Medium Access Control in Wireless IoT

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LIVELLO DATALINK

Goals

- Reliable and efficient communication between two nodes on the same physical medium
  - Cable (Wired)
  - Wireless
- Assumptions from the lower physical layer:
  - The concept of *bit* is defined
  - Bits, if received, arrive in the same order in which they have been transmitted

Functionality

- *Framing* = Bit grouping into layer-2 PDUs
- Error checking
- Ack and retransmission of corrupted/lost PDUs (not in all protocols)
- Policy of use of the channel if more than 2 nodes share the same physical medium
  - Node addressing
  - Channel arbitration

Services provided to the upper network layer

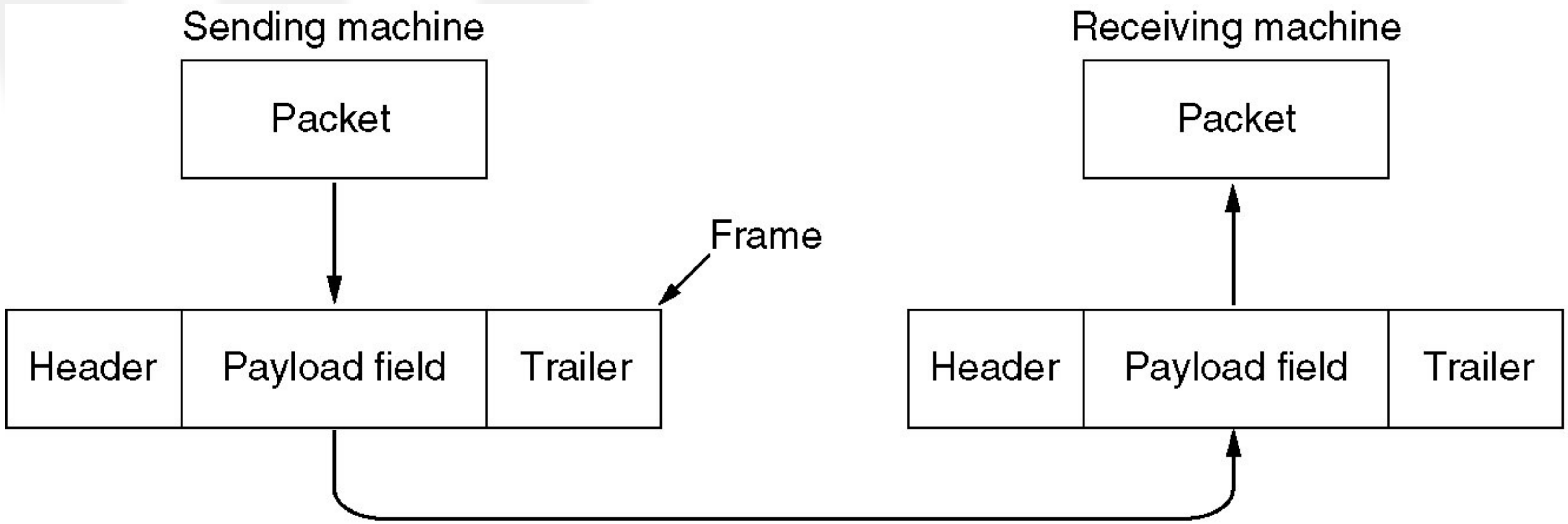
- Un-acknowledged connection-less service (e.g. Ethernet/IEEE802.3)
- Acknowledged connection-less service (e.g. WiFi/IEEE802.11, IEEE802.15.4)
- Connection-oriented service (e.g. IEEE802.16)

- REMARK: the connection-oriented service is also acknowledged and furthermore it provides flow control

Framing

- Improve channel utilisation in case of more than two nodes sharing it
- Requested to check errors and recover PDUs
  - Error detection must be performed on blocks of bits (e.g. CRC)
  - The corrupted PDU can be retransmitted
- Issue: definition of start/end of frame

Framing



Sending machine
Packet
Frame
Header
Payload field
Trailer
Receiving machine
Packet
Header
Payload field
Trailer

Start/end of frame

- We need to use symbols which are not used to send data otherwise a sequence of data bits could be considered erroneously a start/end of frame
  - Physical signal configurations which are not used for data bits
    - Specific configuration choices can improve bit synchronization between TX and RX
  - Particular sequence of data bit values (FLAG)
    - Bit stuffing/de-stuffing is needed to avoid FLAG simulation in the PDU
  - Inter-packet gap minimum between 2 consecutive frames

Bit stuffing/de-stuffing

- Example taken from HDLC protocol
- Byte 01111110 is used as FLAG at the beginning/end of each frame
- The bits of the original frame are modified through *stuffing*
  - After five "1"s a "0" is automatically inserted
- At the receiver the Data Link layer operates de-stuffing

Bit stuffing: example

(a) 0 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 1 0

(b) 0 1 1 0 1 1 1 1 1 0 1 1 1 1 1 0 1 1 1 1 1 0 1 0 0 1 0

Stuffed bits

(c) 0 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 1 0

a) Original data from upper layer
b) Data transmitted on the wire or over-the -air
c) Data at the receiver after de-stuffing.

Error detection

- Some bits may have incorrect values at the RX
  - Interference, low-level signal
  - Often errors are not isolated but group into *burst*
- Hamming distance
- Redundant information must be added to the message to check errors
  - m bits of the original message
  - r bits of the code for error detection
  - n=m+r bits transmitted on the channel
  - Code rate = m/n
- Examples
  - Parity Bit
  - Checksum
  - Circular Redundancy Check (CRC)

Parity bit

- At the TX a bit is appended to the message
  - “1” if the amount of “1” in the message is even
  - “0” if the amount of “1” in the message is odd
- At the RX if the amount of “1” is even then at least one bit flipped its values
  - One bit or an odd number of bits (we cannot distinguish)
  - Errors affecting an even number of bits are not detected

Check sum

- Extension of the concept of parity bit
- The message is decomposed into *r* bit words
- The words are summed and overflow is not taken into account
- The sum (another r-bit word) is appended to the message
- The sum is recomputed at the RX
  - If it is different from the appended value an error occurred
- Errors are not detected if they affect different bits that do not change the sum

Circular Redundancy Check (CRC)

- The message is seen as the coefficients vector of a polynomy $M(x)$ having degree $m-1$
- Let $R(x)$ be the remainder of the polinomial division $x^rM(x)/G(x)$ where $G(x)$ is named *generating polynomy*
- By construction the polynomy $x^rM(x)-R(x)$ is exactly divided by $G(x)$ and it is transmitted on the channel ($m+r$ bit)
- At RX if the received sequence of bits is exactly divided by $G(x)$ then it is considered correct

Channel access methods

channel

Point-to-point (e.g. serial cable)

Point-Point Protocol

Shared (bus, wireless)

Random access

CSMA/CD,

CSMA/CA

Controlled access

Polling, token

Multiplexing

TDMA, FDMA,

WDMA, CDMA

Point-to-point channel access

- In a point-to-point channel the arbitration is trivial since there are always two nodes

Limit of the point-to-point architecture

- In case of *N* nodes the number of point-to-point channels is $N(N-1)$ with a quadratic cost increase
- A shared channel is needed

Access in case of shared channel

- Random access: the node which wants to transmit must wait for the channel to be free (carrier sense)
- Controlled access:
  - Polling: a master asks to each other node if it has something to transmit
  - Token: a token moves among the nodes; the node with the token can transmit for a given amount of time

Access in case of shared channel (2)

- Multiplexing: the physical channel is de-composed into logical channels used by nodes pairs as they were point-to-point channels
- De-composition methodology:
  - Radio frequency for wireless (Frequency Division Multiplexing o FDM) o light color for optical fibers (Wavelength Division Multiplexing o WDM)
  - Time interval (Time Division Multiplexing – TDM)
  - Frequency+time (Code Division Multiplexing – CDM)
    - 3G mobile and beyond

Problems in case of wireless transmission

- Interference and path loss
  - Non-negligible bit error rate
- Collision management more complex
  - Hidden node
  - Exposed Node

Interference and path loss

- More devices use the same frequency band (since it is un-licensed)
  - Other wireless nodes
  - Remote controls
  - Microwave owens
- The signal energy decreases as a function of the distance between TX and RX
- Obstacles (e.g., walls)
- Multiple reflections of the signal cause signal distorsion

Correct frame probability

- Probability to receive a correct bit

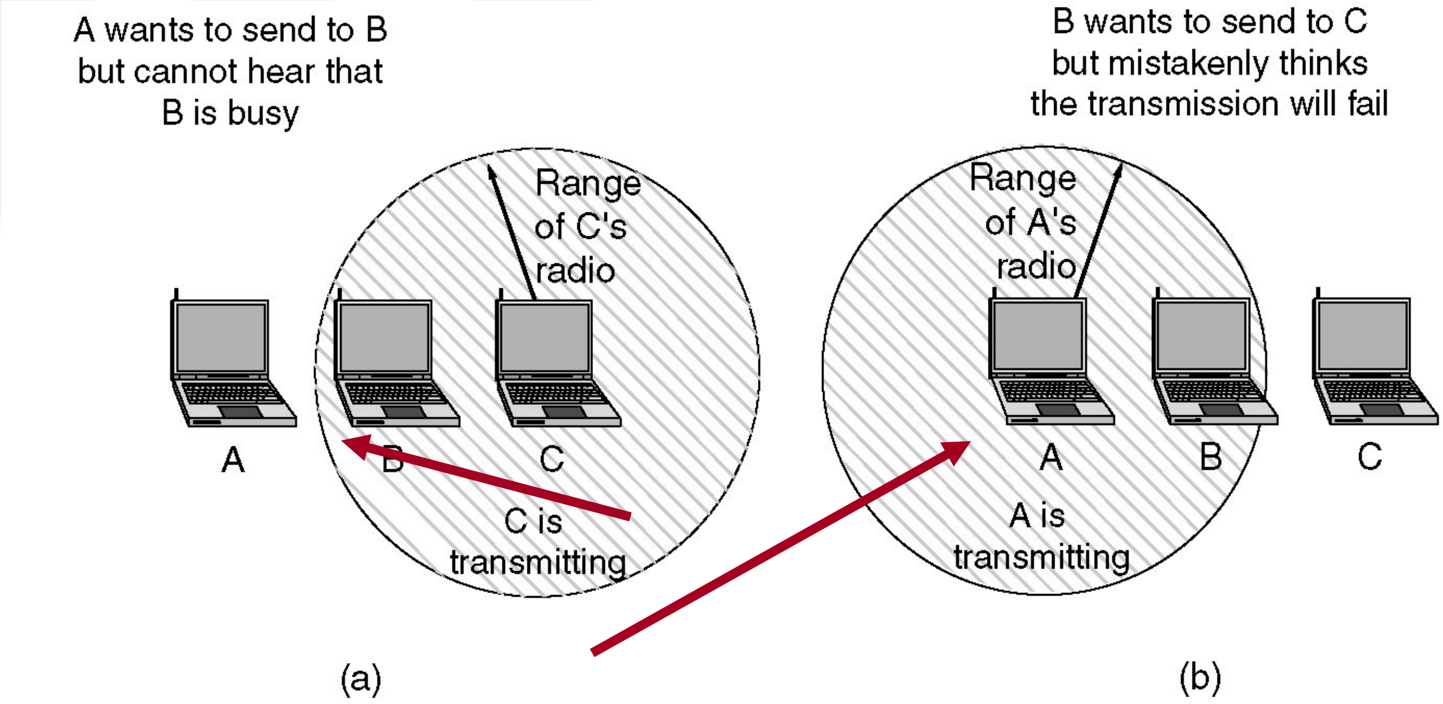
$$\left(1-P_{bit}^{error}\right)$$

- Probability to receive a PDU of length N

$$P_{ok}^{frame}=\left(1-P_{bit}^{error}\right)^{N}$$

  - E.g., N = 1518 byte =12144 bit
- Caso Ethernet $P_{bit}^{errore}=10^{-10}\Rightarrow P_{ok}^{frame}=0.9999988$
- Caso WiFi $P_{bit}^{errore}=10^{-4}\Rightarrow P_{ok}^{frame}=0.2968700$

Limits of carrier sense: Hidden node and exposed node



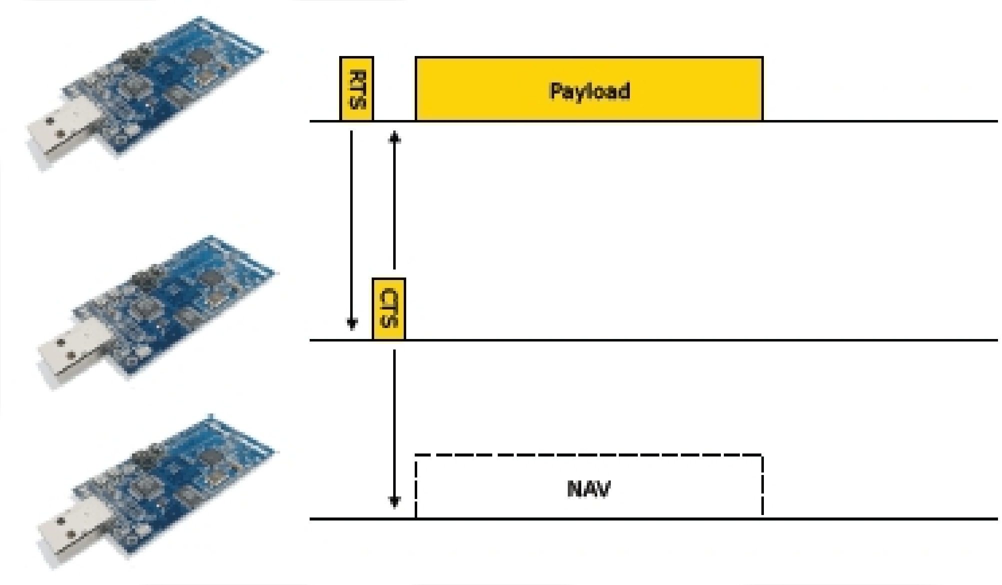
a) Hidden node
b) Exposed node

Limit of collision detection (CSMA/CD)

- Collision Detection phase of CSMA/CD is not suitable
  - A double radio interface (to send and sense concurrently) is expensive…
  - … and useless since most of the collisions happen at the receiver
- --> Collision Avoidance
- --> Stop&Wait ack

CSMA/CA

- Carrier sense
- Collision avoidance via random back-off
- [optional] RTS/CTS



MEDIUM ACCESS CONTROL FOR WSN

MAC Challenges

- Traditionally
  - Fairness
  - Latency
  - Throughput
- For Sensor Networks
  - Power efficiency
  - Scalability

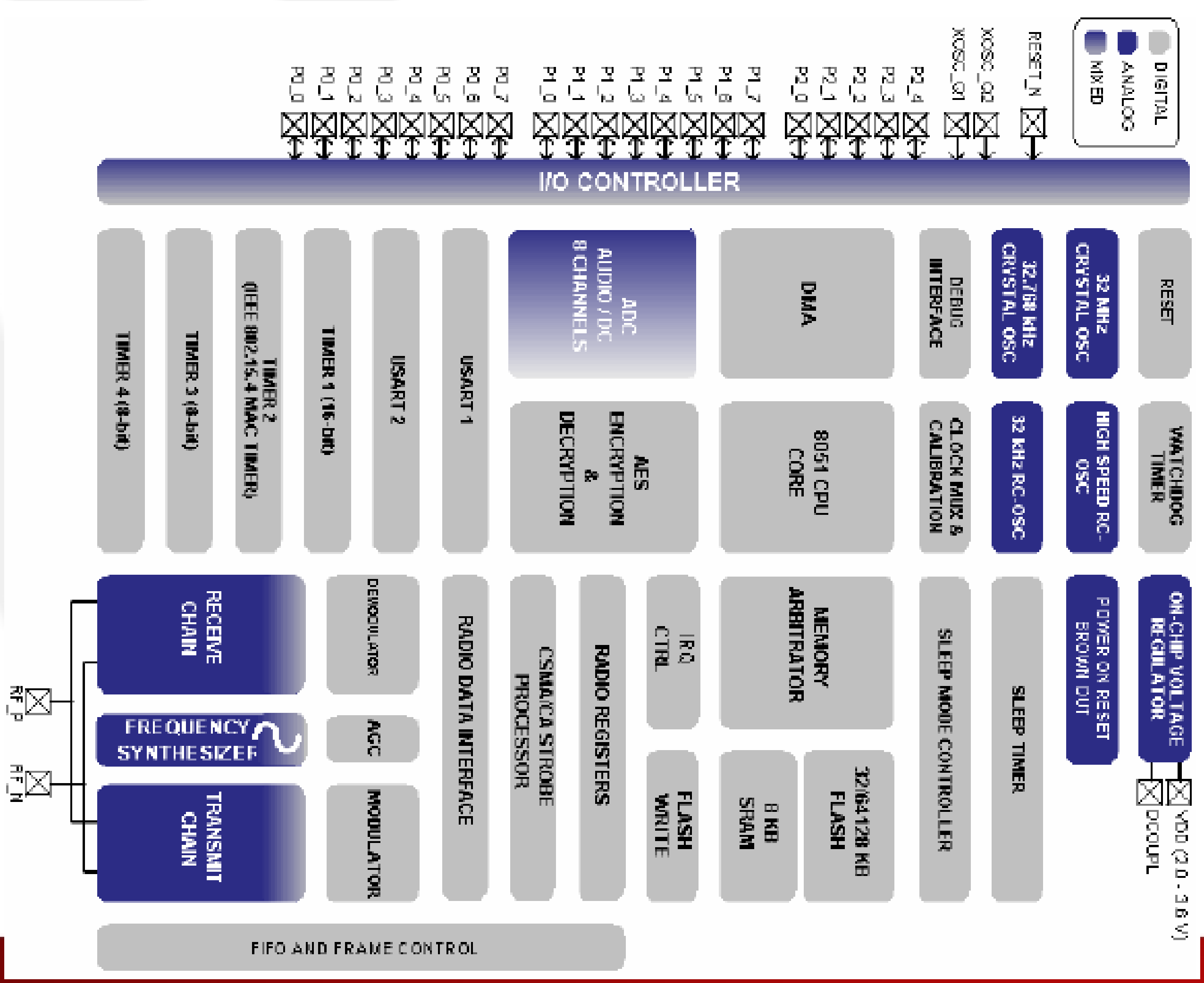
Power consumption of carrier sense

- Expected life time of many WSN applications: Months or years
- Actual lifetime
  - AA batteries: Max. 2000 mAh
  - CC2430 radio: 26.7mA in RX mode
  - 2000mAh / 26.7mA = 75 hours = 3 days

→Keep radio asleep most of the time

→Ideal duty cycle: 0.1% - 1%

Texas Instruments CC2430 architecture



Power modes in TI CC2430

MCU Active Mode, 16 MHz		4.3		mA	Digital regulator on, High frequency (16 MHz) RCOSC running. No radio, crystals, or peripherals active.
MCU Active Mode, 32 MHz		9.5		mA	MCU running at full speed (32MHz), 32MHz XOSC running. No radio or peripherals active.
MCU Active and RX Mode		26.7		mA	MCU running at full speed (32MHz), 32MHz XOSC running, radio in RX mode, -50 dBm input power. No peripherals active.
MCU Active and TX Mode, 0dBm		28.1		mA	MCU running at full speed (32MHz), 32MHz XOSC running, radio in TX mode, 0dBm output power. No peripherals active.
Power mode 1		190		µA	Digital regulator on, High frequency RCOSC and crystal oscillator off. 32.768 kHz XOSC, POR and ST active. RAM retention.
Power mode 2		0.5		µA	Digital regulator off, High frequency RCOSC and crystal oscillator off. 32.768 kHz XOSC, POR and ST active. RAM retention.
Power mode 3		0.3		µA	No clocks. RAM retention. POR active.

Time-out

Time-out

Interrupt

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Example of power-efficient MAC

- 1 s in sleep mode (power mode 2) → 0.5 µA
- 0.005 s in RX mode for carrier sense → 26.7 mA
- 0.005 s in TX mode to send packet → 28.1 mA
- Weighted current consumption
  - (0.0005*1000+26.7*5+28.1*5)/(1010) ~ 0.27 mA
- With AA batteries: 2000mAh / 0.27 mA ~ 7359 hours ~ 307 days

Sources of energy waste

- Collision
  - Retransmissions
- Idle listening
  - Continuously sense the channel
- Overhearing
  - Listen to packets addressed to other nodes
- Packet overhead
  - Header
  - Control packets (e.g., RTS/CTS)

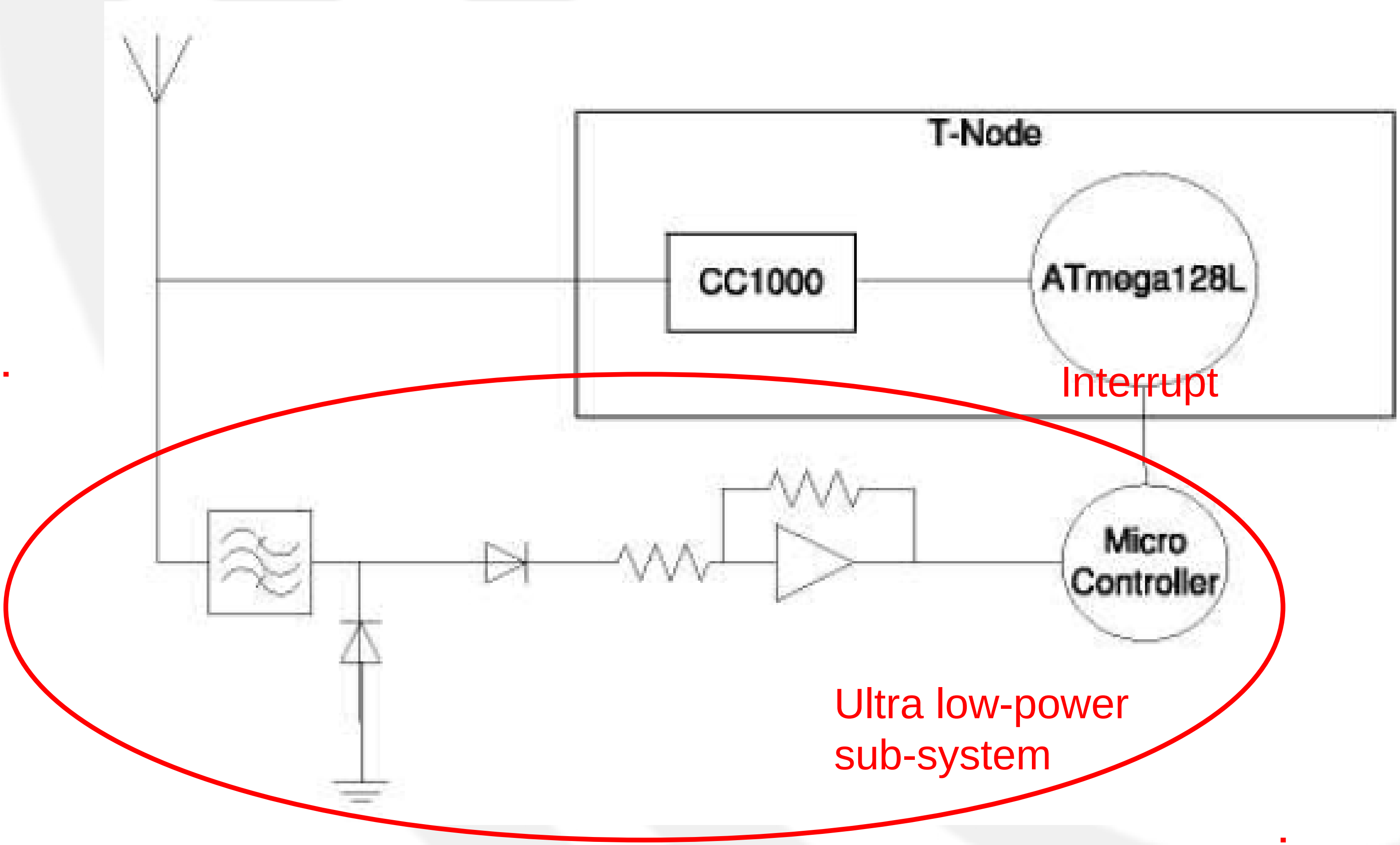
Power Save Design Alternatives

- Wake-up radio
  - A sleeping node can be woken at any time by a secondary receiver (wake-up radio)
- Asymmetric polling
- Timer-Based
  - When a node enters sleep mode, it sets a timer to wakeup at a pre-determined time
- Hybrid
  - Timer-Based plus Wake-up radio

Wake-up radio

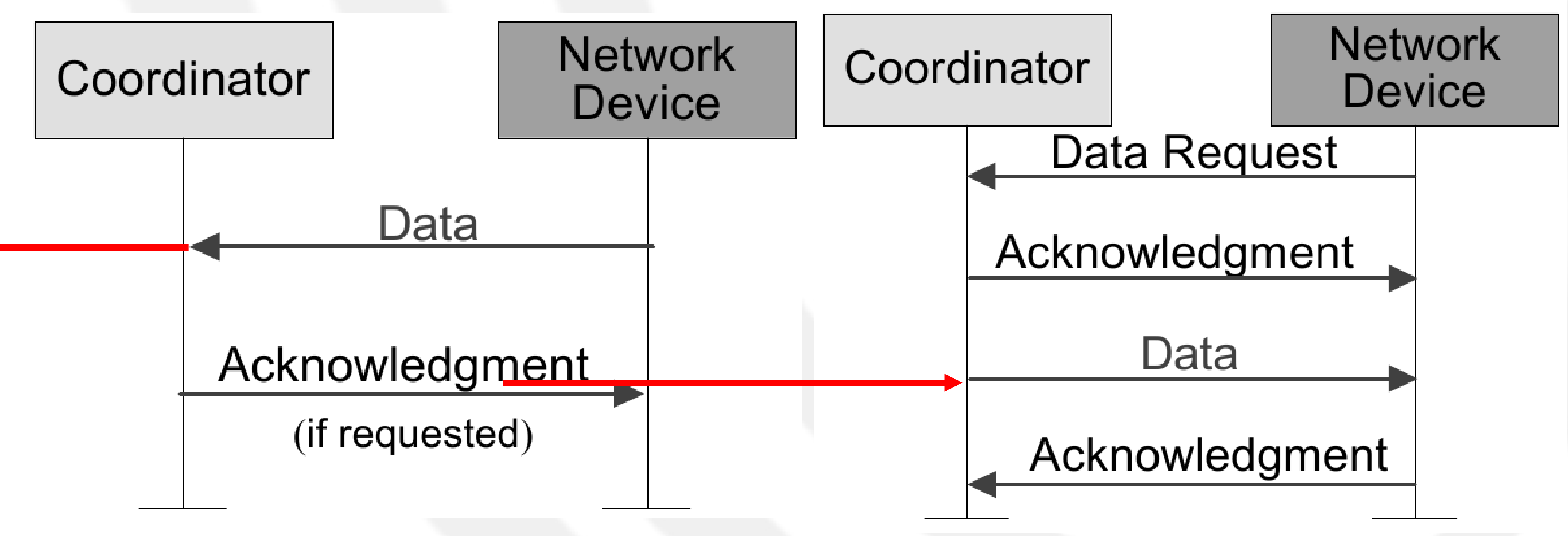
- Add second, low-power receiver to wakeup the main system on-demand
- Low-power could be achieved by:
  - Simpler hardware with a lower bit-rate and/or less decoding capability
  - Periodic listening using a radio with identical physical layer as data radio

Wake-up radio



Asymmetric polling

- Implemented in IEEE802.15.4
- Rules depend on the direction of the transfer



Timer-based MAC

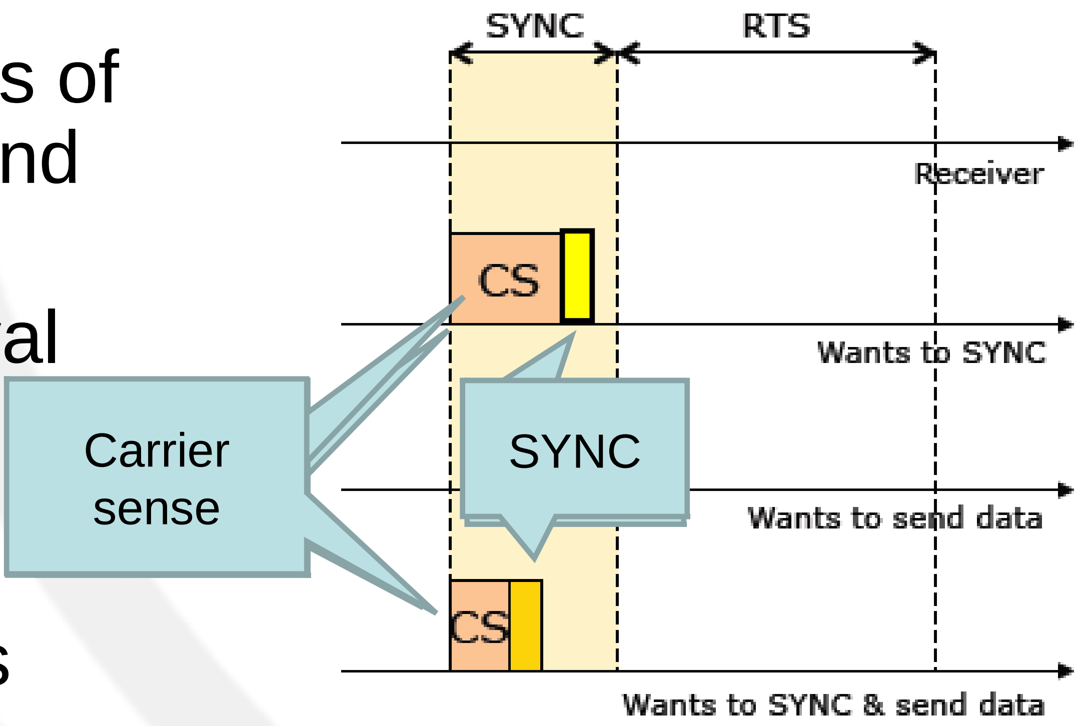
- Scheduled contention (slotted access): Nodes periodically wake up together, contend for channel, then go back to sleep
  - S-MAC
- Channel polling (random access): Nodes independently wake up to sample channel
  - B-MAC, X-MAC
- TDMA (Time Division Multiple Access): Nodes maintain a schedule that dictates when to wake up and when they are allowed to transmit
  - DRAND
- Hybrid: SCP, Z-MAC, 802.15.4 (contention access period + contention free period)

S-MAC (Sensor MAC)

- A node sleeps most of the time
- Periodically wake up for short intervals to see if any node is transmitting a packet
- Accept latency to extend lifetime

S-MAC: SYNC interval

- Listen time consists of two parts: SYNC and RTS
- In the SYNC interval some nodes periodically send SYNC packet to synchronize clocks
- They use CSMA/CA for channel contention



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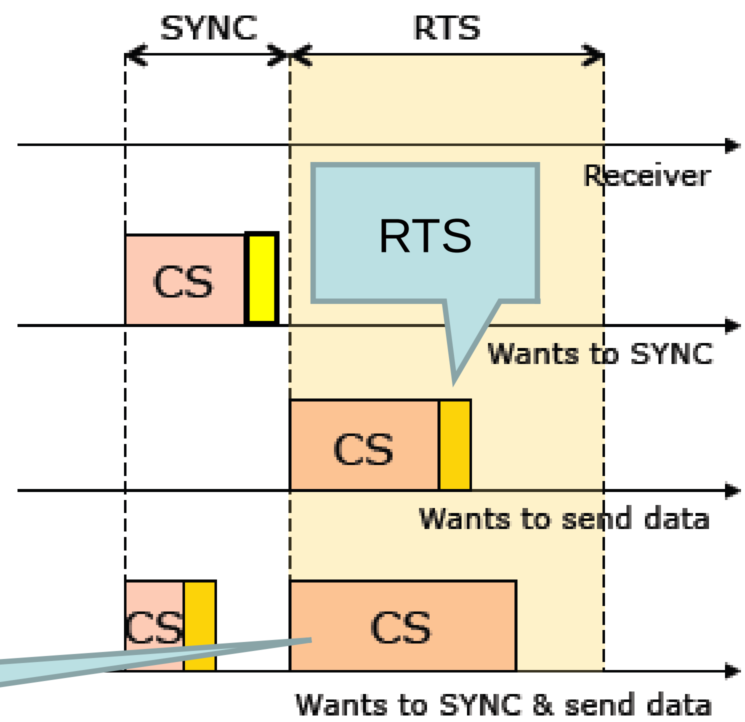
S-MAC: RTS interval

- RTS/CTS is used to transmit data
- CSMA/CA followed by RTS/CTS



It lost contention

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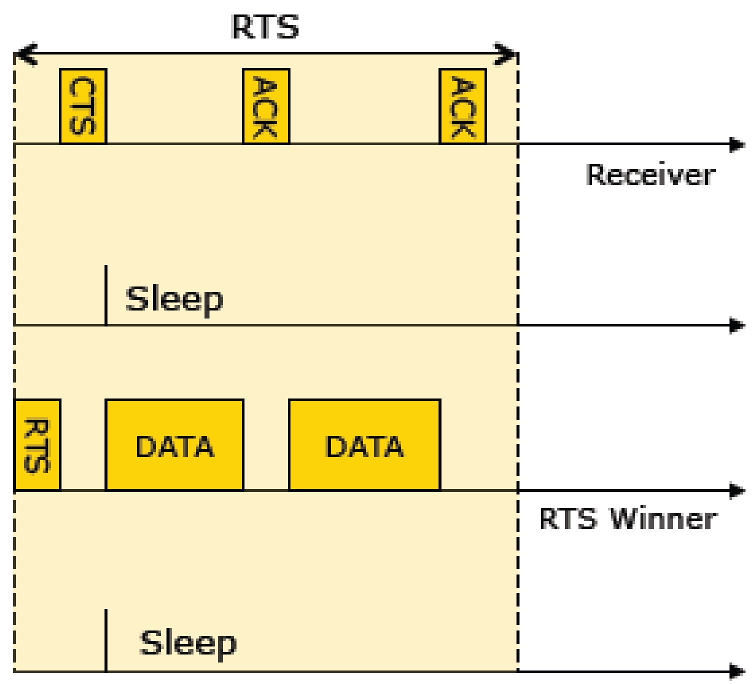
S-MAC: data transmission

- RTS/CTS contain the expected data TX time
  - Listeners not interested can sleep to save energy
- Sender does one RTS/CTS and then sends data for the rest of the frame
  - Prefer application performance to node level fairness
- ACK every data packet
  - Packet fragmentation for higher reliability



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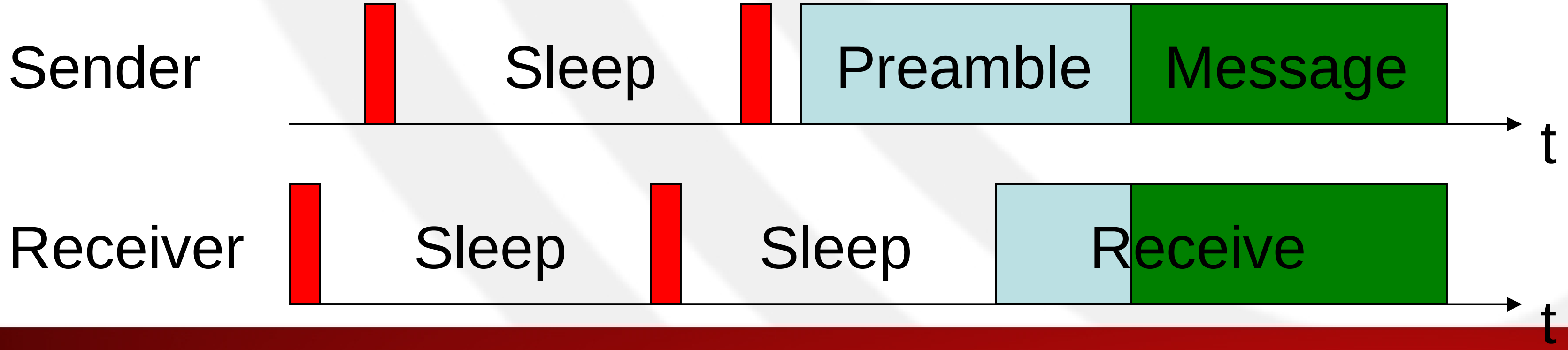
Pros and Cons of S-MAC

- More power conserving than standard CSMA/CA
- During the listening interval, everyone needs to stay awake unless someone transmits
  - Waste energy
- Time sync overhead
- RTS/CTS/ACK overhead
- Complex to be implemented

B-MAC (Berkeley MAC)

- Low Power Listening (LPL)
  - Periodic preamble sampling → Preamble > Sleep period
  - No sync between nodes
- Hidden terminal avoidance and multi-packet mechanisms not provided

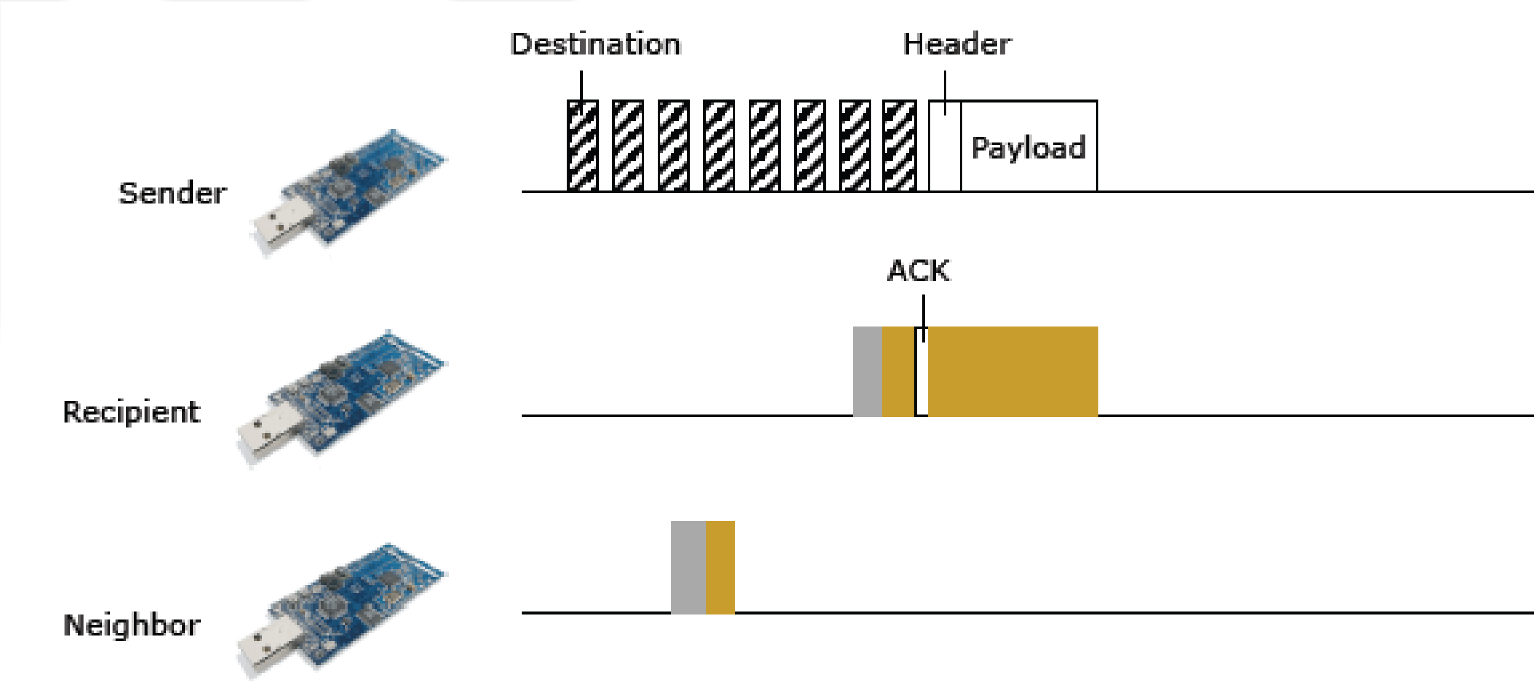


Pros and Cons of B-MAC

- No need for everybody to stay awake when there is no traffic
  - Just wake up for preamble sampling and go back to sleep
- Better power conservation, latency and throughput than S-MAC
- Simpler to implement

- Low duty cycle → longer preamble
  - Little cost to receiver yet higher cost to sender
  - Longer delay
  - More contention

X-MAC: Early ACK



- Include destination address in short preambles
- Non-receiver avoids overhearing
- Receiver acknowledges preamble → Sender stops sending preamble

Thoughts on X-MAC

- Better than B-MAC in terms of latency, throughput and power consumption
- Energy consumption due to overhearing reduced
- Simple to implement
- On average the preamble size is reduced by half compared to B-MAC → Still considerable overhead

SCP-MAC

- Scheduled Channel Polling by everybody
  - Avoid long preambles in LPL (Low Power Listening) supported by B-MAC
- Wake up tone
  - Much shorter than preamble in LPL followed by data
- Assumption: the listening intervals must be synchronized

SCP-MAC (2)

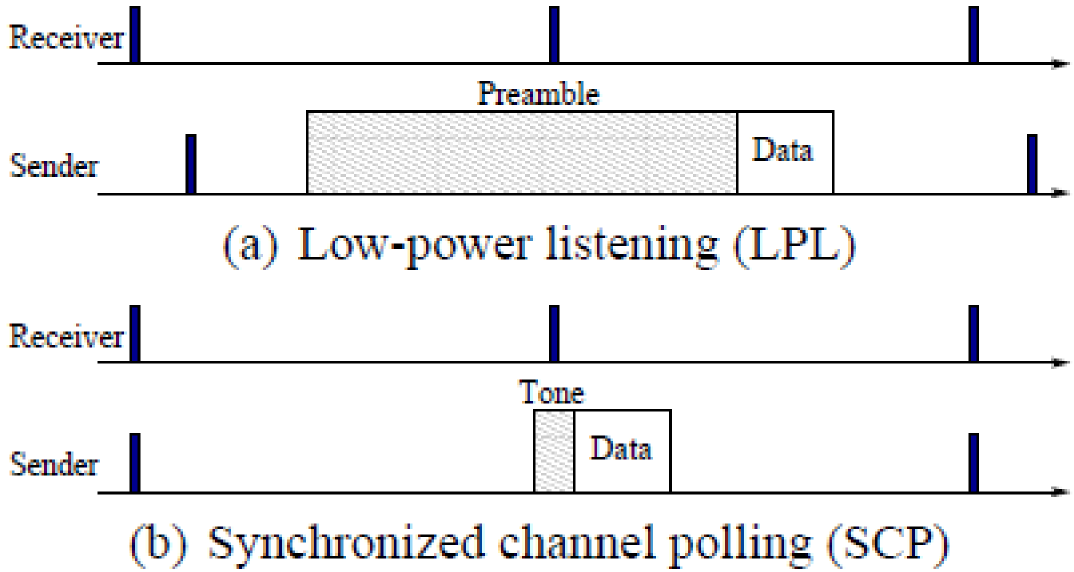
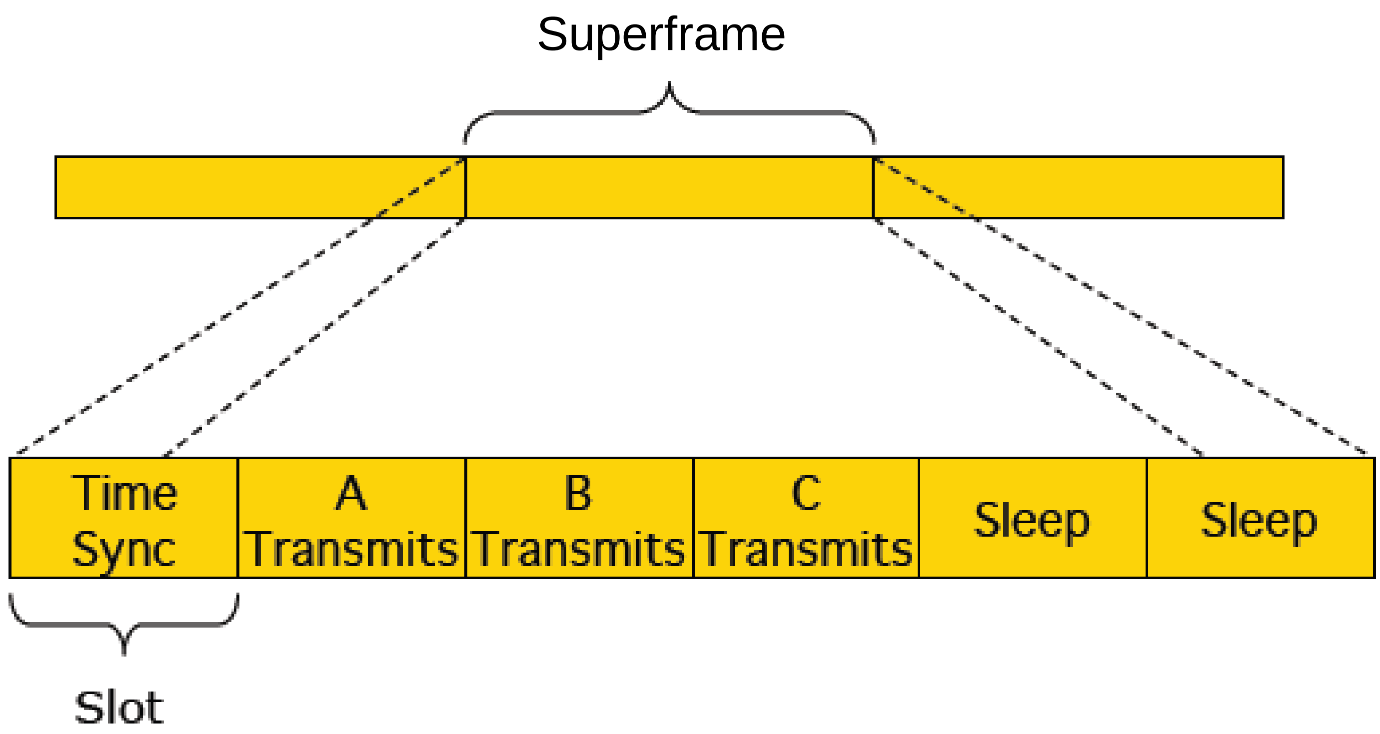


Figure 1. Sender and receiver synchronization schemes.

Time Division Multiple Access (TDMA)

- Predictable delay, throughput and duty cycle
- Little packet losses due to contention
- Scheduling and time sync are difficult
- Slots are wasted when a node has nothing to send

TDMA


Superframe
Time Sync
A Transmits
B Transmits
C Transmits
Sleep
Sleep
Slot

Z-MAC (Zebra MAC)

- Runs on top of B-MAC
- Rely on CSMA under light load → Switch to TDMA under high contention

Z-MAC (Zebra MAC)

CSMA

- Pros
  - Simple
  - Scalable
- Cons
  - Collisions due to hidden terminals
  - RTS/CTS is overhead

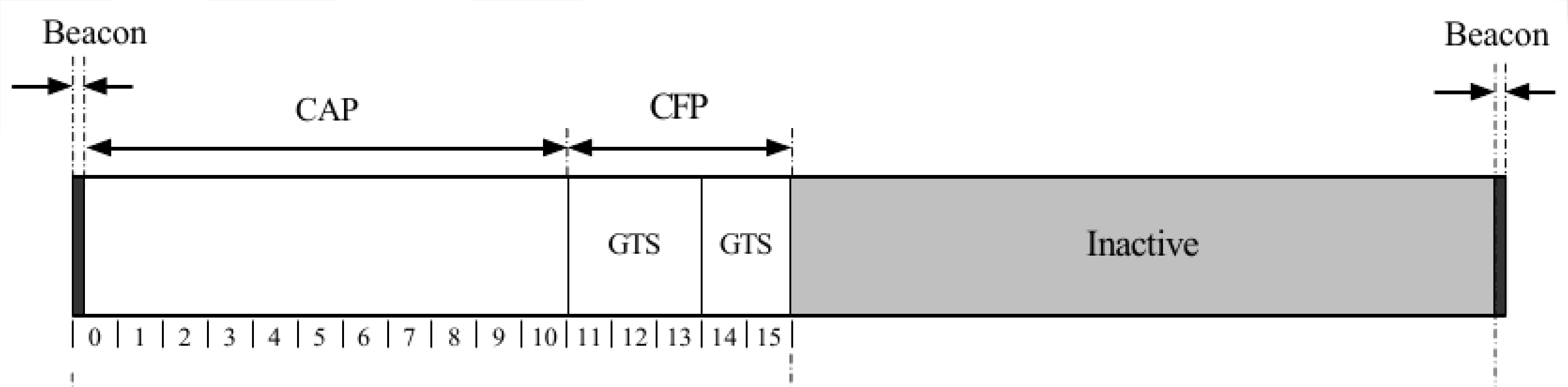
TDMA

- Pros
  - Naturally avoids collisions
- Cons
  - Complexity of scheduling
  - Synchronization needed

Thoughts on Z-MAC

- Good idea to combine strengths of CSMA and TDMA
- Complex
- Especially hard to implement TDMA part
  - How to deal with topology changes?

IEEE 802.15.4 superframe



IEEE 802.15.4 superframe

- Beacon frame sent periodically by the coordinator
  - It contains the superframe structure and the slot-transmitter association map
- CAP: Contention Access Period
  - CSMA/CA
  - For new nodes to join & reserve slots and for delay-insensitive flows
- CFP: Contention Free Period
  - TDMA for delay-sensitive flows
  - GTS: Guaranteed Time Slot
- Inactive period: also the coordinator can sleep

MAC protocols supported by TinyOS

- CC1100: experimental B-MAC
- CC2420: X-MAC