Medium Access Control in Wireless Sensor Networks & challenges

Summer school
"Sensor Networks: impacts and challenges for society"
University of Béjaia, Algeria
July 3rd, 2013

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LIUPPA
T2I team
T2i

UNIVERSITÉ
DE PAU ET DES
PAYS DE L'ADOUR

Les couches d'accès au support dans les réseaux de capteurs sans fils et les défis associés

École d'été
"Réseaux de capteurs: impacts et défis pour la société"
Université de Béjaia, Algérie
3 juillet, 2013

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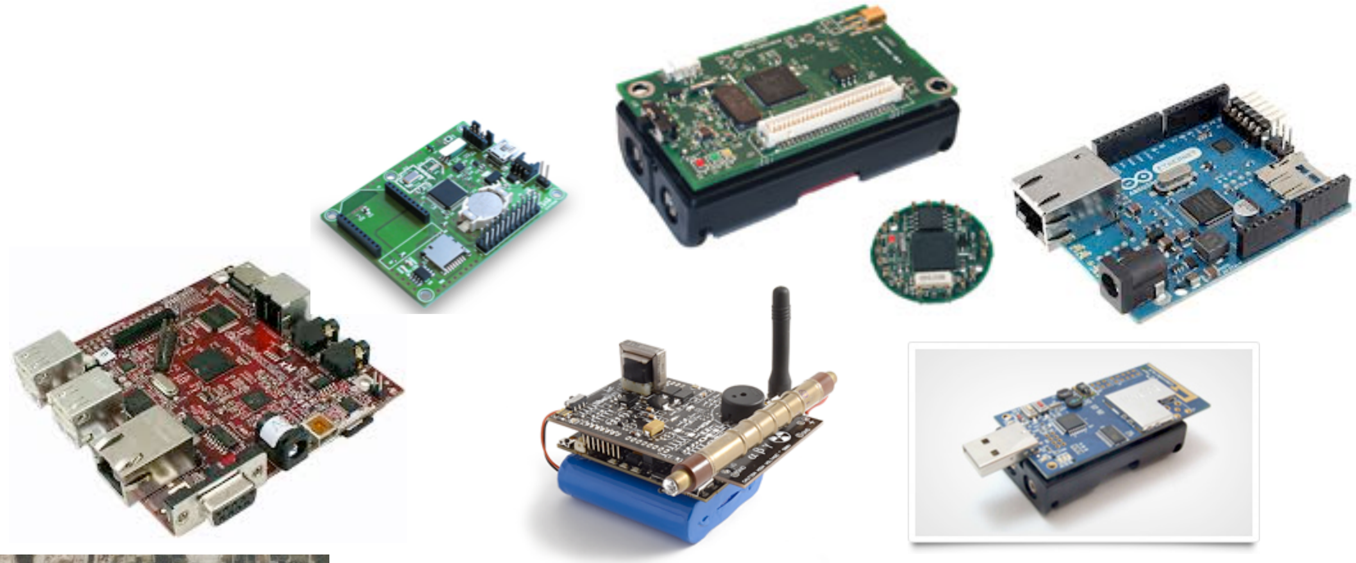
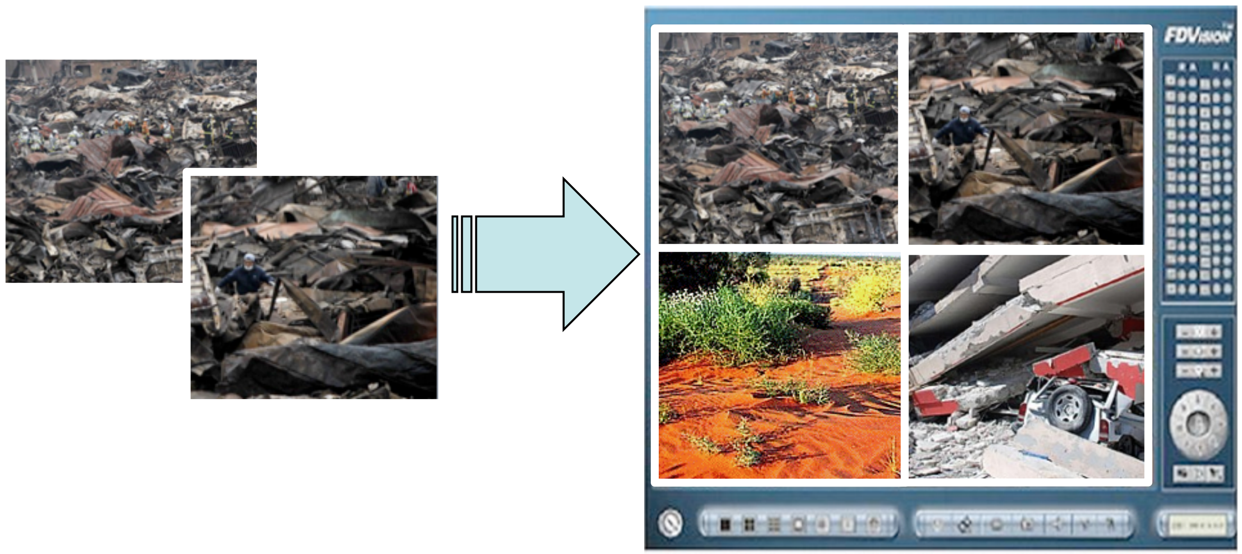
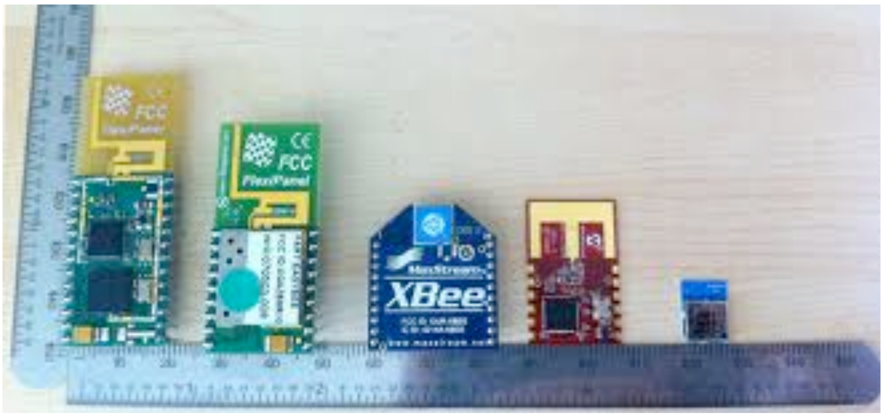
Sensor network

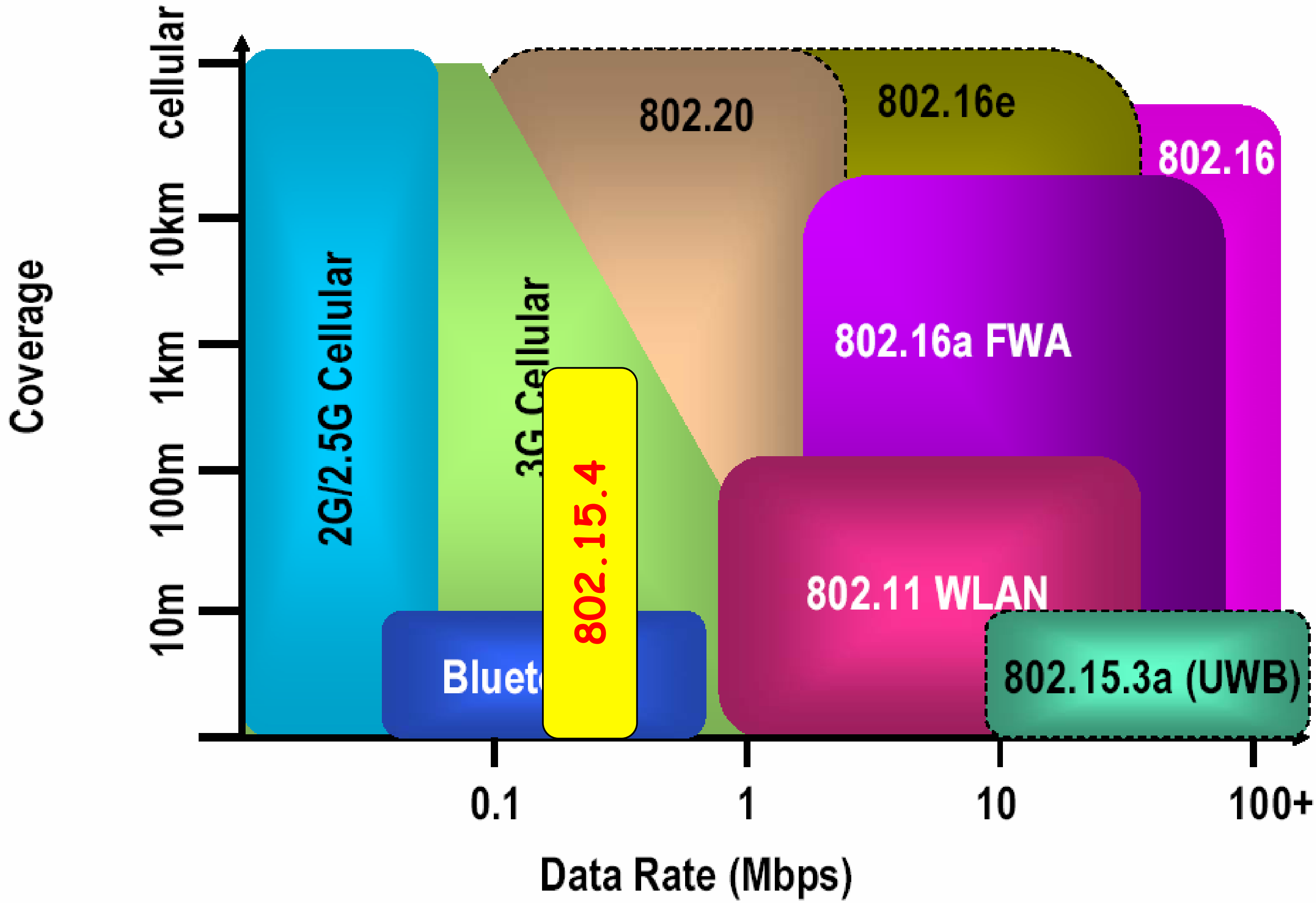




Wireless Communication made easy



Wireless technologies



IEEE 802.15.4

Caractéristiques Radio dans les réseaux de capteurs

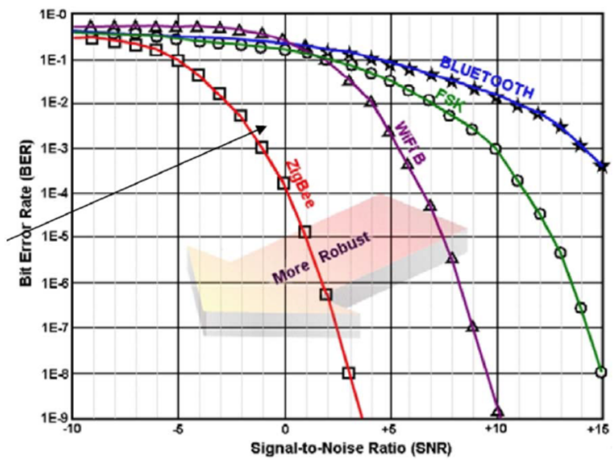
- Norme ZigBee (IEEE 802.15.4 PHY)

La norme IEEE802.15.4a, adaptées aux réseaux de capteurs, au contrôle industriel et aux dispositifs médicaux (CMI)

IEEE802.15.4 (couches 1 et 2):

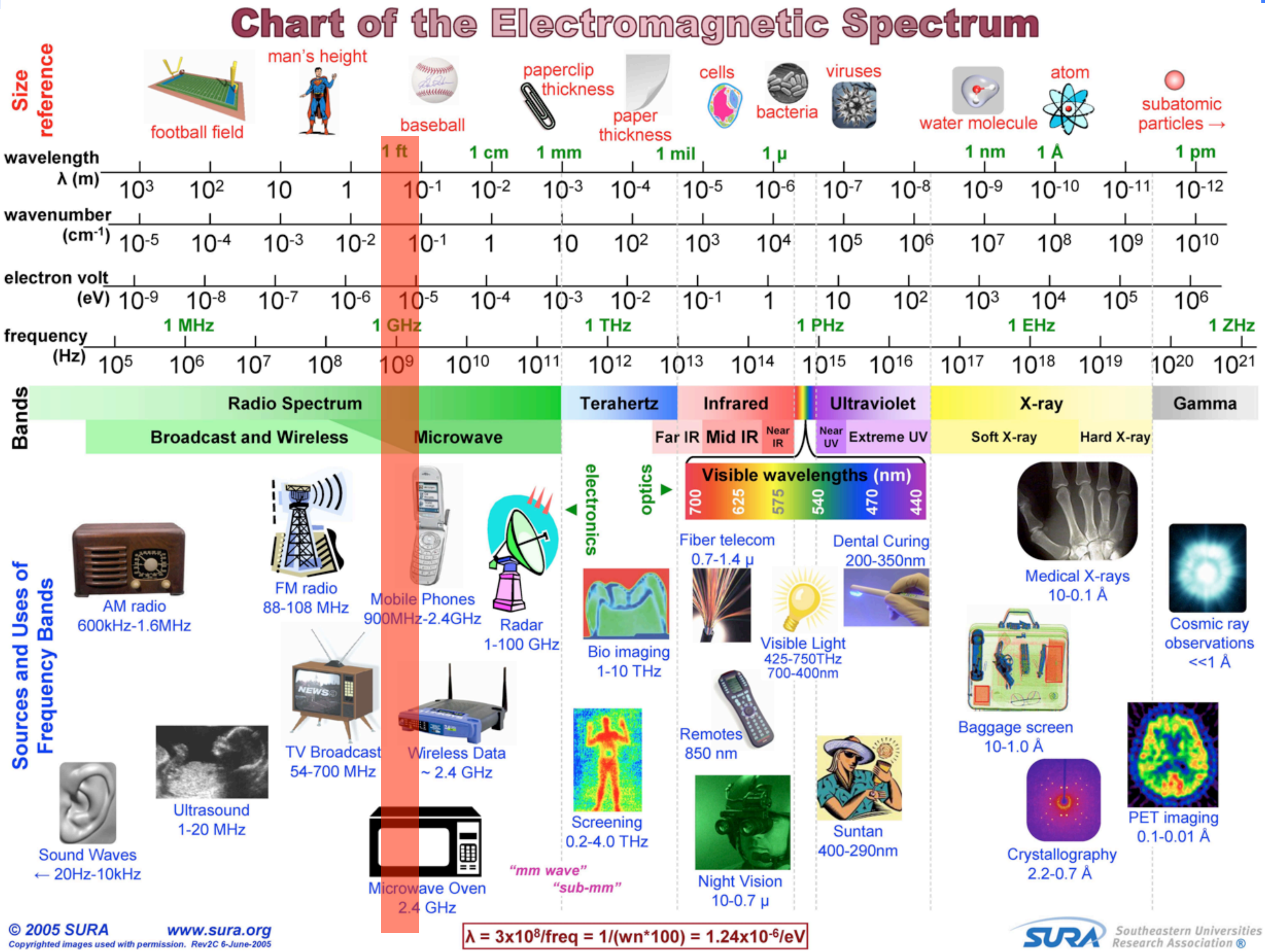
- Three bands, 27 channels specified
  - 2.4 GHz: 16 channels, 250 kbps
  - 868.3 MHz : 1 channel, 20 kbps
  - 902-928 MHz: 10 channels, 40 kbps

Protocole	Zigbee	Bluetooth	Wi-Fi
IEEE	802.15.4	802.15.1	802.11a/b/g
Besoins mémoire	4-32 Kb	250 Kb +	1 Mb +
Autonomie avec pile	Années	Jours	Heures
Nombre de nœuds	65 000+	7	32
Vitesse de transfert	250 Kb/s	1 Mb/s	11-54 et + Mb/s
Portée	100 m	10-100 m	300 m



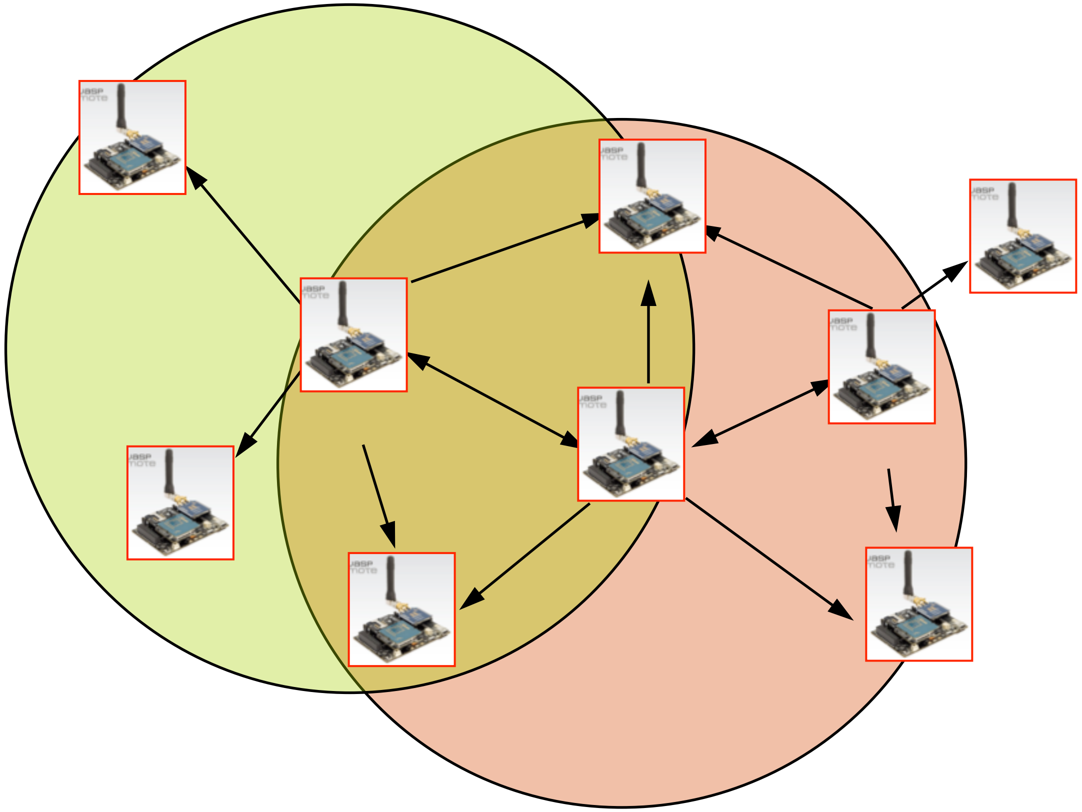
- Comparaison entre les normes ZigBee, Bluetooth et Wifi

The radio spectrum

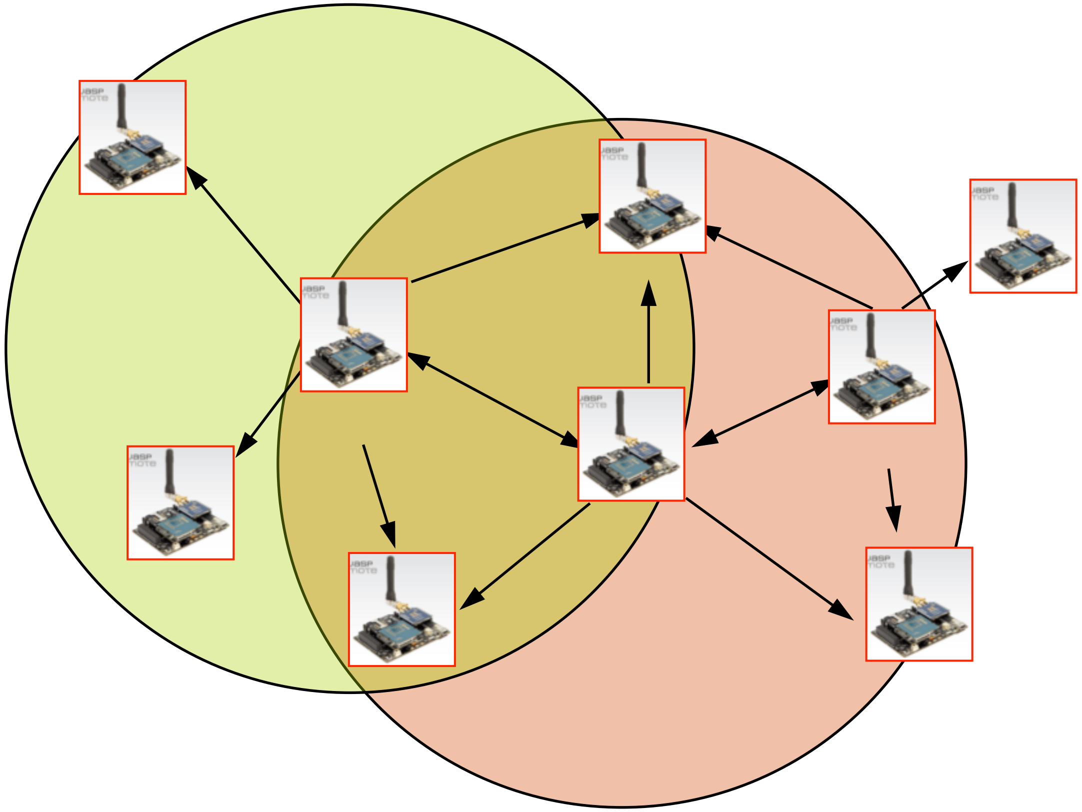


WSN are ad-hoc networks

- Infrastructure-less networks
- MANET (Mobile Adhoc NETworks)



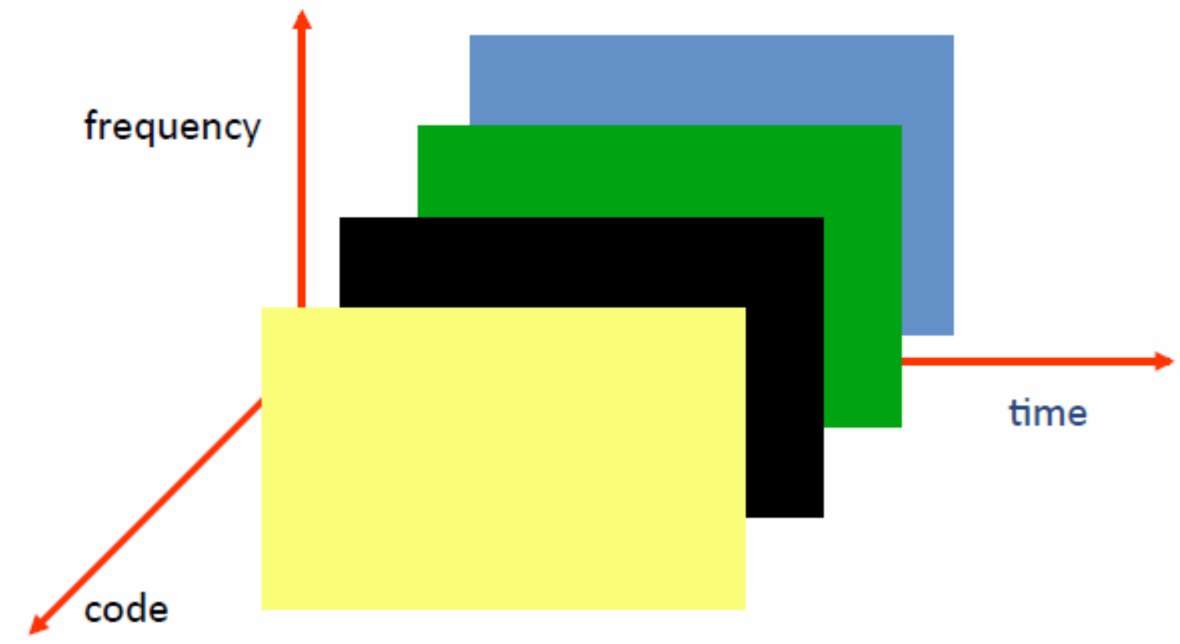
Wireless Medium is a Shared Medium!



Collisions when multiple transmissions

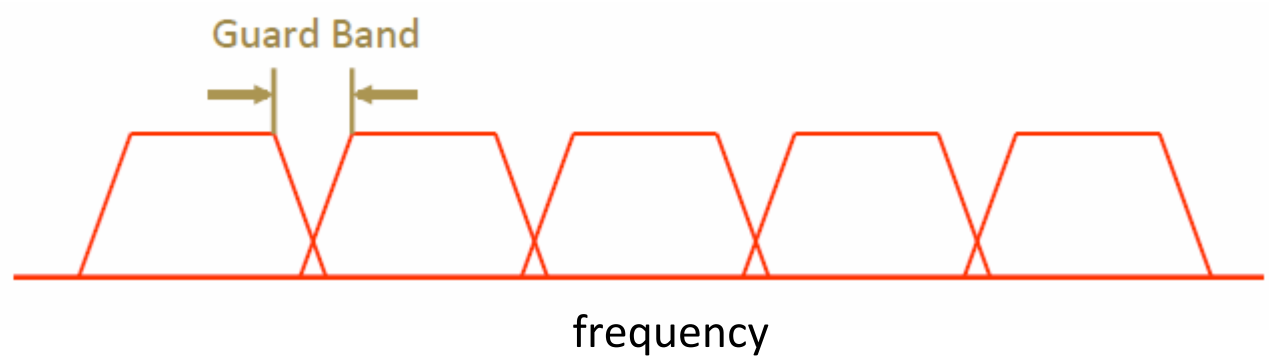
Need to control access to the medium

Multiple Access Schemes



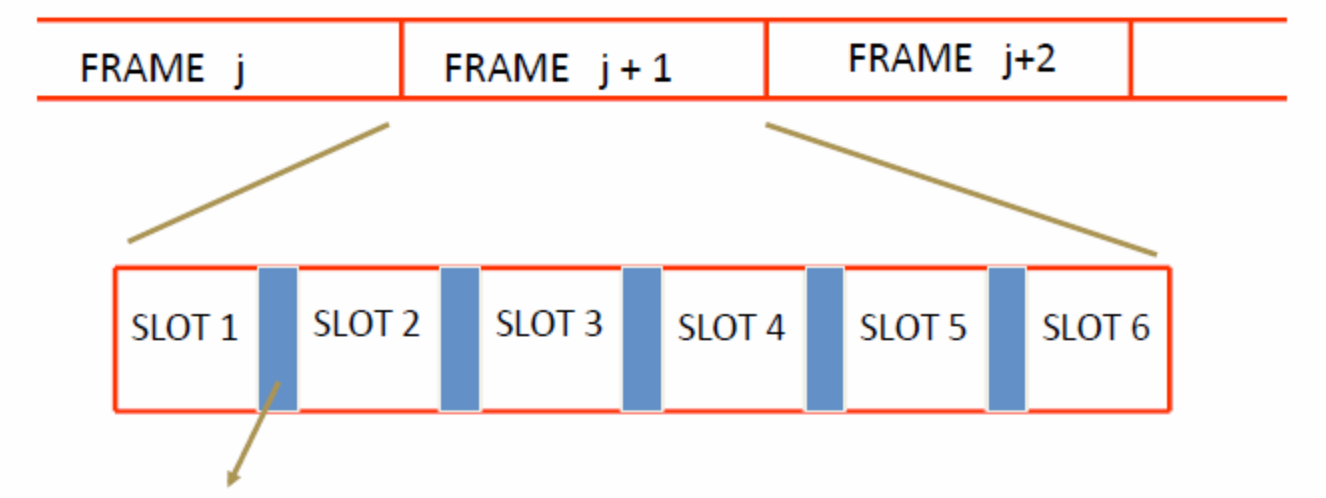
- 3 orthogonal Schemes:
  - Frequency Division Multiple Access (FDMA)
  - Time Division Multiple Access (TDMA)
  - Code Division Multiple Access (CDMA)

Frequency Division Multiple Access



- Each mobile is assigned a separate frequency channel for the duration of the call
- Sufficient guard band is required to prevent adjacent channel interference
- Usually, mobile terminals will have one downlink frequency band and one uplink frequency band
- Different cellular network protocols use different frequencies
- Frequency is a precious and scare resource. We are running out of it

Time Division Multiple Access

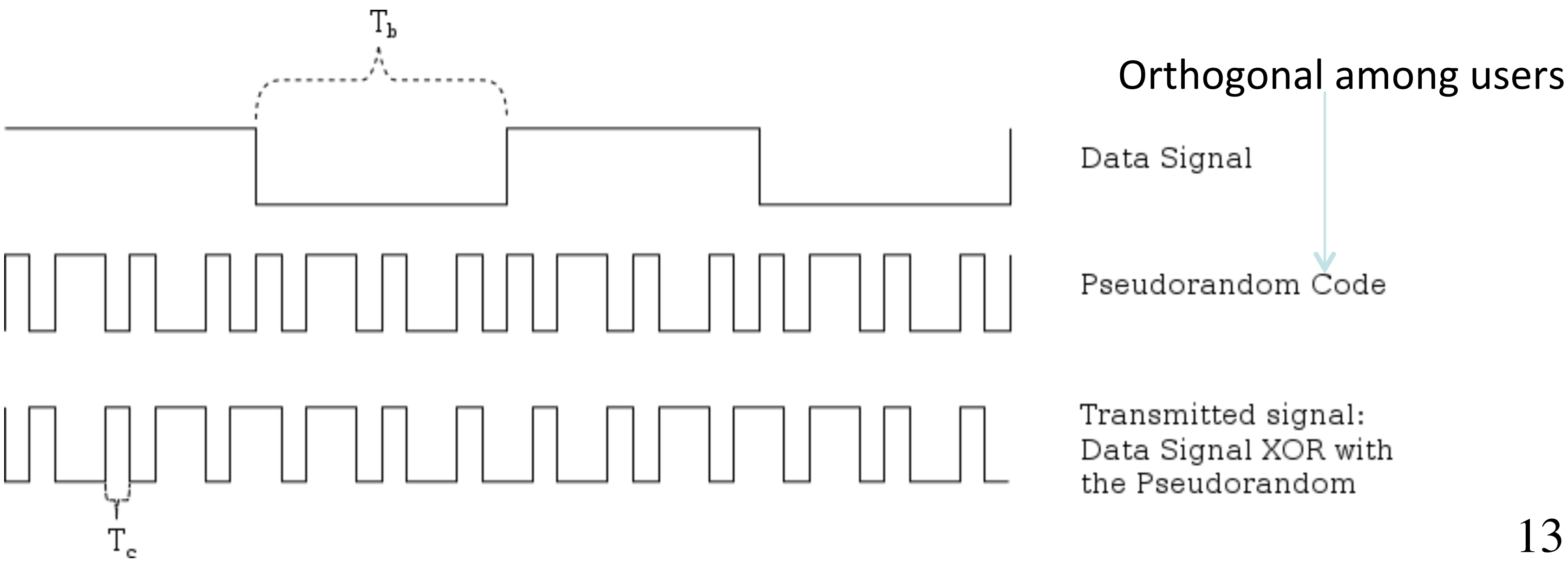


Guard time – signal transmitted by mobile terminals at different locations do no arrive at the base station at the same time

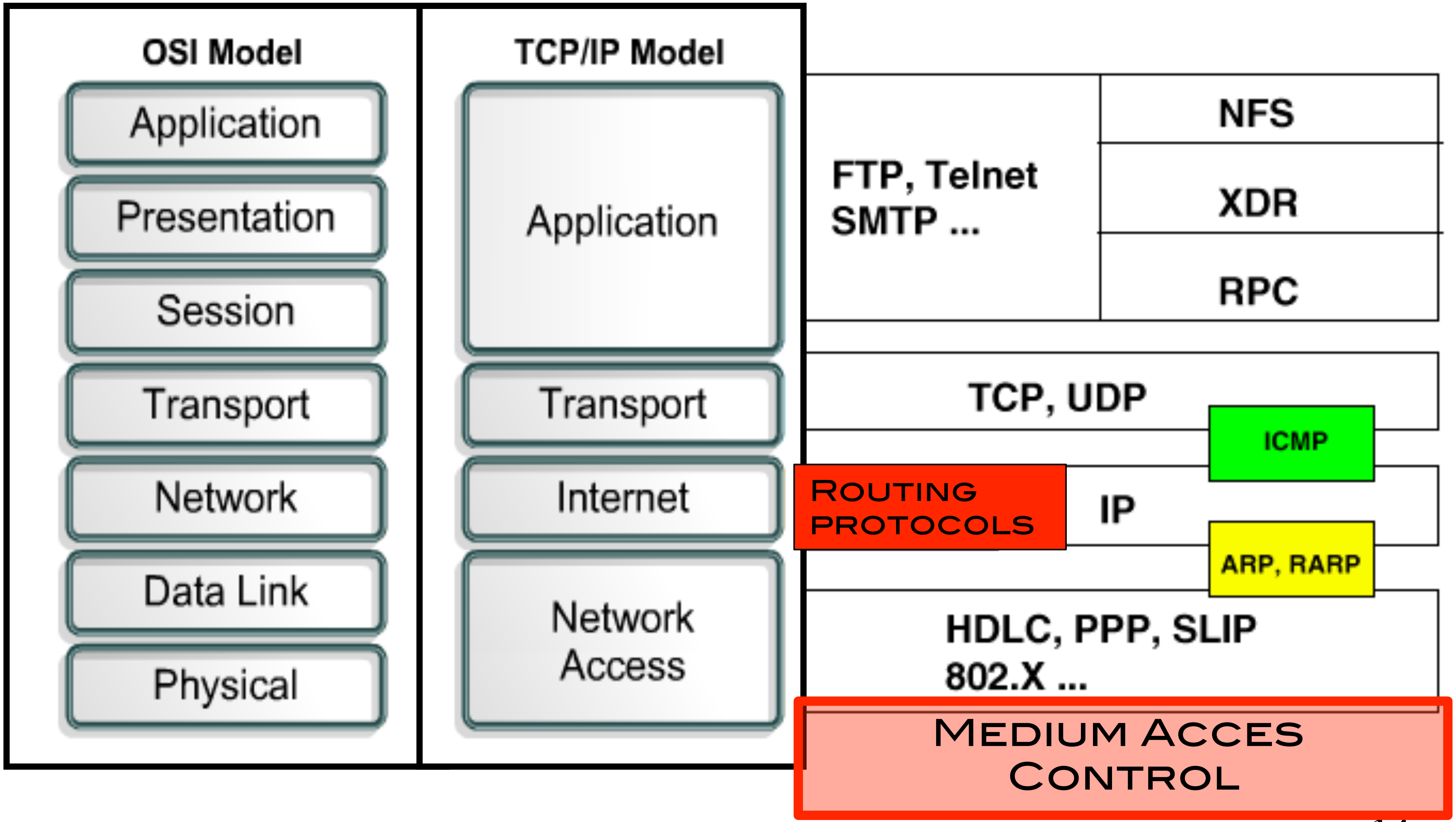
- Time is divided into slots and only one node transmits during each slot
- Each user is given a specific slot. No competition

Code Division Multiple Access

- Use of orthogonal codes to separate different transmissions
- Each symbol of bit is transmitted as a larger number of bits using the user specific code – Spreading
  - Bandwidth occupied by the signal is much larger than the information transmission rate
  - But all users use the same frequency band together



Review of Communication Architecture

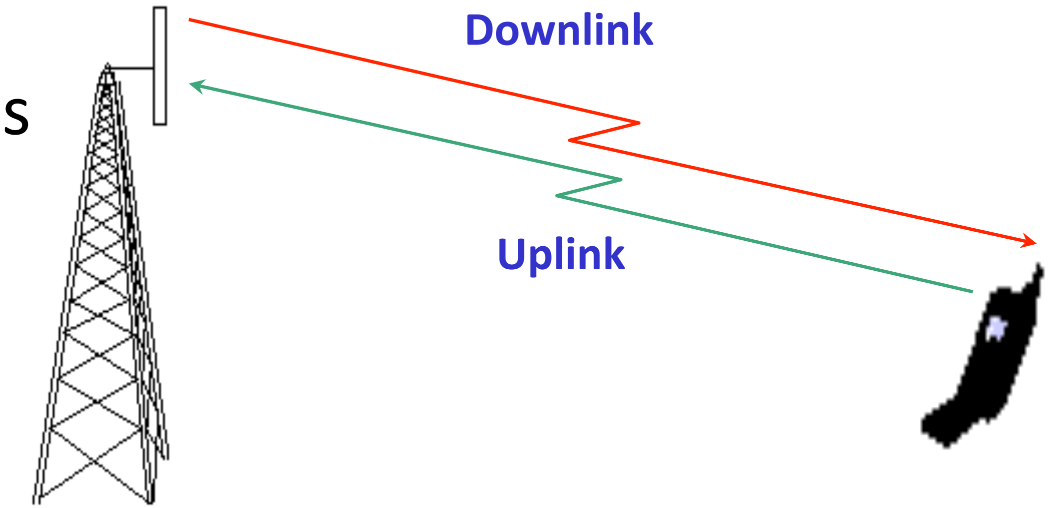


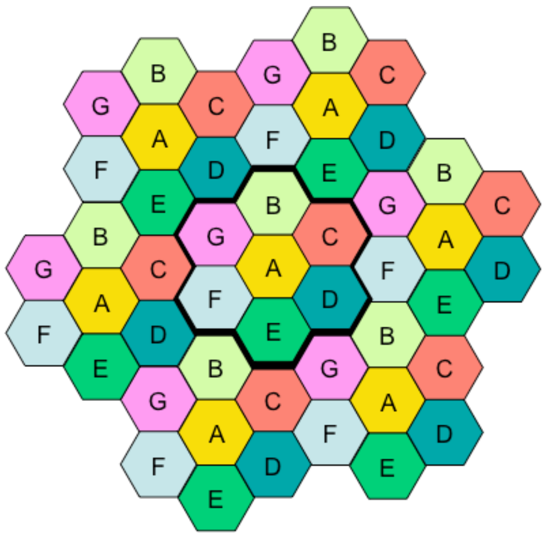
Other wireless network technologies

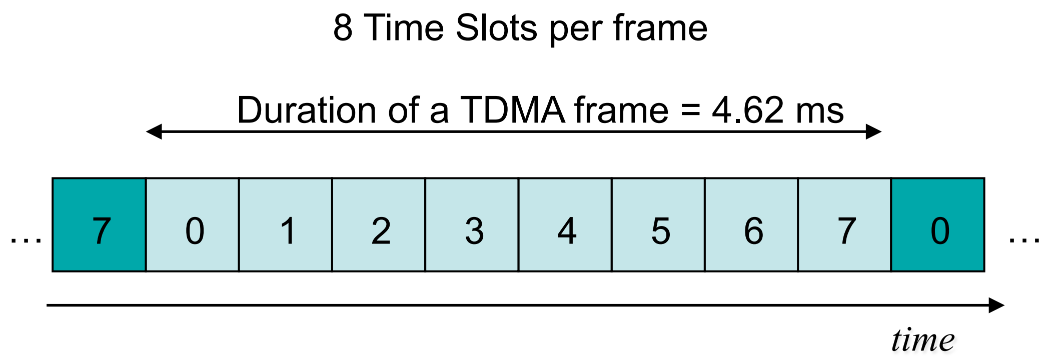
- Mobile phone
  - GSM (2G), EDGE (2.5G)
  - 3G
  - LTE, 4G,...
- Bluetooth
- WiMAX
- Wifi 802.11

GSM (2G)

Channels

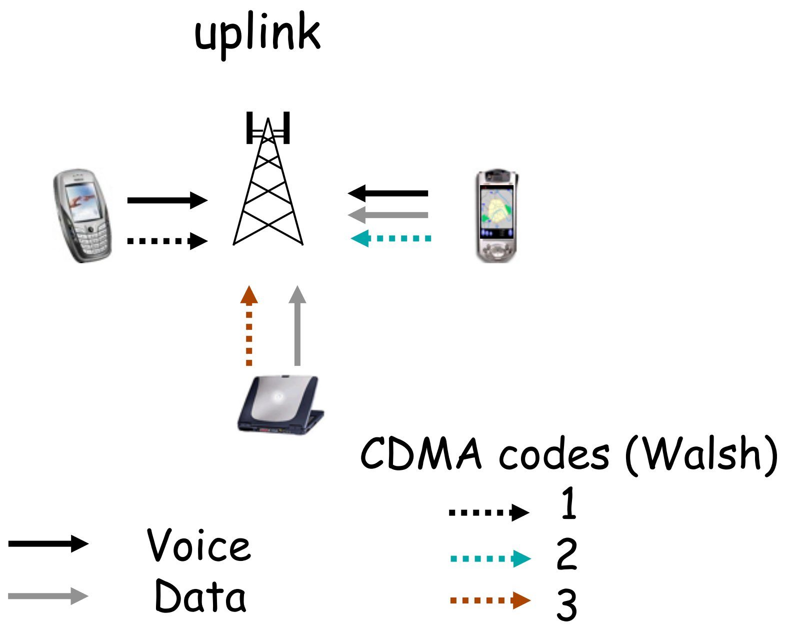






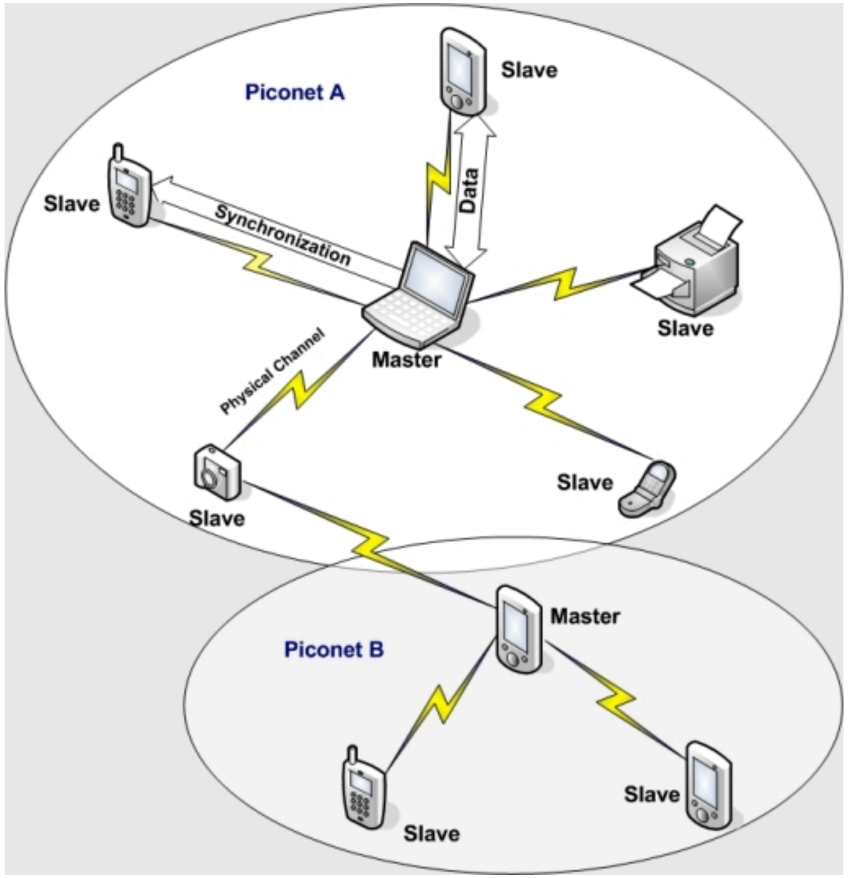
3G and Beyond

- 3G and beyond use CDMA techniques



Bluetooth

- 802.15 : Personal Area Network
  - 802.15.1 -> 802.15.3
- Master-slave, Piconet organization
- Master will poll slaves for data

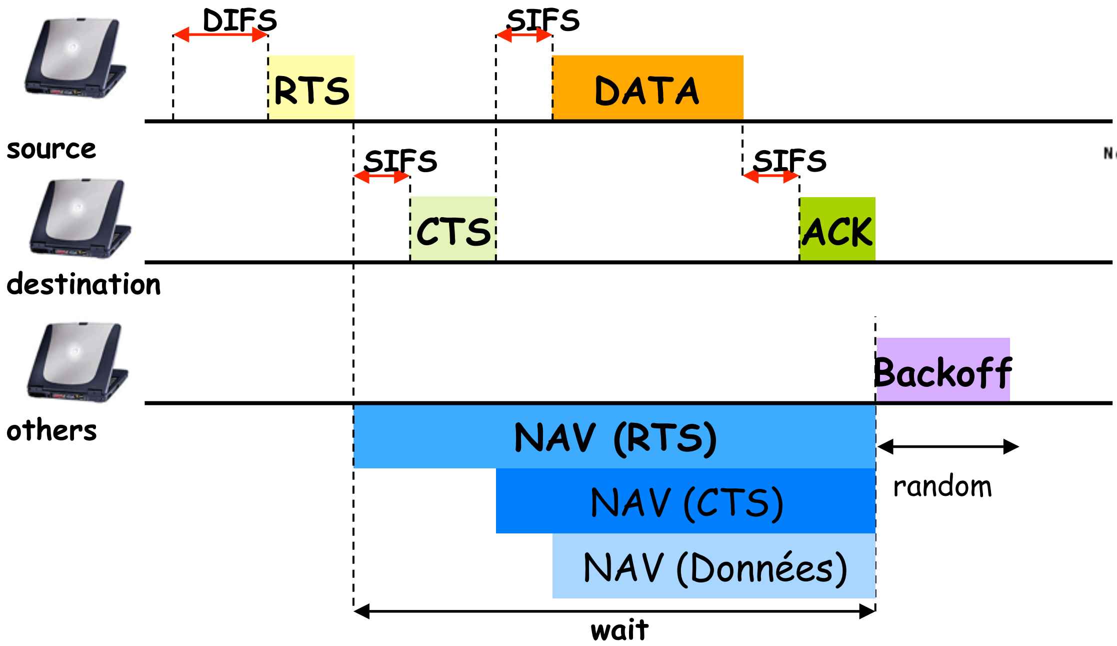


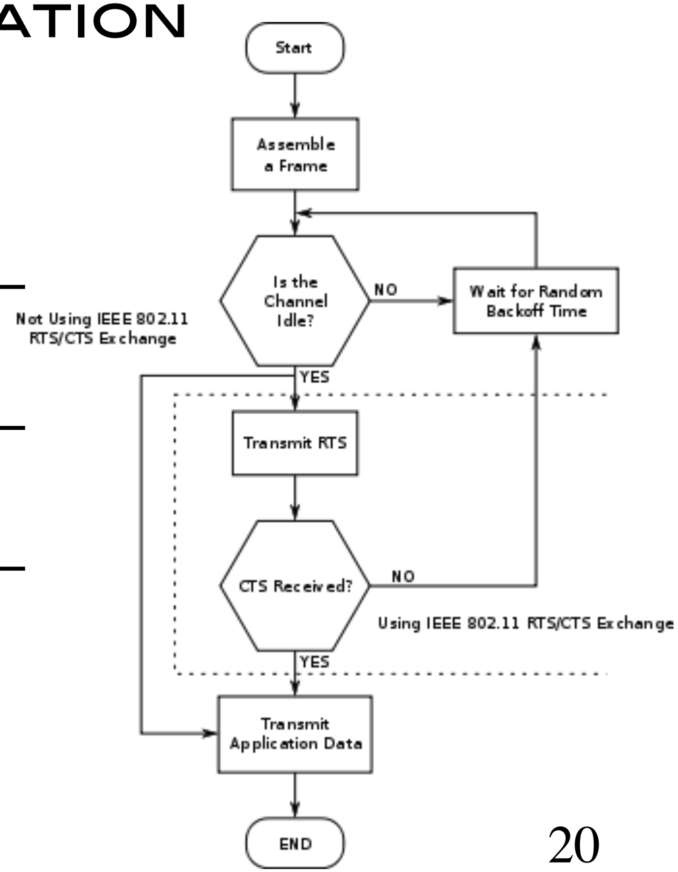
WiFi 802.11

- Uses CSMA/CA, a contention-based access method

CSMA/CA

- Collision Avoidance with RTS/CTS to limit the hidden terminal problem
- DCF (Distributed Coordination Function)

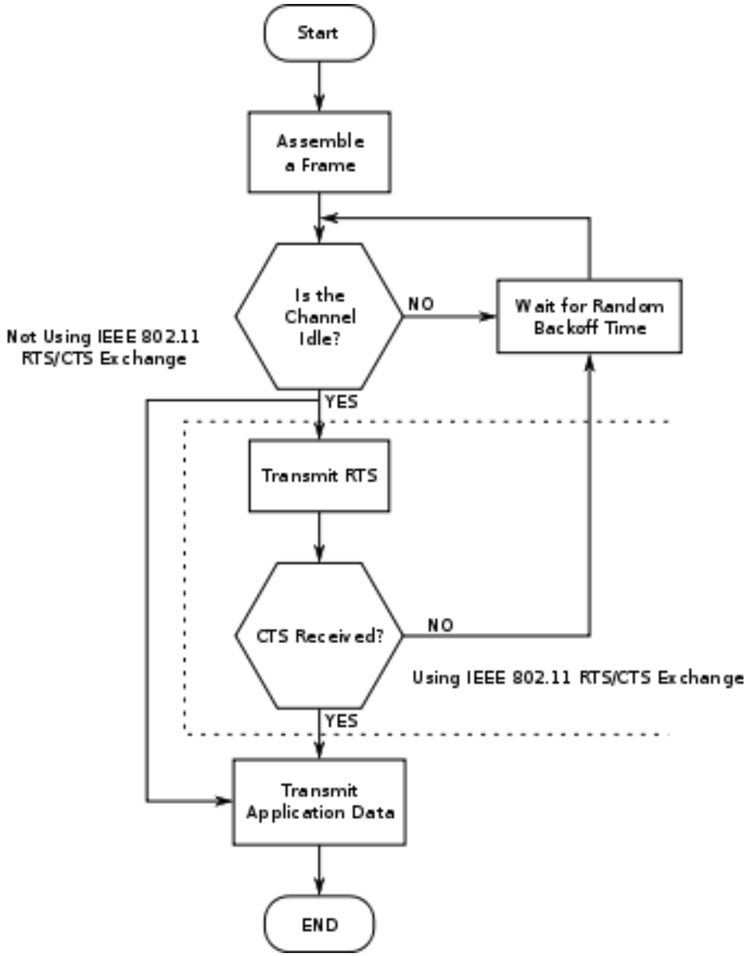




What technology for WSN?

- TDMA is possible but wastes a lot of resources, difficult to scale
- FDMA is not very flexible for dynamic, spontaneous ad-hoc networks
- CDMA is not very suitable for ad-hoc network, without master or base stations
- Wifi consumes a lot of energy, but the contention-based access seems the most suitable

Medium Access Control in IEEE 802.15.4



Review of Medium busy time

- Depends on the radio throughput
- Examples with a 100-bytes pkt
  - 100 bytes = 800 bits
  - Ethernet 10Mbps: $800/10.10^6$=80us
  - Ethernet 100Mbps: $800/100.10^6$=8us
  - WiFi 11Mbps: $800/10.10^6$=72us
  - WiFi 54Mbps: $800/54.10^6$=14.8us
  - 802.15.4 350kbps: $800/250.10^3$=3.2ms
- If 3.2ms is a 10-meter bus
  - 72us is a 20cm rule!
  - 14.8us is a 4cm toy car!

Principles

- IEEE 802.15.4 MAC defines the following data transfer models
  - To/From coordinator node
  - Peer-to-peer
- The coordinator mode defines a star tolopogy and severals MAC mechanisms can be used: beacon and non-beacon mode, GTS,...
- Peer-to-Peer data transfer model allows any node to communicate with other nodes provided that they are in (radio) communication range. Non-beacon unslotted CSMA/CA is used.

Supported topologies

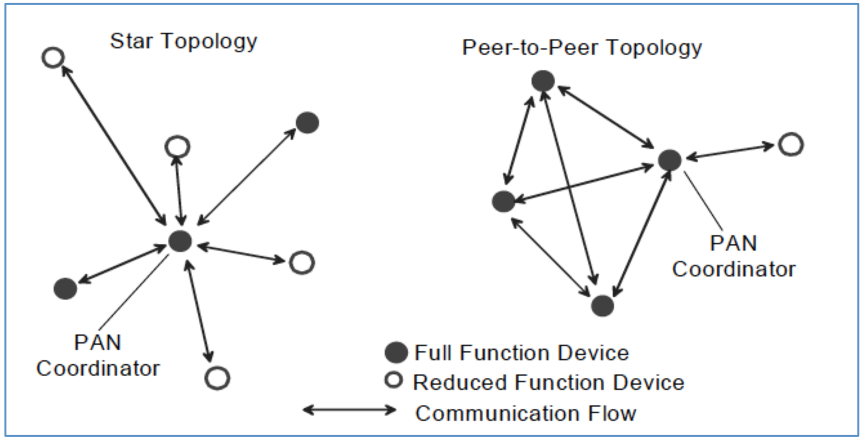


Figure from IEEE document standard on 802.15.4

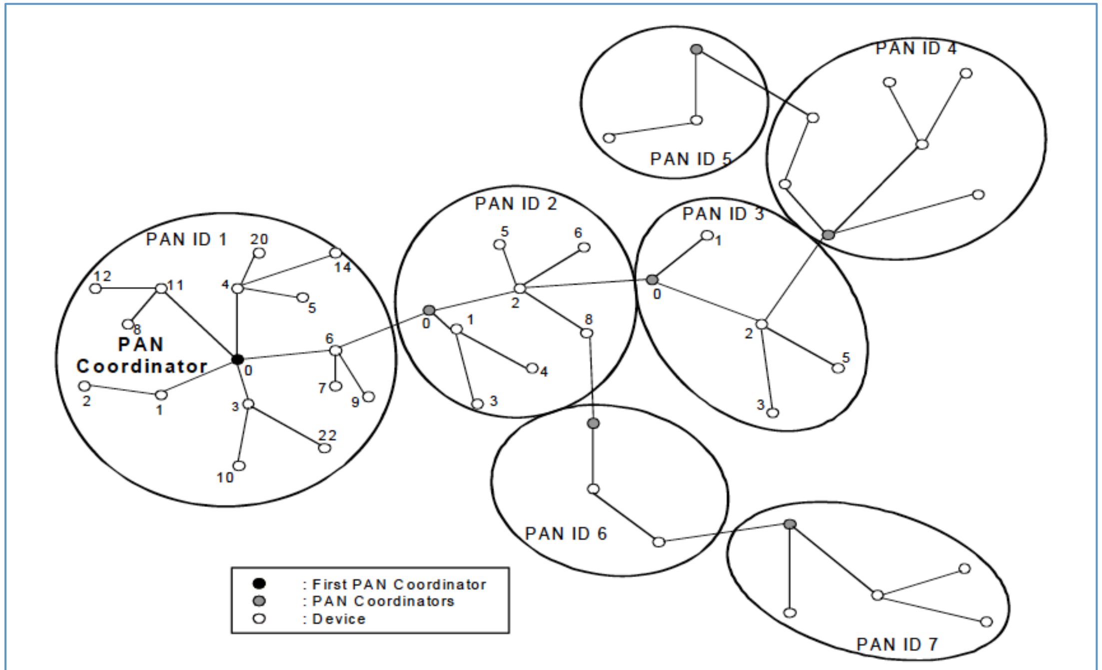
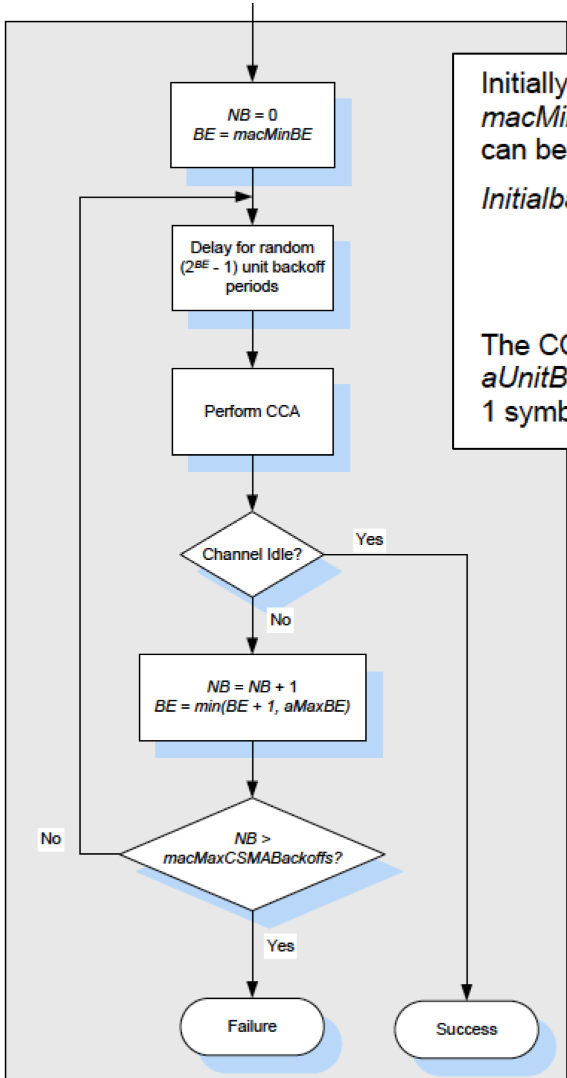


Figure from IEEE document standard on 802.15.4

Non-beacon unslotted CSMA & CCA



From Jennic

Initially, the back-off exponent *BE* is set to *macMinBE*. Using the default value of 3 for *macMinBE* and assuming the channel is found to be free, the worst-case channel access time can be calculated as:

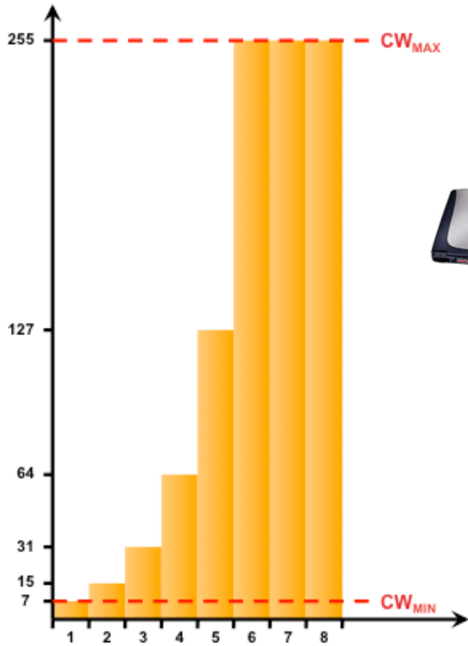
InitialbackoffPeriod + *CCA* = $(2^3 - 1)$ x *aUnitBackoffPeriod* + *CCA*

= 7 x 320 µs + 128 µs

= 2.368 ms

The CCA detection time is defined as 8 symbol periods.
aUnitBackoffPeriod is defined as 20 symbol periods.
1 symbol period is equal to 16 µs.

From Jennic



802.15.4 CCA is somehow similar to WIFI DIFS interframe spacing

Beacon-enabled PAN

- "The standard allows the optional use of a superframe structure. The format of the superframe is defined by the coordinator."
- "The superframe is bounded by network beacons sent by the coordinator (see Figure 4a) and is divided into 16 equally sized slots. Optionally, the superframe can have an active and an inactive portion (see Figure 4b)."
- "The beacon frame is transmitted in the first slot of each superframe. If a coordinator does not wish to use a superframe structure, it will turn off the beacon transmissions."

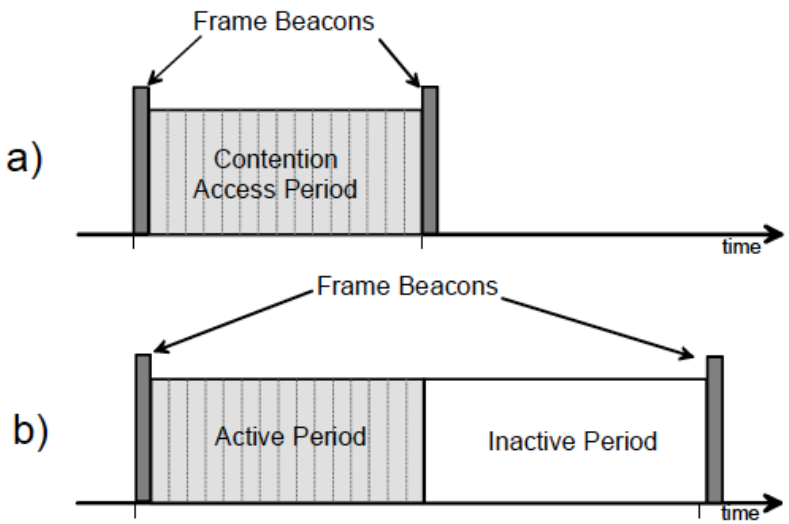


Figure 4—Superframe structure without GTSs

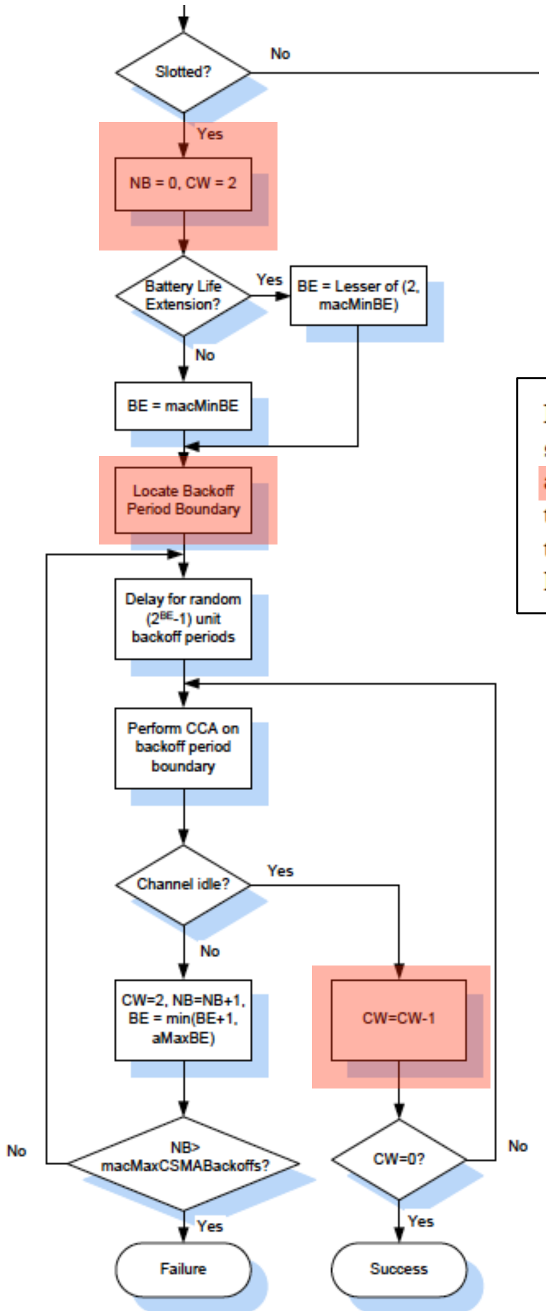
Figure and text from IEEE document standard on 802.15.4

Beacons-mode and CAP

- "The beacons are used to synchronize the attached devices"
- "Beacon-enabled PANs use a slotted CSMA-CA channel access mechanism, where the backoff slots are aligned with the start of the beacon transmission."
- "Any device wishing to communicate during the contention access period (CAP) between two beacons competes with other devices using a slotted CSMA-CA mechanism."

Text from IEEE document standard on 802.15.4

Slotted CSMA



In slotted CSMA-CA, the backoff period boundaries of every device in the PAN shall be aligned with the superframe slot boundaries of the PAN coordinator, i.e., the start of the first backoff period of each device is aligned with the start of the beacon transmission. In slotted CSMA-CA, the MAC sublayer shall ensure that the PHY commences all of its transmissions on the boundary of a backoff period. In unslotted CSMA-CA, the backoff periods of one device are not related in time to the backoff periods of any other device in the PAN.

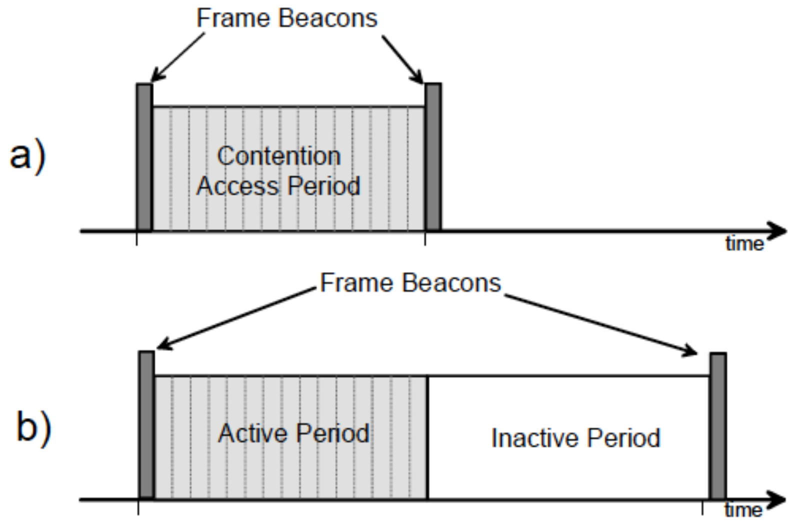


Figure 4—Superframe structure without GTSs

Hybrid access

- "For low-latency applications or applications requiring specific data bandwidth, the PAN coordinator may dedicate portions of the active superframe to that application. These portions are called guaranteed time slots (GTSs)."
- "The GTSs form the contention-free period (CFP), which always appears at the end of the active superframe starting at a slot boundary immediately following the CAP, as shown in Figure 5."
- "All contention-based transactions is completed before the CFP begins. Also each device transmitting in a GTS ensures that its transaction is complete before the time of the next GTS or the end of the CFP."

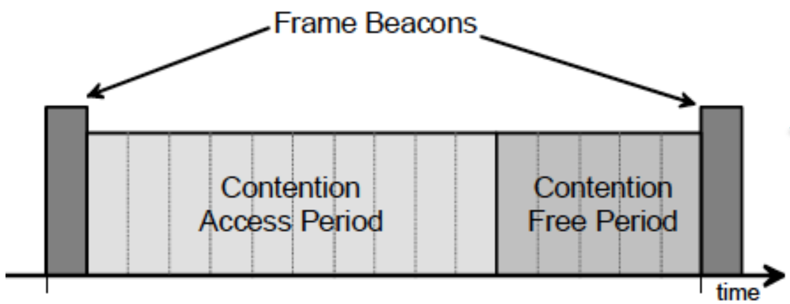


Figure 5—Superframe structure with GTSs

GTS mode needs a PAN coordinator which will allocate up to 7 GTS slots in the frame. Nodes can reserved a given number of GTS slots to send data to the PAN coordinator, which acts as the sink.

Figure and text from IEEE document standard on 802.15.4

Superframe definition

- The structure of the superframe is described by the values of `macBeaconOrder` and `macSuperframeOrder`.
- The MAC PIB attribute `macBeaconOrder` , describes the interval at which the coordinator shall transmit its beacon frames. The value of `macBeaconOrder`, BO , and the beacon interval, BI, are related as follows: for 0≤ BO ≤ 14, BI = `aBaseSuperframeDuration` * 2^{BO} symbols.
- PANs that do not wish to use the superframe structure (referred to as a non beacon-enabled PAN) shall set both `macBeaconOrder` and `macSuperframeOrder` to 15. Transmissions use unslotted CSMA/CA and GTSs shall no be permitted.

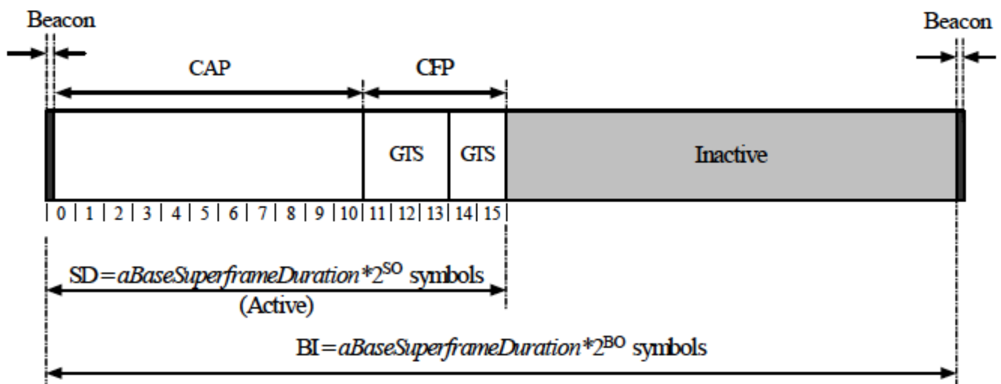


Figure and text from IEEE document standard on 802.15.4

Beacon, Data and ACK frame structure

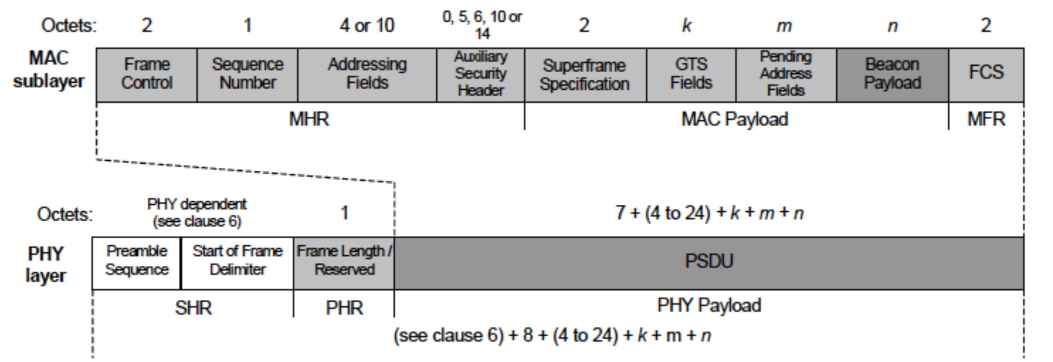


Figure 10—Schematic view of the beacon frame and the PHY packet

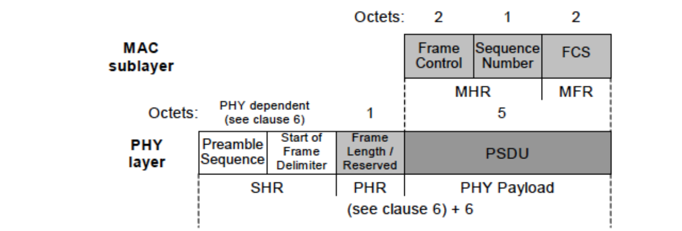


Figure 12—Schematic view of the acknowledgment frame and the PHY packet

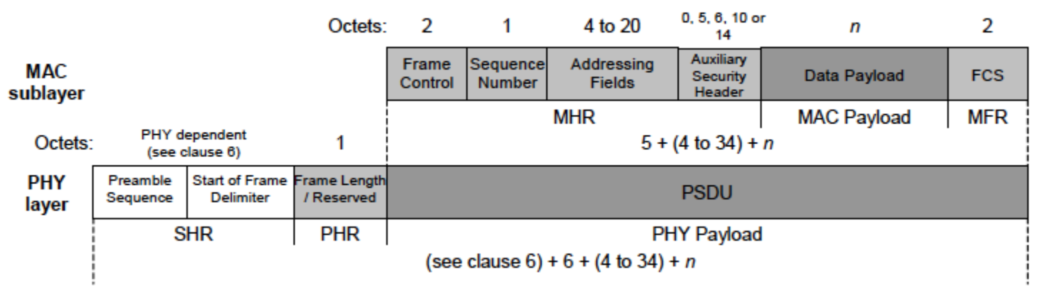


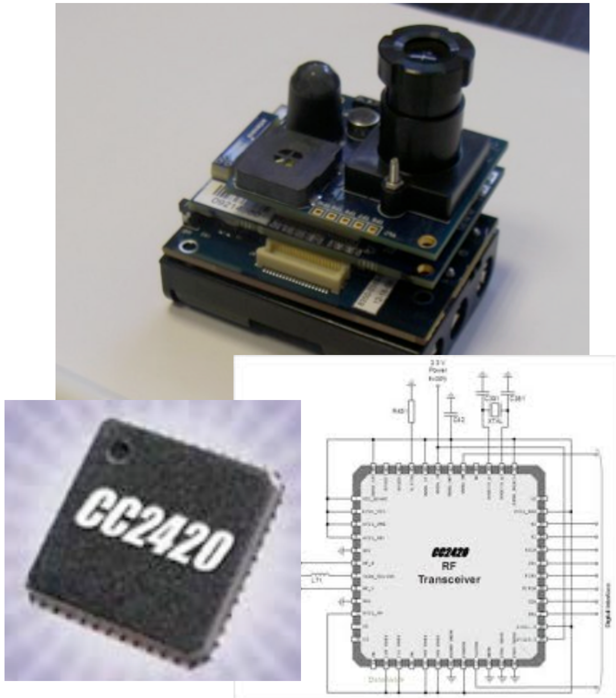
Figure 11—Schematic view of the data frame and the PHY packet

Figure and text from IEEE document standard on 802.15.4

802.15.4 MAC is far from perfect

- Radio circuits, if always on, can consume all the battery's energy
- WSN have a very sporadic behavior: idle for a long period of time, then burst of data
- Passive listening, i.e. receiving a packet that is not for you, can consumes as much as energy than packet transmission!

Energy consideration



18720 Joules

TX power 0dbm: 17.4mA

P = I x V = 17.4 x 3.3 = 57.42mW

E = P x t -> t = E/P

326018s or 90.5h

Haven't considered:

- Baseline power consumption of the sensor board
- RX consumption: 18.8mA!
- Image capture consumption
- Image processing consumption

Chipcon Products from Texas Instruments

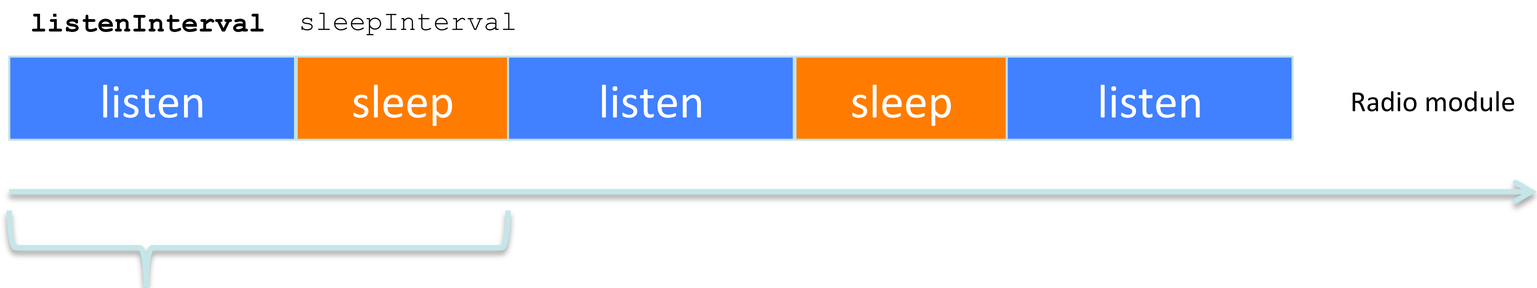
CC2420

Parameter	Min.	Typ.	Max.	Unit	Condition / Note
Current Consumption, transmit mode:					
P = -25 dBm		8.5		mA	The output power is delivered differentially to a 50 Ω singled ended load through a balun, see also page 55.
P = -15 dBm		9.9		mA	
P = -10 dBm		11		mA	
P = −5 dBm		14		mA	
P = 0 dBm		17.4		mA	

Duty-cycled MAC based on CSMA(/CA), with optional beacons

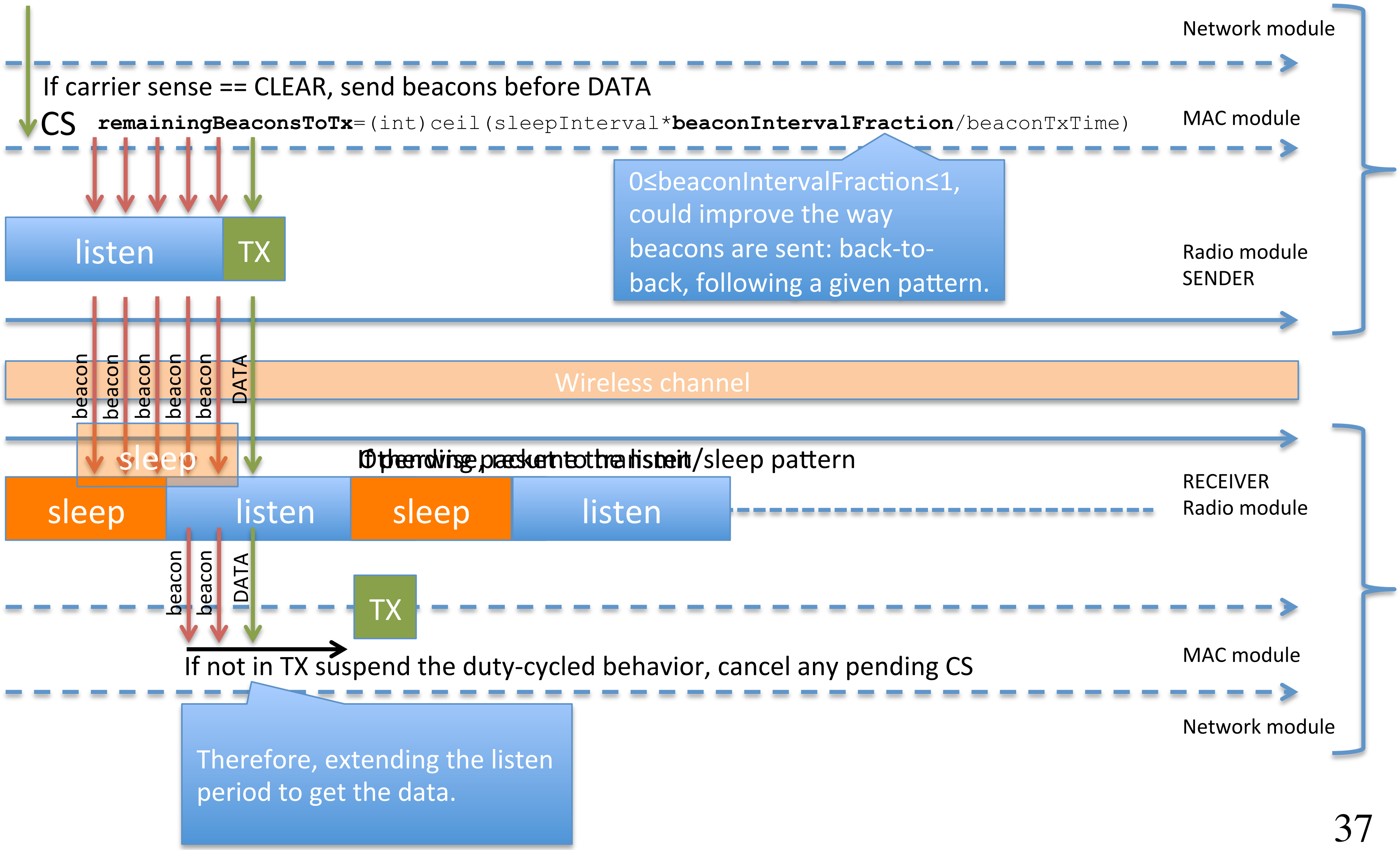
Principles

- Alternate « listen » and « sleep » periods. In « sleep » period, the radio is shut off to save energy
- Note: most of duty-cycled MAC means duty-cycling the radio module, not the MAC module
- Optional beacons can be used as a « preamble » to inform the receiver of imminent data packet arrival. This preamble length should usually be at least longer than the sleep period (cf LPL)

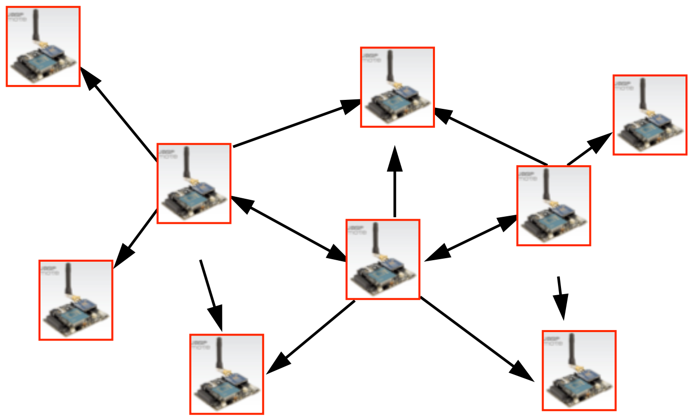


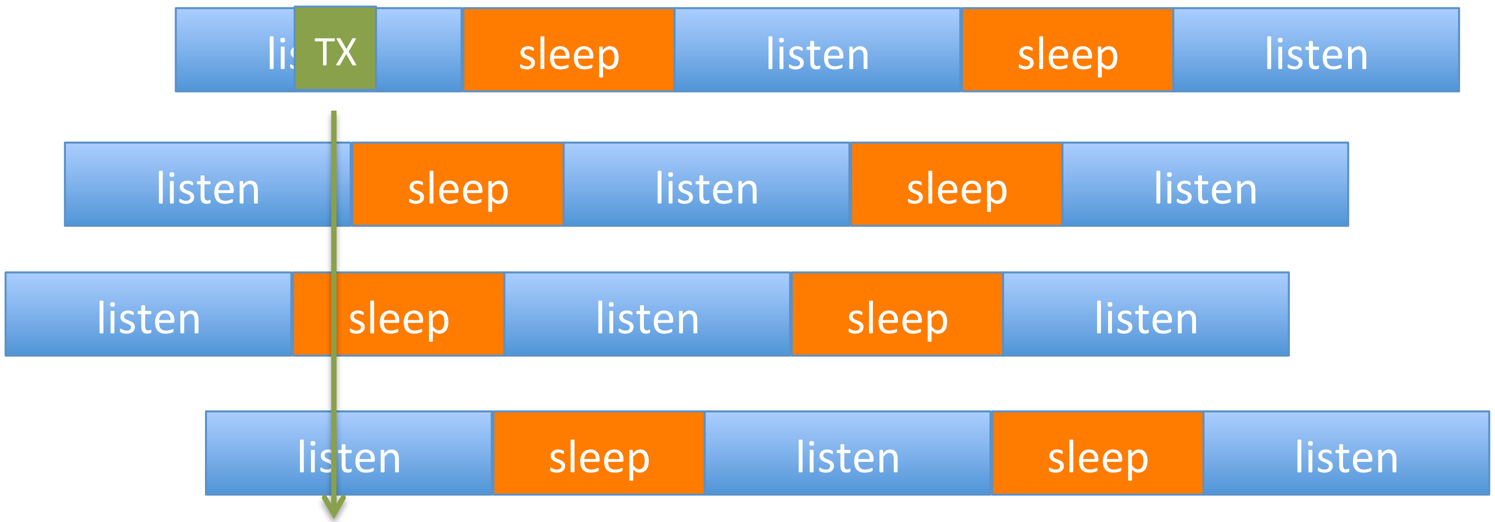

```
cycleLength=listenInterval+sleepInterval
listenInterval=dutyCycle*cycleLength -> cycleLength=listenInterval/dutyCycle
sleepInterval=listenInterval/dutyCycle-listenInterval
-> sleepInterval=listenInterval*(1-dutyCycle)/dutyCycle
```

Example with optional beacons



Multi-hop is challenging!





Synchronized MAC:
SMAC, TMAC,...

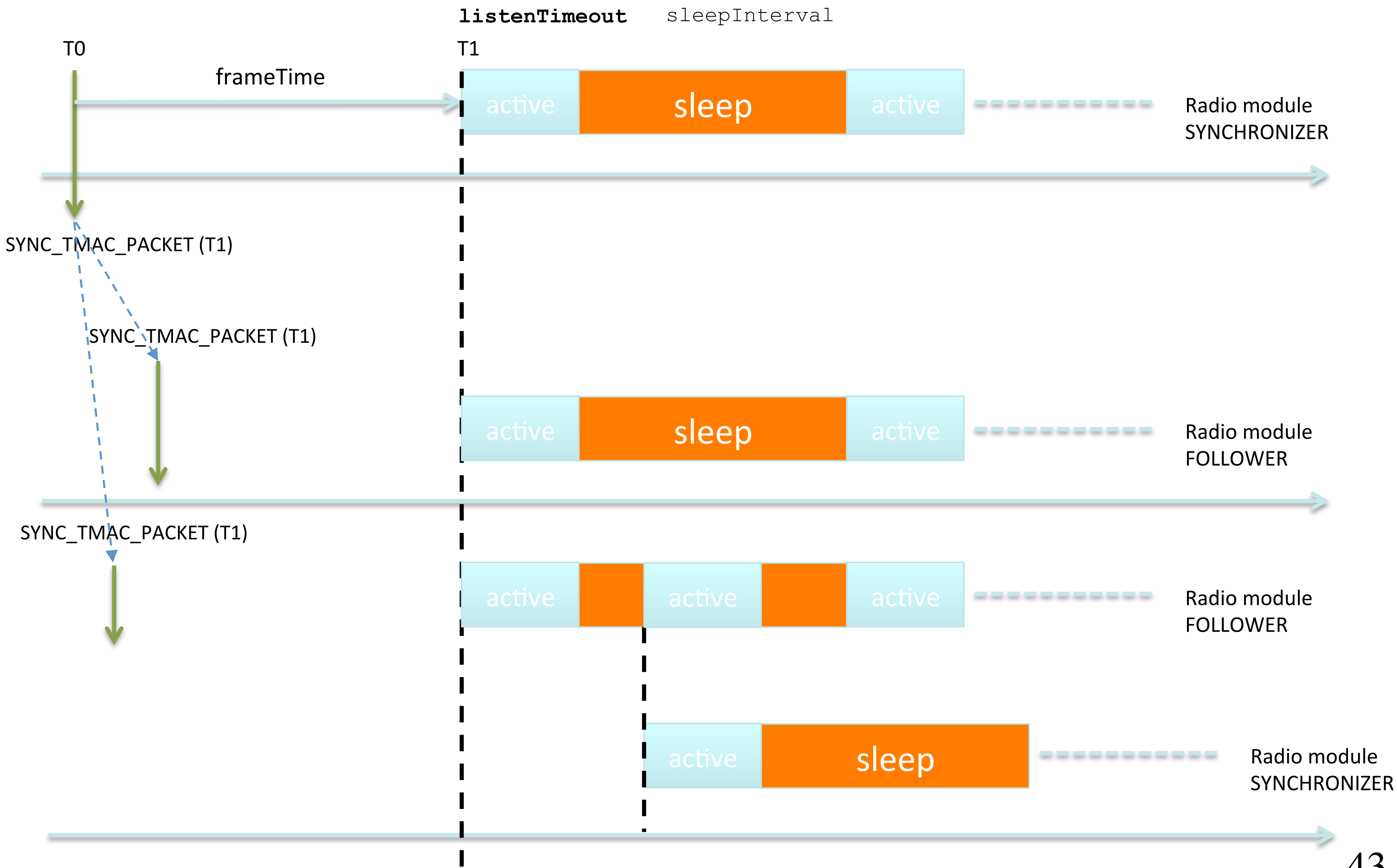
S-MAC - Sensor MAC

- Nodes periodically sleep such as duty-cycled approach
- Proposes a synchronization mechanisms between neighboring nodes to leverage the issues related to unsynchronous duty-cycled approaches
- Synchronization issues can become tough, nodes can be synchronized to 2 masters

Synchronized schedule

- If a node receives a schedule from a neighbor before choosing its own schedule, it just follows this neighbor's schedule.
- This node is called a FOLLOWER and it waits for a random delay and broadcasts its schedule.
- If a node receives a neighbor's schedule after it selects its own schedule, it adopts to both schedules and broadcasts its own schedule before going to sleep.
- FOLLOWER nodes can have 2 masters to enable data transfers between parts of the network

Synchronizing with Schedules in Image

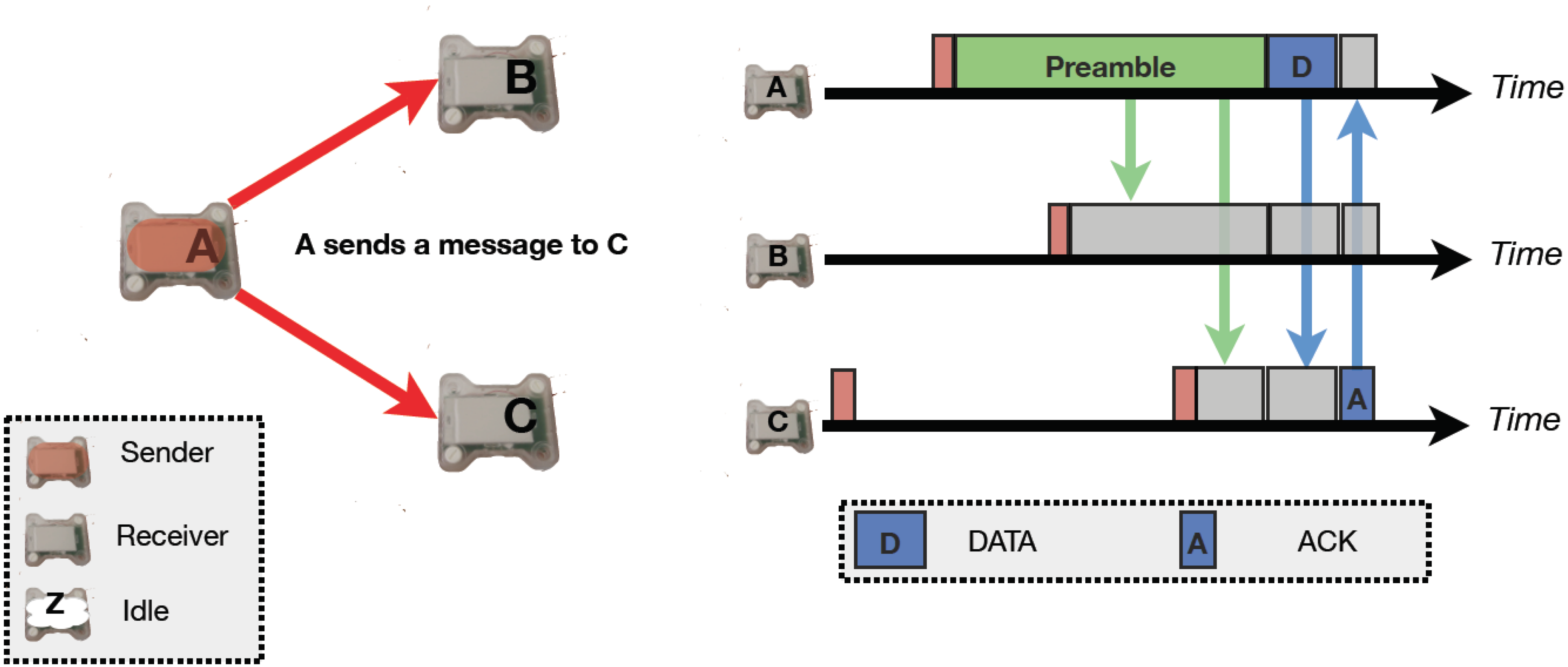


Low Power Listening MAC: LPL, BMAC, XMAC, ...

Principles

- Low Power Listening usually refers to the usage of a preamble to announce an imminent data packet
- Can be similar to duty-cycled with beacon packet, but strictly speaking, LPL needs radio capabilities to listen for the preamble with a lower energy consumption
- Need to distinguish preamble from noise floor

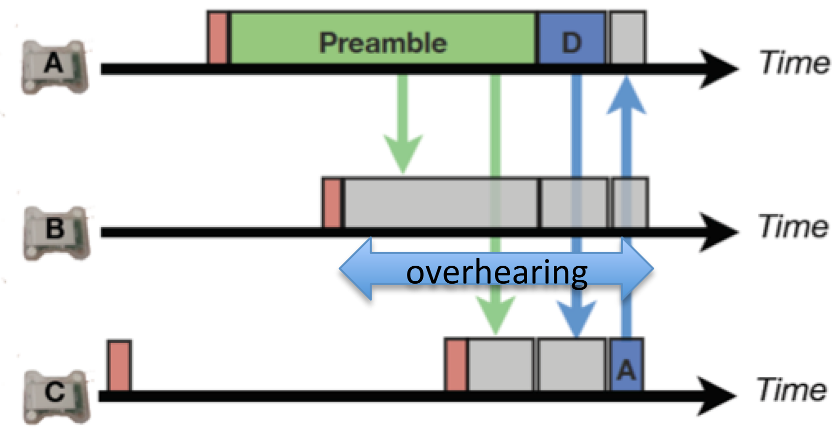
LPL ILLUSTRATED



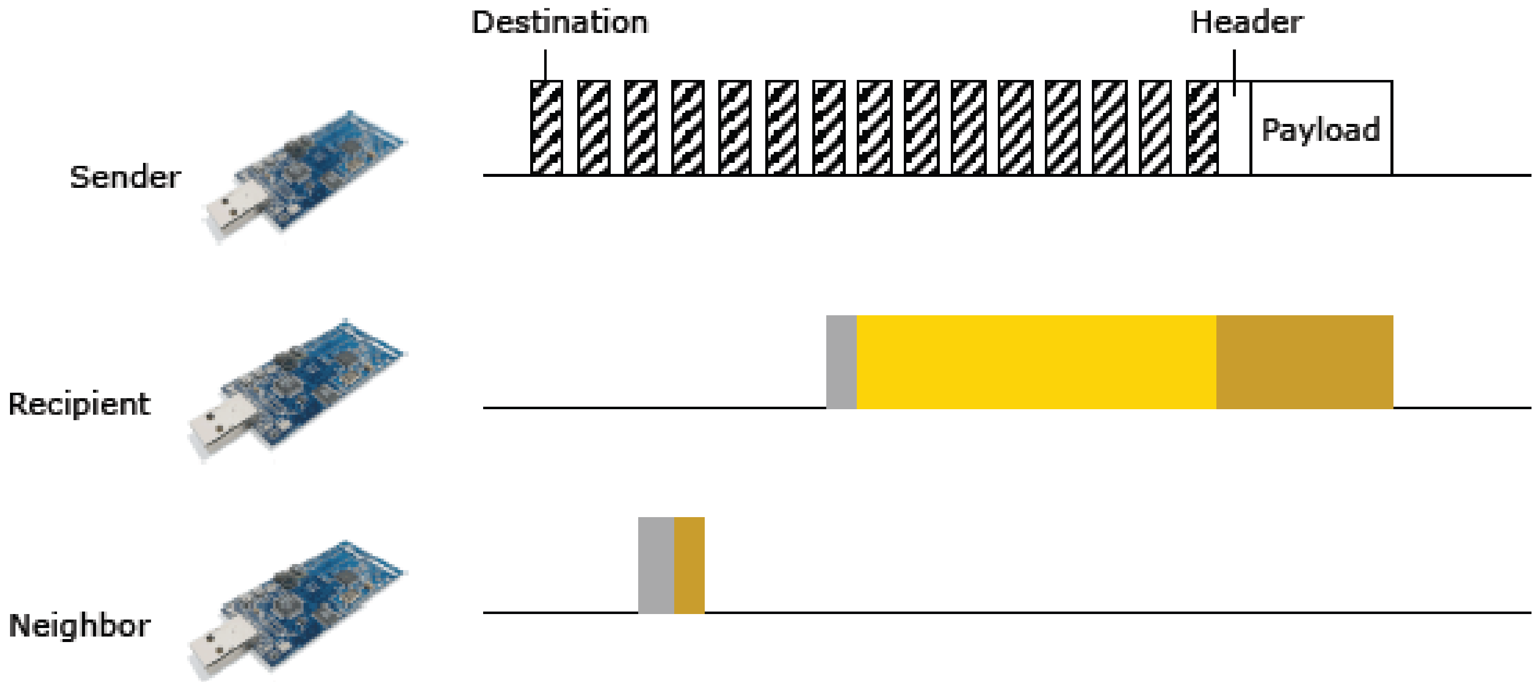
From R. Kuntz

B-MAC

- Berkeley-MAC, based on LPL
- Improved LPL with Clear Channel Assessment
  - Measures the SNR by taking a moving average when there seems to be no traffic
  - Reduces the number of false negative
- Known problems
  - Long preamples are constly for the sender
  - High cost of collisions due to long preamples
  - Still the overhearing problem

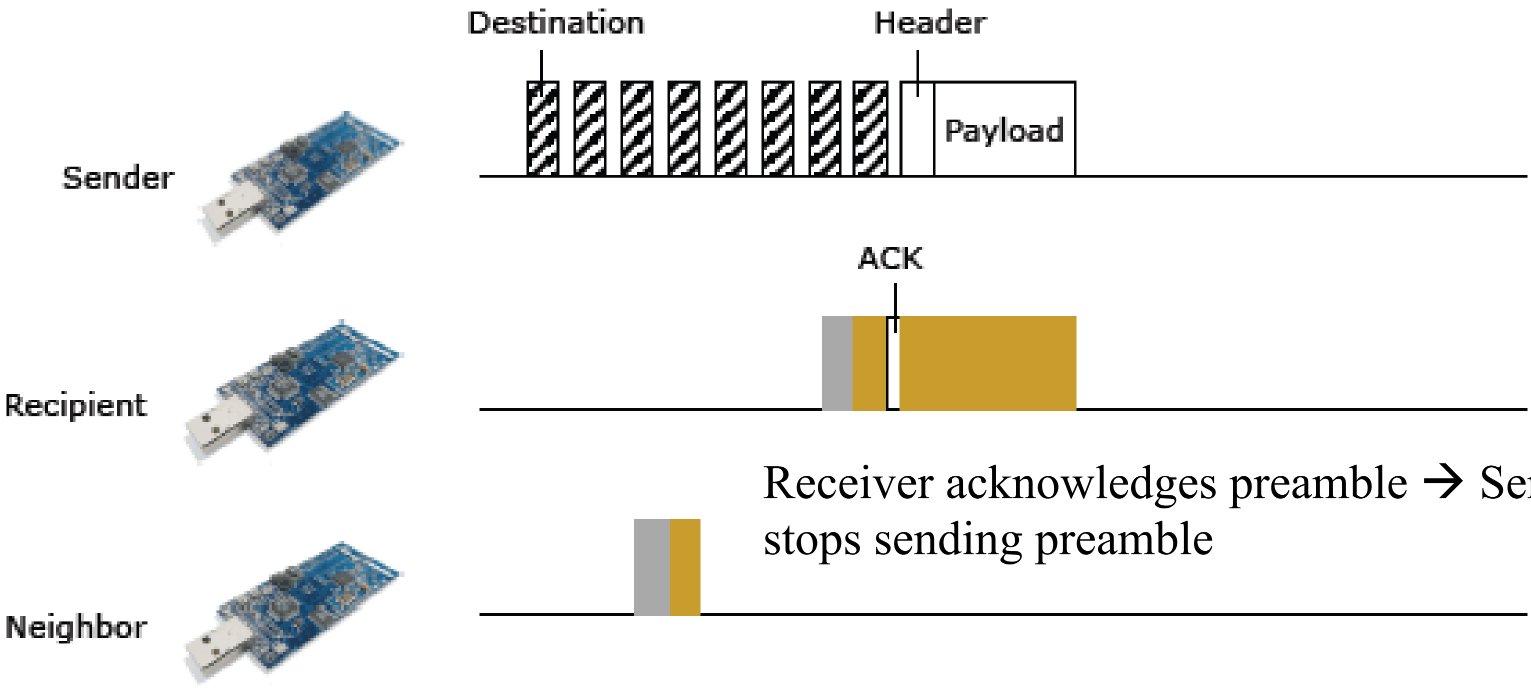


Overhearing avoidance



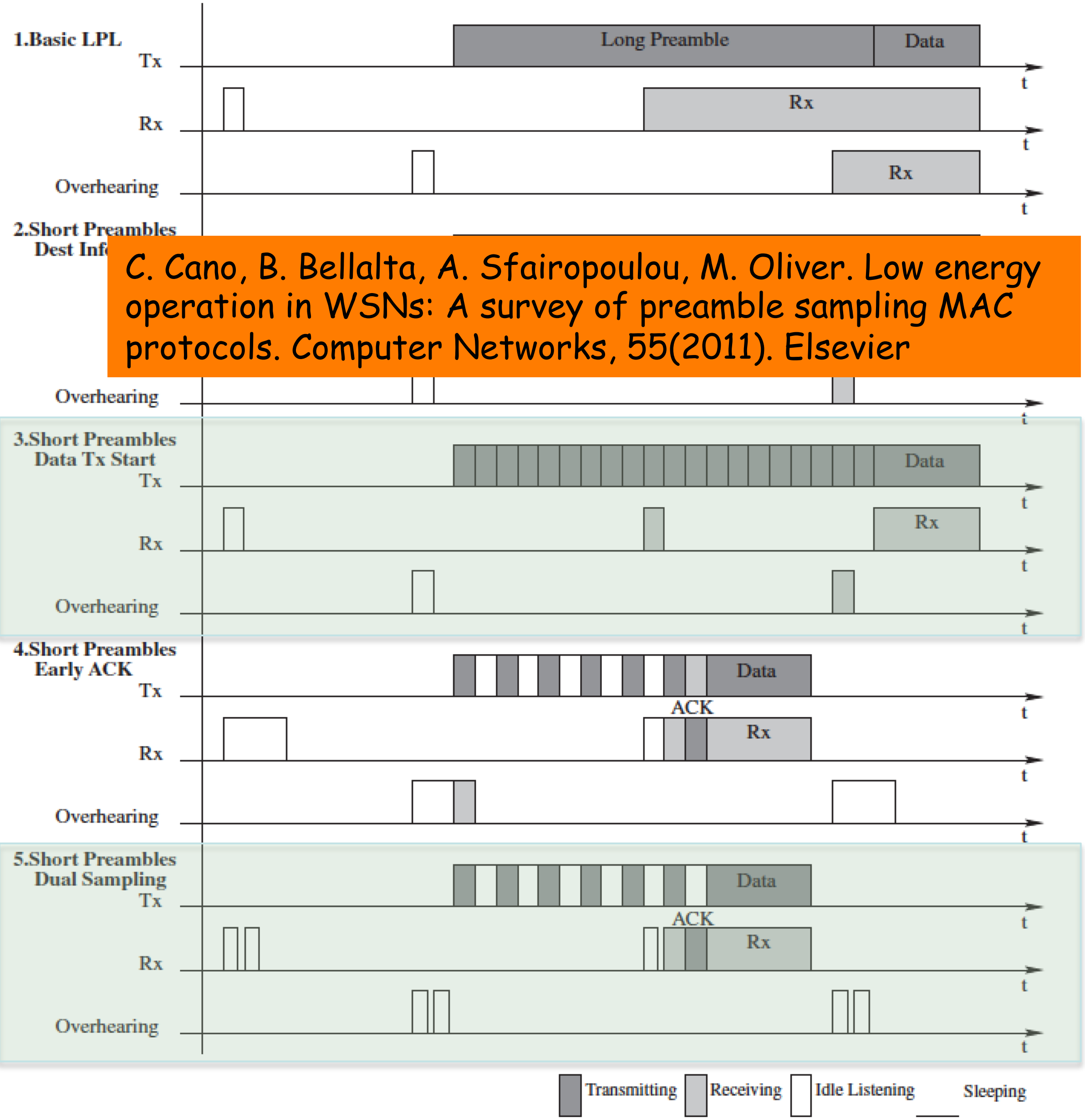
- Include destination address in short preambles
- Non-receiver avoids overhearing

Early ACK



Receiver acknowledges preamble → Sender stops sending preamble

Lot's of variants!!



C. Cano, B. Bellalta, A. Sfairopoulou, M. Oliver. Low energy operation in WSNs: A survey of preamble sampling MAC protocols. Computer Networks, 55(2011). Elsevier

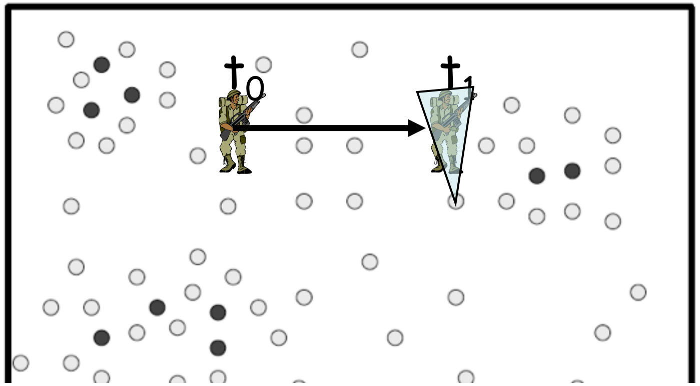
Lot's of variants, con't

- Packet-dependent behavior
- Duty-cycle length adaptation
  - Based on traffic load
  - Based on topology information
- Adapted for broadcast traffic
  - Hash of data in short packets
  - Identify « best » receiver for early ack
- Combined with synchronized approaches

Challenges for MAC protocols in WSN (1)

- Energy efficiency
- Low latencies
- Fairness

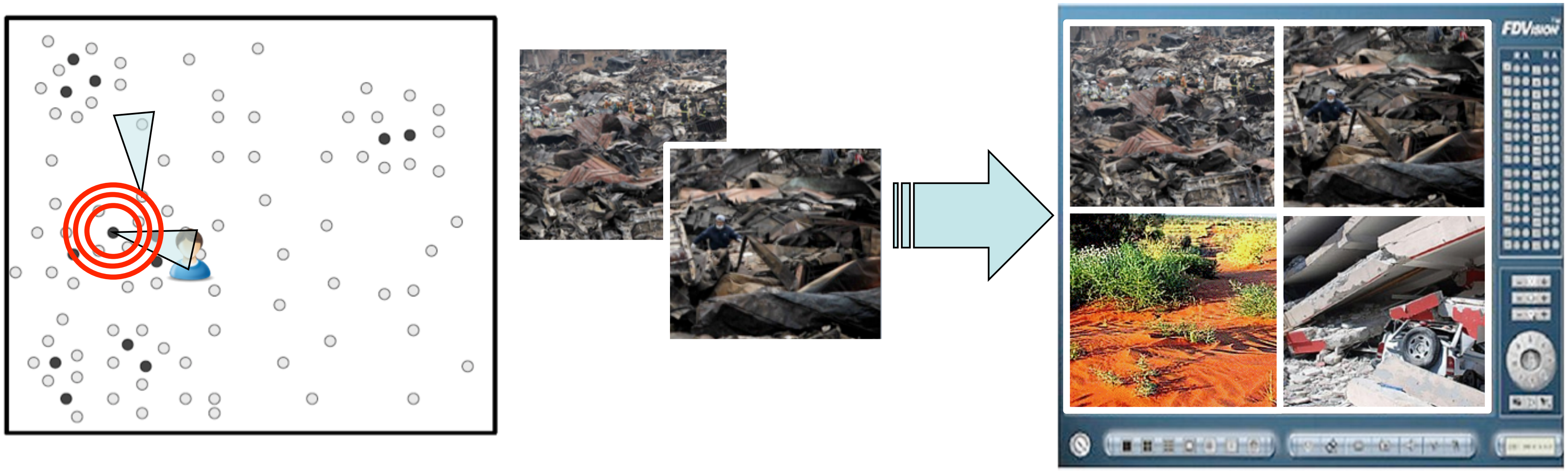
A CHALLENGE FOR MISSION-CRITICAL APPLICATION



Challenges for MAC protocols in WSN (2)

- Synchronous MAC
  - Adds latency
  - Difficult to maintain sync along the path
- Duty-cycle length adaptation
  - How to adapt?
  - Both traffic-based or topology-based do not take into account criticality

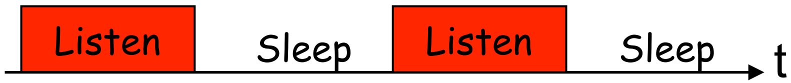
Image sensors for mission-critical surveillance



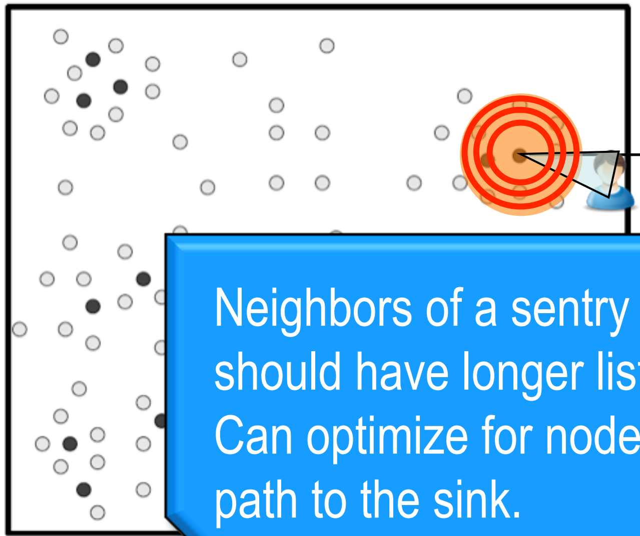
- Intrusion detection, identification, disambiguation
- Situation awareness

Our current research on MAC layer

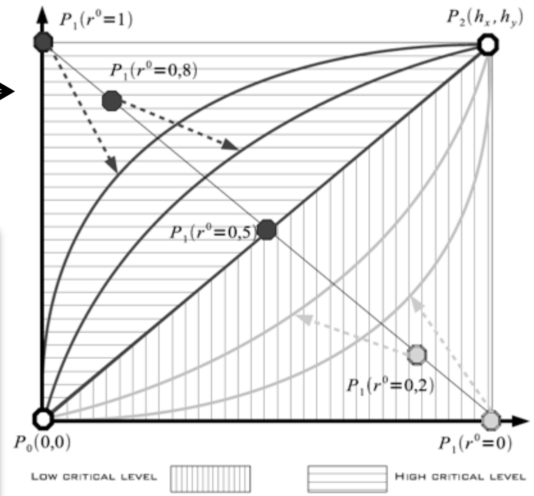
- Duty-cycled MAC



- Link the listening time to the criticality model



Neighbors of a sentry nodes should have longer listening time. Can optimize for nodes on the path to the sink.



Node's cover set

$\color{red}{Co(V)}$ = {

{V },

$\{V_1, V_3, V_4\}$,

$\{V_2, V_3, V_4\}$,

$\{V_3, V_4, V_5\}$,

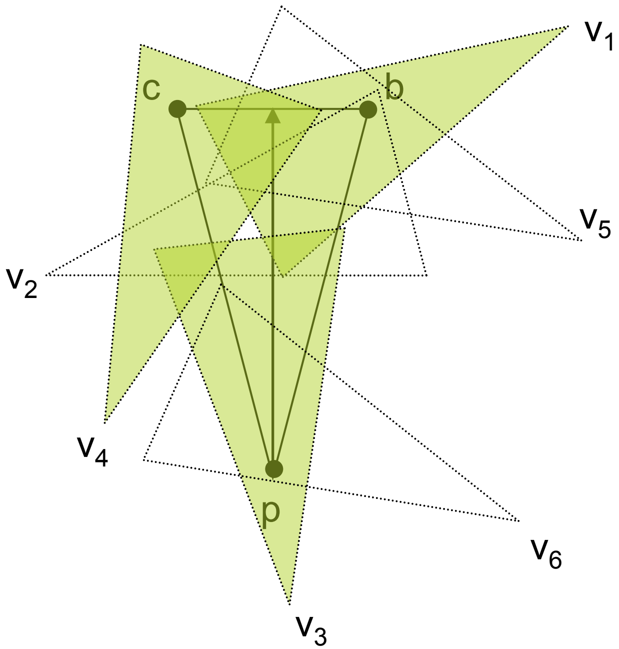
$\{V_1, V_4, V_6\}$,

$\{V_2, V_4, V_6\}$,

$\{V_4, V_5, V_6\}$

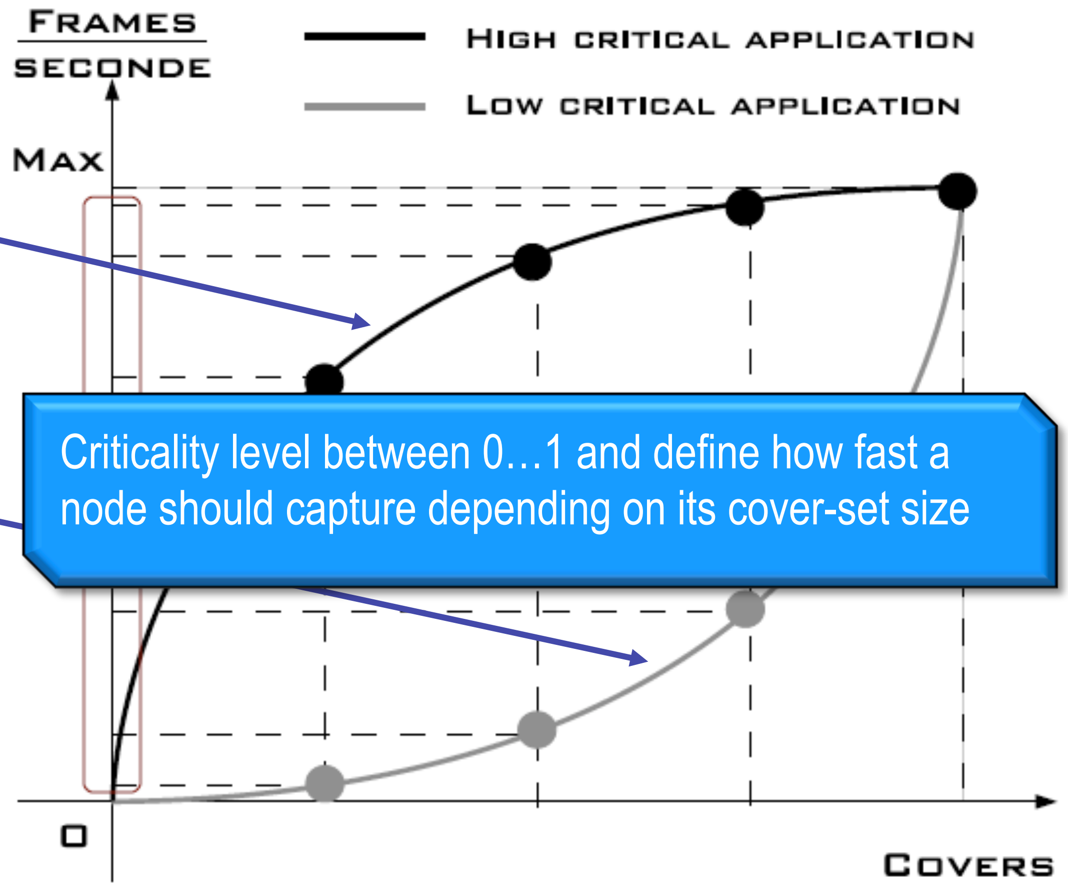
}

$\color{red}{|Co(V)|}$ = 7

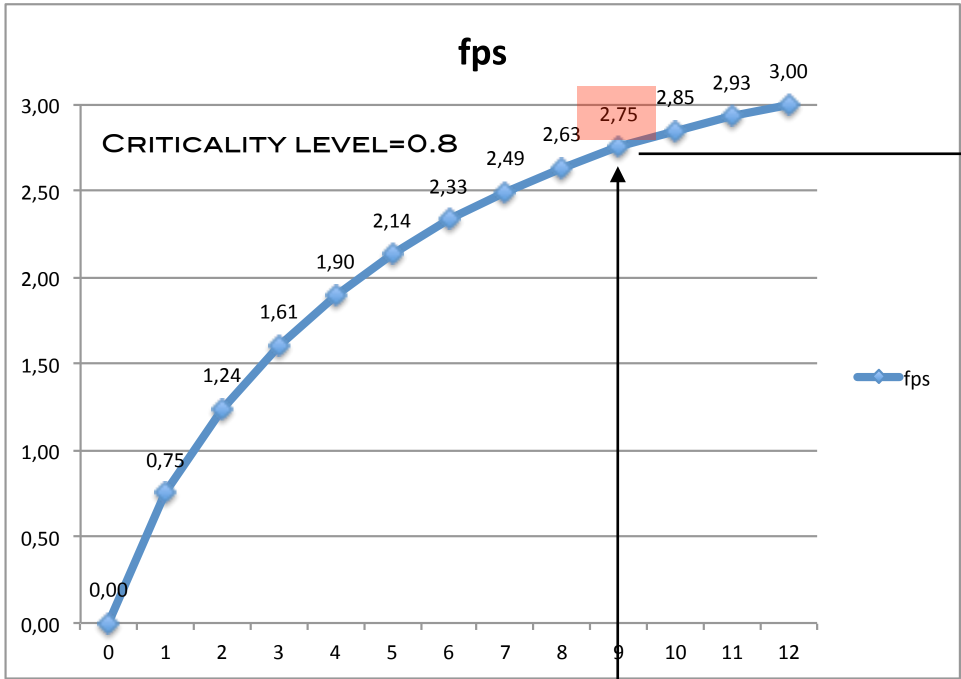


Criticality model (1)

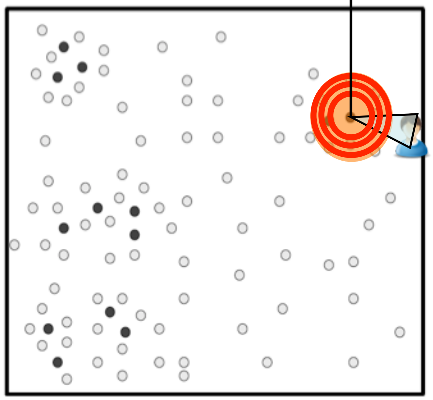
- Link the capture rate to the size of the cover set
- High criticality
  - Convex shape
  - Most projections of x are close to the max capture speed
- Low criticality
  - Concave shape
  - Most projections of x are close to the min capture speed
- Concave and convex shapes automatically define sentry nodes in the network

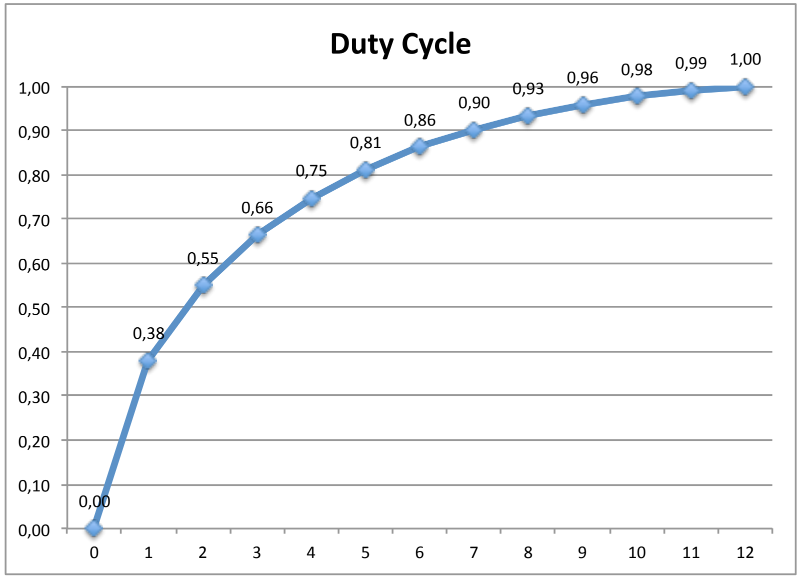


Criticality level and duty-cycle



2.75/3.00=0.91
new criticality level for neighbors





Each neighbors of a sentry node may have different listening time depending on the size of their respective cover-set.

Question?

RESSACS'13 à Brest

www.univ-pau.fr/~cpham/iWEB/RESSACS13