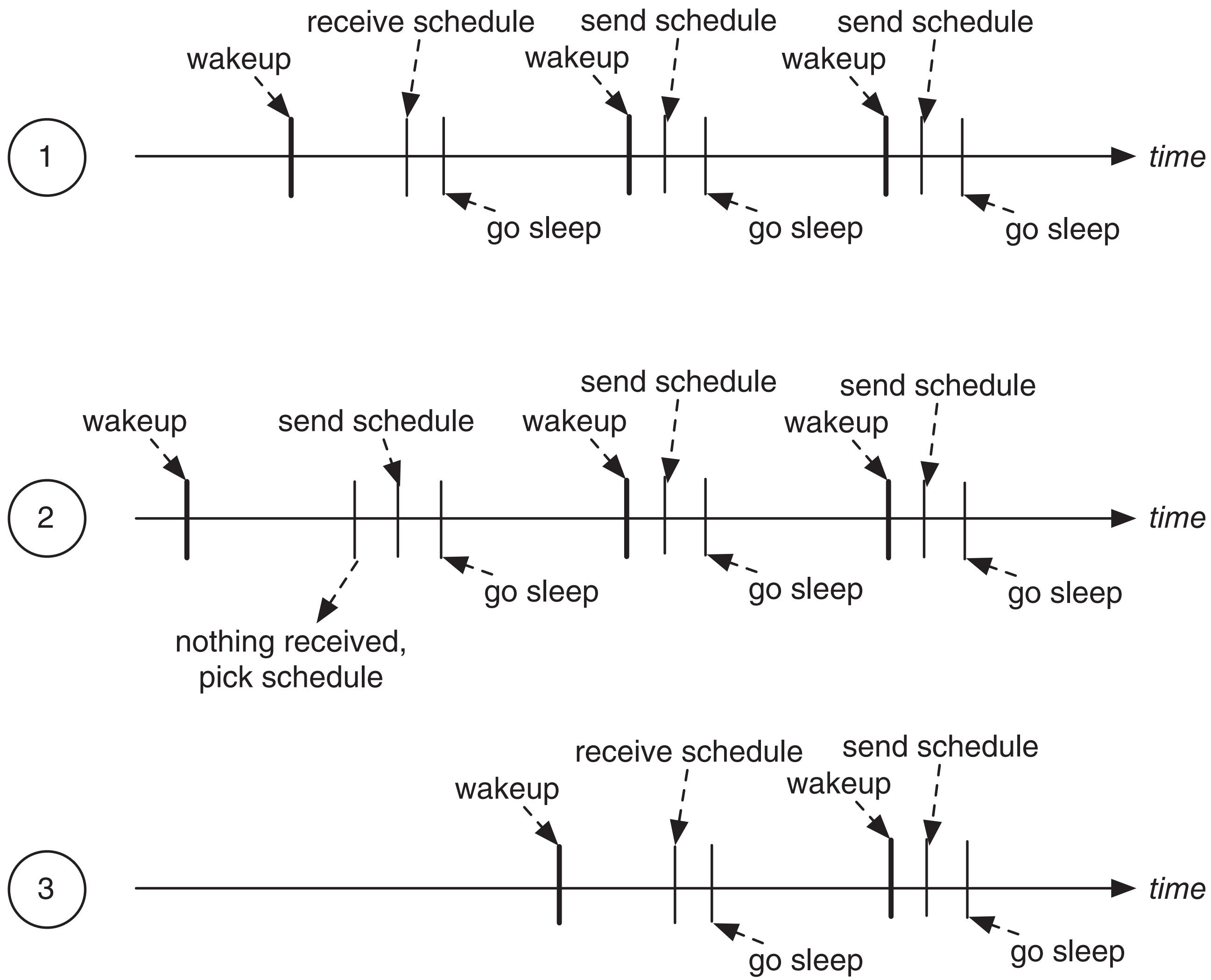
$$duty\_cycle = \frac{time\_active}{period}$$



Sensor MAC (S-MAC)

- Especially designed to enable low duty cycles
- Nodes communicate only during their active cycles
- How to synchronize the nodes’ active cycles?
  - At startup, a node listens first to receive a schedule from a neighbor
  - If none received, start your own schedule
  - Every active cycle, send your own schedule
- Results in **synchronized islands**, where **bridge nodes** need more power to support two schedules
- Needs a time synchronization protocol (Chapter 7)

S-MAC General Scenario



Timeout MAC (T-MAC)

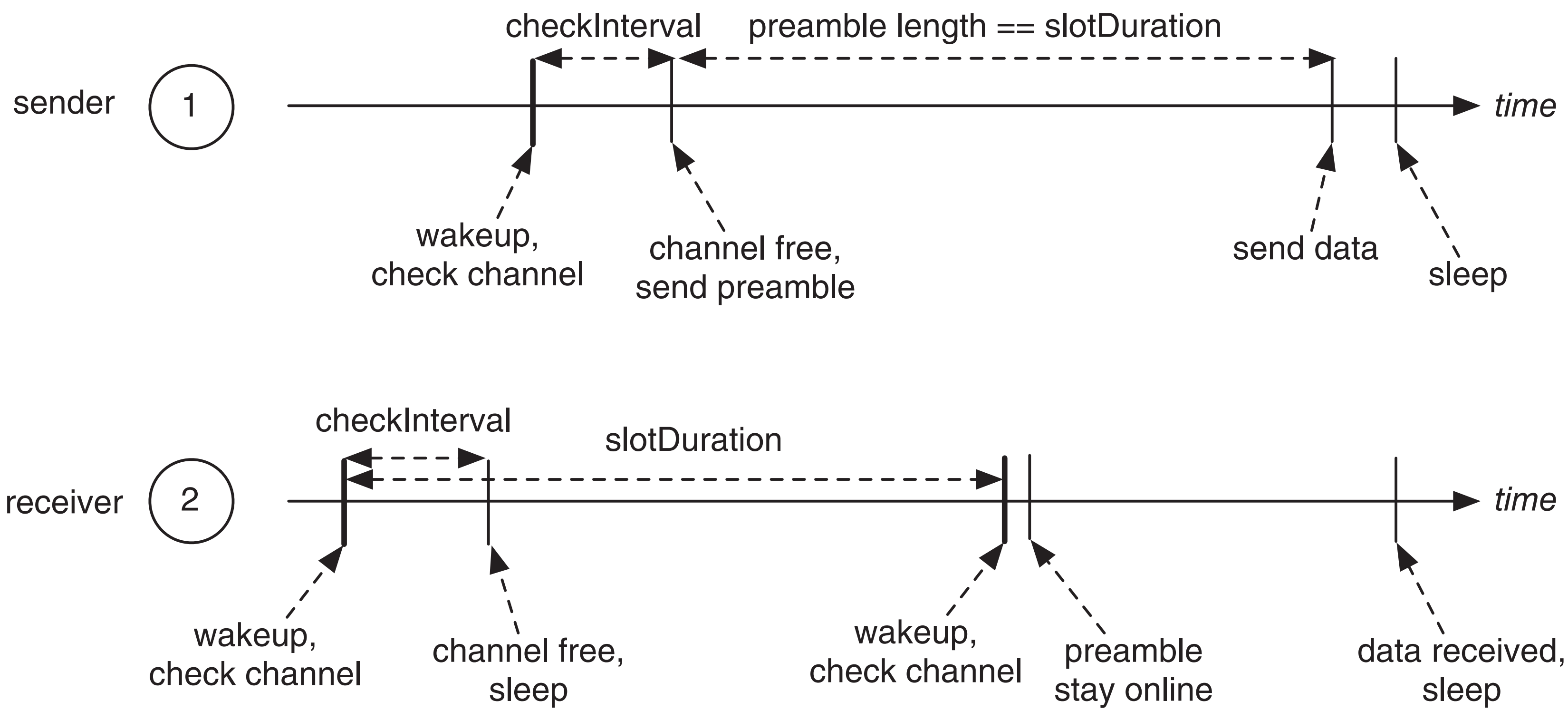
- S-MAC wastes a lot of energy with very low traffic, as the nodes stay awake during the complete active cycle
- Timeout-MAC solves this problem:
  - At active cycle and no traffic, go back to sleep.

Berkeley MAC (B-MAC)

- Tackles the problems of S-MAC
- Does not need time synchronization
- Solution: Long preambles

A preamble is a special communication message of varying lengths, which does not carry any application data or other payloads. Instead, it signals to neighbors that a real message is waiting for transmission. The preamble can carry sender, receiver, and packet size information or other administrative data to simplify the communication process.

B-MAC General Scenario



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Optimizations of B-MAC

- X-MAC: Interrupt the preamble sender, when the receiver is awake
  - Minimize the idling time of sender and receiver
  - Only for unicast transmissions
- Box-MAC: Considered an implementation of X-MAC with clearly defined parameters
- Tackle broadcast transmissions:
  - Avoid the preamble sending, send repeatedly the data itself
  - Inform the receivers when the data will be send, so they can go to sleep

IEEE 802.15.4

- CSMA-CA based protocols
- Operates on free-license channels
  - 868/915 MHz
  - 2450 MHz
- S-MAC, B-MAC, X-MAC work on top of it
- Basis for many standards:
  - Zigbee
  - WirelessHART
  - ISA100
  - and many more

Summary (1)

Main properties of wireless communications:

- They are an error-prone process whose properties and quality fluctuates significantly with environment, distance, and time.
- Interference between different nodes and other technologies greatly impact the quality of links.

A MAC protocol needs to enable the following properties:

- Collision-free communication.
- Minimal overhearing of packets not destined to the node.
- Minimal idling when no packets are arriving.
- Minimal overhead and energy for organizing the transmissions.
- Minimal delay and maximum throughput of packets.

Summary (2)

There are several general approaches you can take:

- *Time division multiple access* (TDMA) refers to a mechanism in which each node gets full control for some predefined amount of time (a slot). This is collision-free, but it suffers from large delays.
- *Carrier Sense Multiple Access* (CSMA) refers to “first listen, then talk.” While the delay is low, the energy expenditure is high (the nodes never sleep) and it is not collision-free.
- *Duty cycling* is the preferred way of organizing the sleep and awake cycles of sensor nodes. Sensor MAC, Berkeley MAC, and BoX MAC all work with duty cycling and are able to save considerable amounts of energy.
- *BoX MAC* is based on B-MAC, but offers optimized communications for both unicast and broadcast transmissions, and is currently the preferred MAC protocol for sensor nodes. It does not need synchronization, has low delay, and low energy expenditure.

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