Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: [NICT's MAC proposal for TG6]
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Abstract: [NICT's MAC proposal to TG6]

Purpose: [In response to TG6 call for proposals]

NICT's MAC proposal

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National Institute of Information and Communications Technology (NICT)

Outline

- TG6 requirement and overview
- TDMA based BAN superframe
  - Slot design
  - Contention access period (CAP), contention free period (CFP) and ACK
  - Priority access period (PAP)
- BAN group superframe
  - Concept of group superframe
  - Non-beacon mode
  - Power efficient beacon
  - Usage cases and coexistence
- Self-evaluation
- Backup slides
  - Simulation
  - Protocol diagram
  - Major questions to previous proposal

§1. TG6 requirements and overview of proposed MAC protocol

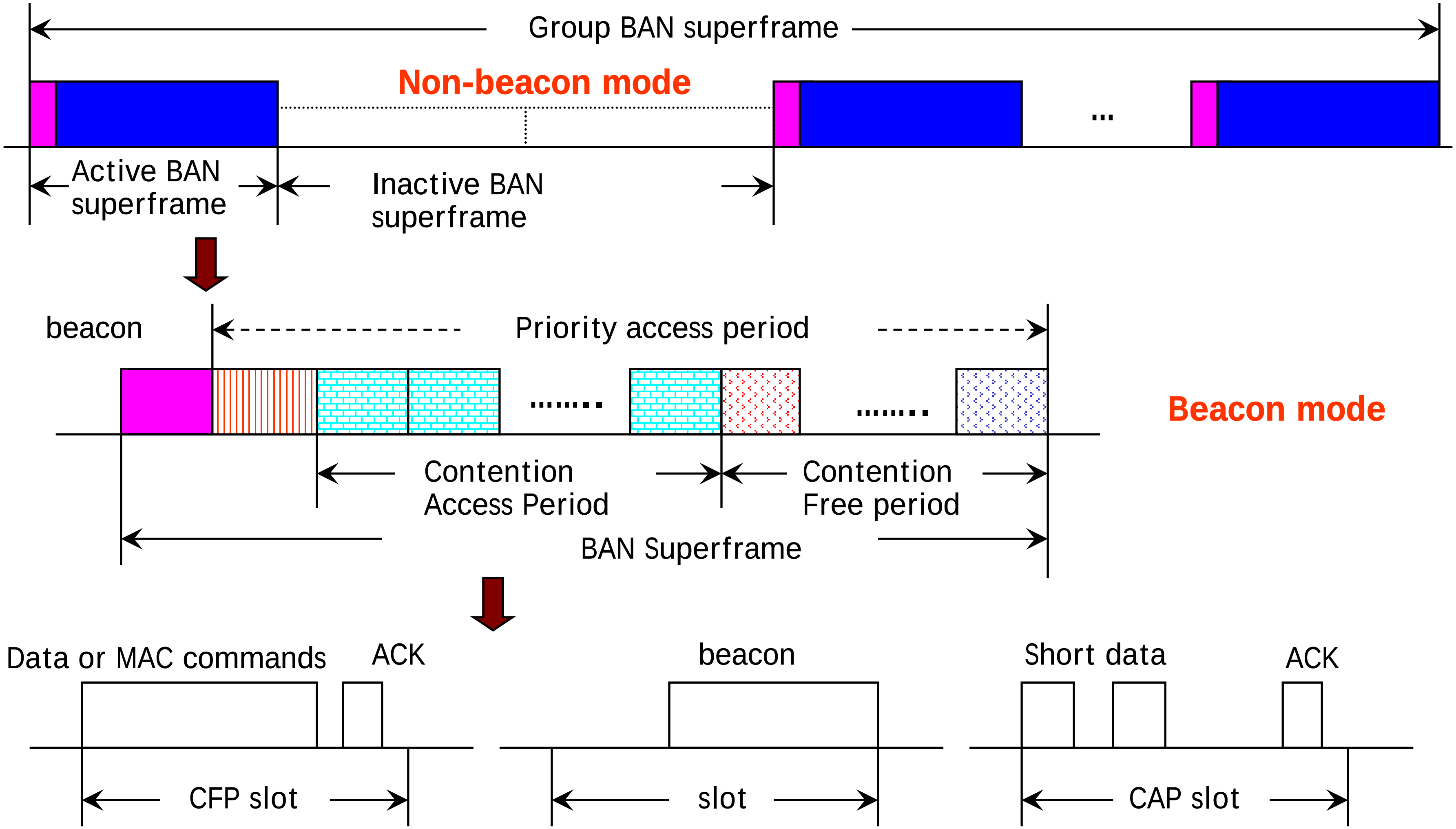
Usage scenarios

- Medical and multi-media applications on/in a same person or near space
  - Periodical vital information collection or diagnosis command from doctor
  - Video and audio for entertainment
- Operation environment includes home, hospital, small clinic, fitness center, etc
- Up to 256 sensors/actuators or device in a piconet
  - Devices can be on the surface of body, under the skin or in the deep tissue

MAC requirements

- Dependability and QoS guarantee
  - Real time and life-critical message → Priority access and CFP
- Scalability
  - Possible multiple PHYs → TDMA based BAN superframe
  - data rate
  - duty cycle and network size → (group) BAN superframe
- Low power consumption
  - → Power efficient beacon, non-beacon mode

Overview of MAC proposal



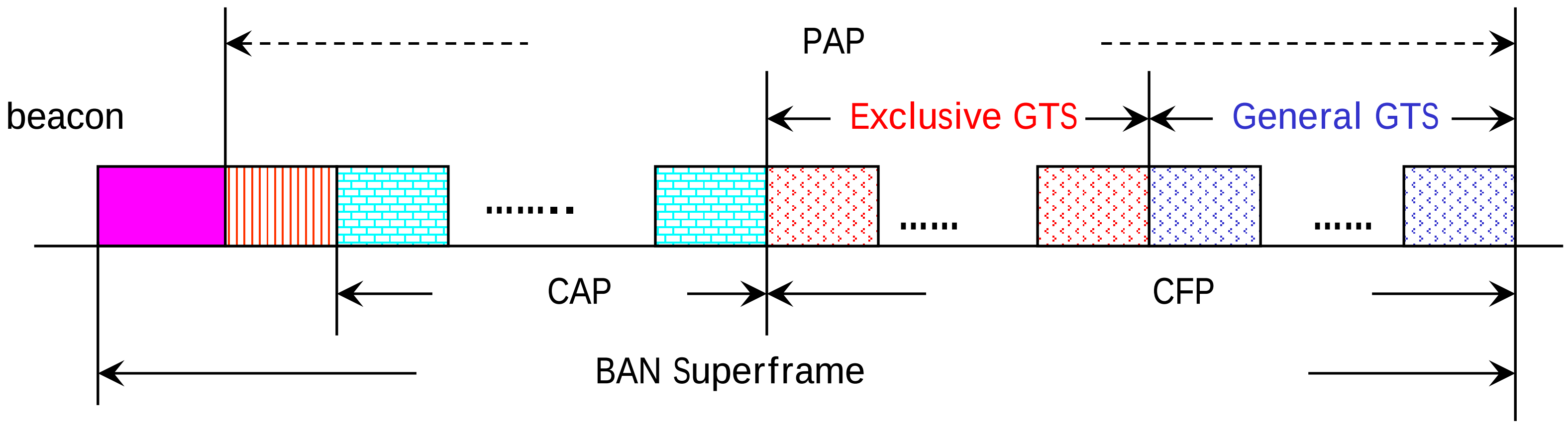
- Beacon mode: TDMA based BAN superframe
  - Contention access period (CAP)
    - Minislots in CAP and group ACK → to increase contention efficiency
  - Contention free period (CFP) → to guarantee QoS
  - Priority access period (PAP)
    - Priority slot and embedded priority period → for life-critical and emergency traffic
  - All slots in BAN superframe are equal duration → easy implementation
  - Mandatory ACK except beacon
  - Power efficient beacon → for low duty cycle node
- Non-beacon mode
  - → for very low duty cycle traffic and uplink medical event
- Group BAN superframe
  - → for dynamic duty cycle and network scale

§2. TDMA-based BAN superframe

Motivations

- A unified MAC to meet BAN requirements
  - QoS, network scalability, different PHYs
  - Different priorities: ECG vs. music
- Easy to be implemented by chip maker

TDMA-based BAN superframe



- A superframe consists of beacon, CAP and CFP
  - CFP is further divided into exclusive portion and general portion
    - Exclusive portion: for life-critical traffic whose radio resource cannot be withdrawn due to other's applications, e.g. waveforms in ICU
    - General portion: for general purposes of guaranteed traffic
  - Priority access period (PAP) is partially overlapped with CAP and CFP
    - One fixed priority slots is optional

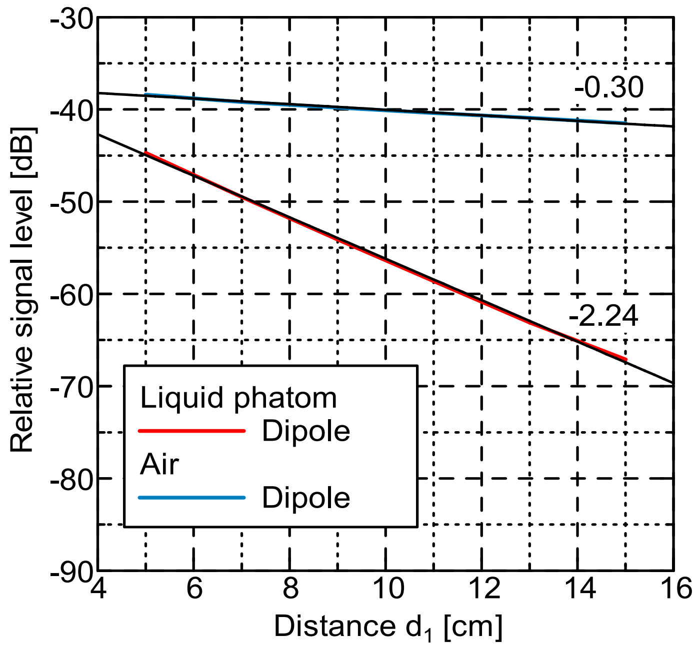
- A BAN superframe consists of constant number of equal duration slot
  - Even number of slots in a superframe, e.g. 16 or 32
  - A BAN superframe has *1+1+Na+Nf* slots
- CAP
  - Mainly for uplink GTS request and short data packet
    - Asynchronous short data packet, link management
  - Contention based slotted ALOHA
- CFP
  - For both uplink and downlink communication
    - Isochronous stream and allocated burst traffic
  - Contention free slot allocation by BAN coordinator
- PAP
  - Especially for priority traffic

Why TDMA-based BAN superframe?

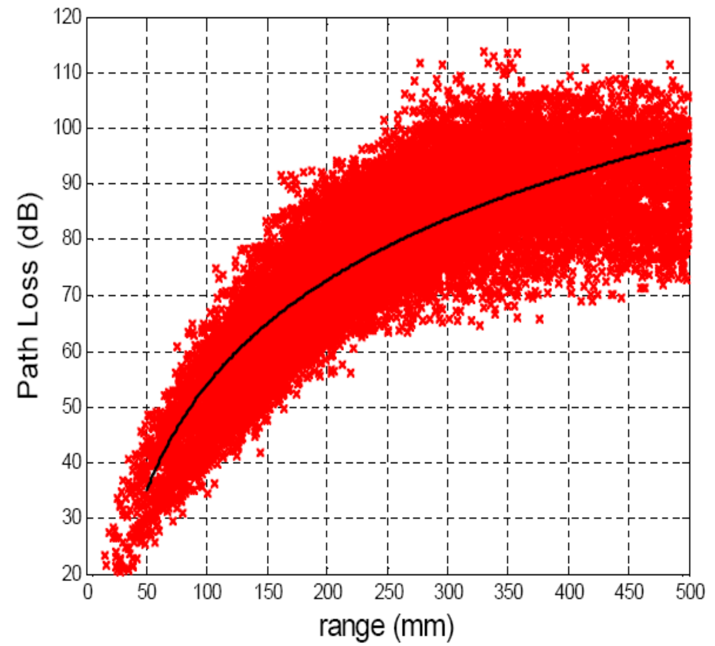
- Channel sensing cannot be guaranteed in all BAN frequency bands and scenarios
  - UWB systems
  - NLOS of on-body of narrow band systems
  - Implant systems (<300mm)
  - Dynamic environment with human movement
- Unreliable channel sensing leads to ‘hidden nodes’ in CSMA, which deteriorate system performance severely.

- MICS systems

- For both implant-implant and implant-on body, the device can conduct channel sensing within 250 mm
  - This distance is too short for most applications

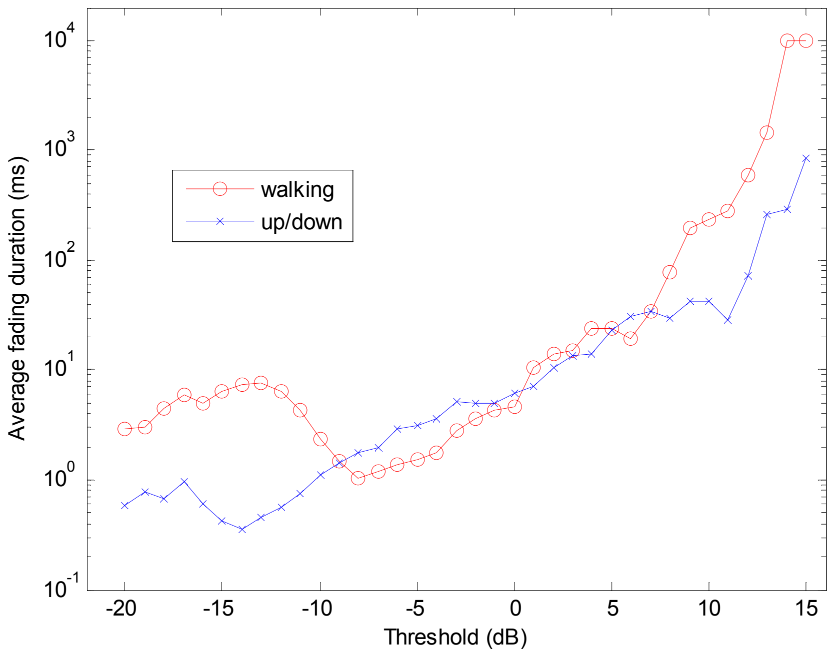


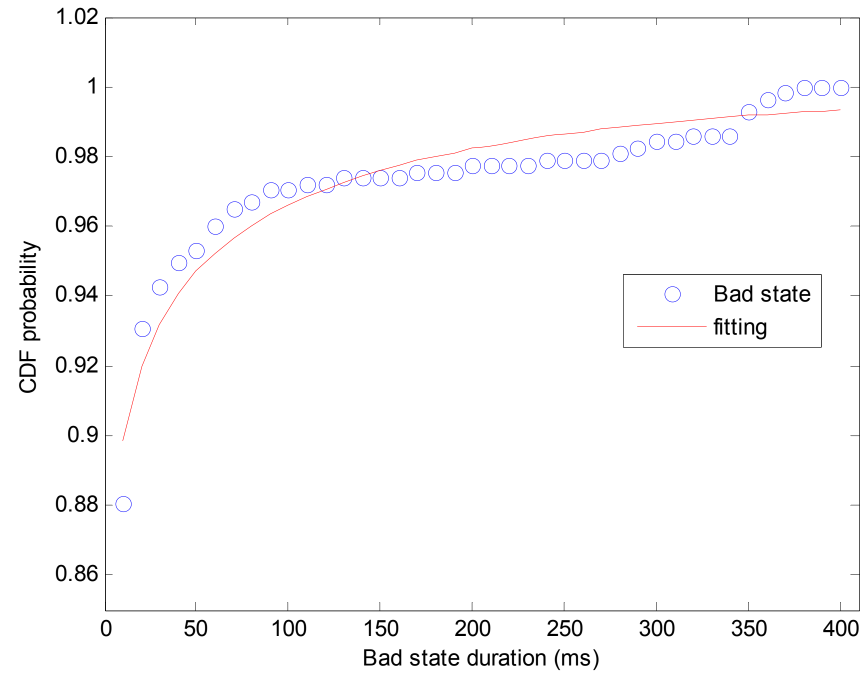
Implant-body surface (08-0416-03)



Implant-implant (08-0519-01)

-Human movements





-10 dB threshold

- Signal lower than a threshold, e.g. -10dB, usually leads to frame error or channel sensing error
- It is true even for narrow band systems

§2.1 Slot design

Motivations

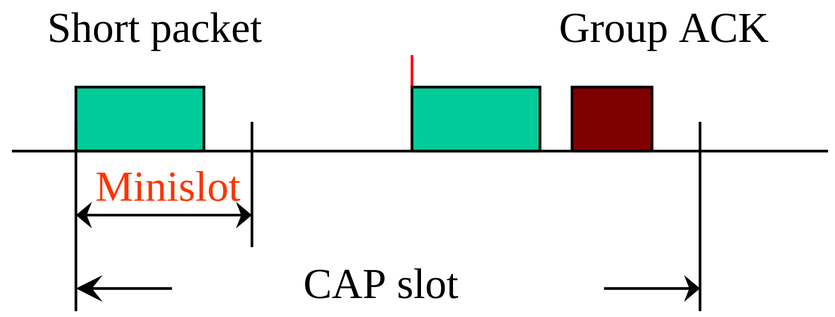
- To increase contention efficiency in CAP
- To guarantee QoS in CFP
- To consider easy implementation

Slot design

- Slot in the BAN superframe consists of data packet and ACK
- An equal slot duration for easy implementation
  - To be determined by the lowest mandatory data rate in a PHY
  - Slot duration should be optimal for most applications
    - High data rate may have more payload bytes
  - Duration of slot is configurable
    - Optional feature
- Communication only starts at the beginning of the slot

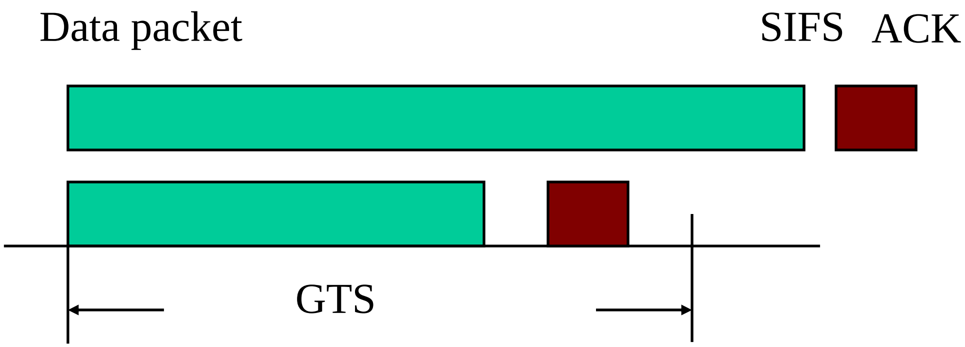
Minislots in CAP

- Slots in CAP are for channel contention
- 4 minislots in a CAP slot
  - 3 times capacity slotted ALOHA
  - The number of 4 is tradeoff
- Three minislots share a group ACK
  - The last minislot is for group ACK
- No cross-boundary communication in CAP



Guaranteed time slot in CFP

- Slots in CFP are Guaranteed time slots (GTS)
- A GTS consists of a data packet and an ACK
  - A data packet may cross two continuous GTS if they are allocated to the same link



§2.2 CAP, CFP and ACK

Beacon slot

- Beacon transmit depends on PHY
  - For MICS PHY, channel sensing by coordinator is mandatory before beacon per FCC rule
  - For other PHYs, beacon can be directly transmit
- Beacon can do time hopping or frequency hopping to avoid jamming attacks
  - Beacon can be in wakeup radio channel

CAP

- CAP is mainly for channel contention
  - The number of slot in CAP is configurable
- Minislot can be used for GTS request and short uplink data packet
  - The short packet can be ID packet, link request etc.
- Limited payload for packet in a minislot
  - 1/4 of a slot

CFP

- CFP is mainly for data transmit and/or re-transmit
  - GTS can be uplink/downlink
- GTS are classified into general GTS and exclusive GTS
  - To support different priorities of data streams, e.g. music vs. ECG
    - Exclusive and general are attributes of GTS. They are not necessary consecutive in physical
  - BAN coordinator can actively de-allocate the general GTS allocation for the new exclusive traffic
- GTS in CFP are allocated by BAN coordinator
  - Life time attribute of GTS allocation
    - It can be a BAN superframe, group BAN superframe or more
- Free GTS are unallocated GTS in a BAN superframe
  - Re-transmission in case of packet error
  - Down link traffic
- Number of GTS in BAN superframe is configurable
  - Scalability in QoS

Information piggybacked ACK

- Mandatory ACK packet in CAP, CFP and PAP
  - ACK in CAP is group ACK
- To confirm packet reception
- To piggyback GTS allocation in CFP
  - ACK to packet in CAP
    - To receive downlink command or data from coordinator
  - ACK to packet in CFP and PAP
    - The second chance for corrupted packet in the same BAN superframe
- Benefits of piggybacked information
  - To increase capacity of CAP
  - To reduce latency and power consumption in CFP and PAP

§2.3 Priority access period

Motivations

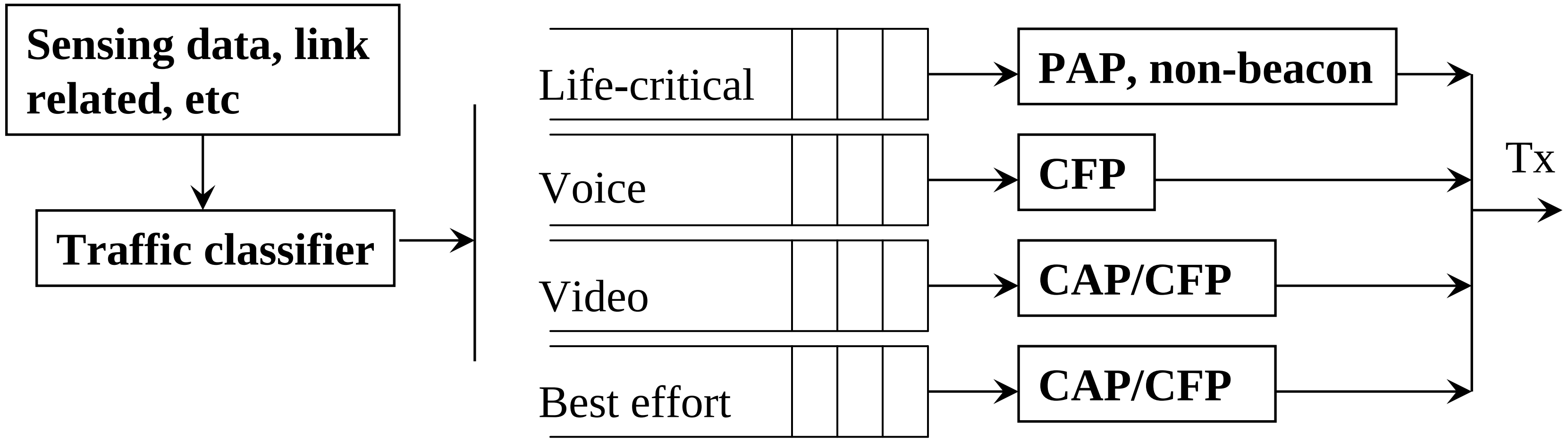
- Medical events that are life-critical
  - Abnormal vital information or state
    - Body temperature > 40ºC, fall
  - Abnormal sensor states
    - Sensor is out of order
- Transmit of life-critical medical message should be guaranteed and ASAP
- FDA requires guaranteed medical communications

What is priority traffic?

- The life-critical medical events are priority traffic
  - Priority traffic is a segment of data stream with an abrupt change in (usually more stringent) QoS and reliability requirement
    - A waveform in intensive-care-unit (ICU) can be done by the exclusive GTS
- Characteristic of priority traffic
  - Priority traffic can be uplink or downlink after the link have been established
  - Very low duty cycle (e.g. <0.01%)
  - Limited payload (maybe several bytes)

Priority traffic

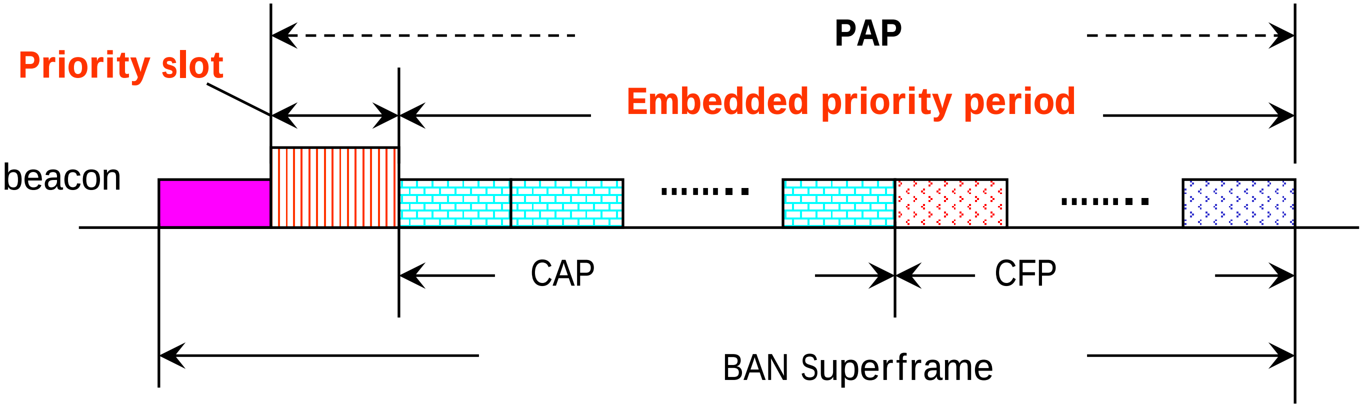
- Traffics must be classified and buffered in queues
  - Different traffic categories should be buffered in different queues
- Priority traffic go first in a BAN superframe



(IEEE 802.1D)

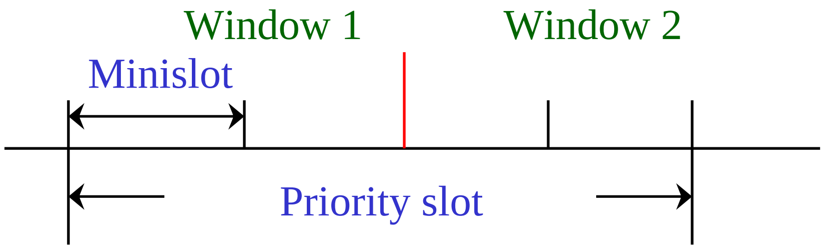
Priority access period

- Only priority traffic can take PAP
- PAP can be
  - an optional priority slot, and
  - embedded priority period: the free period in CAP and CFP

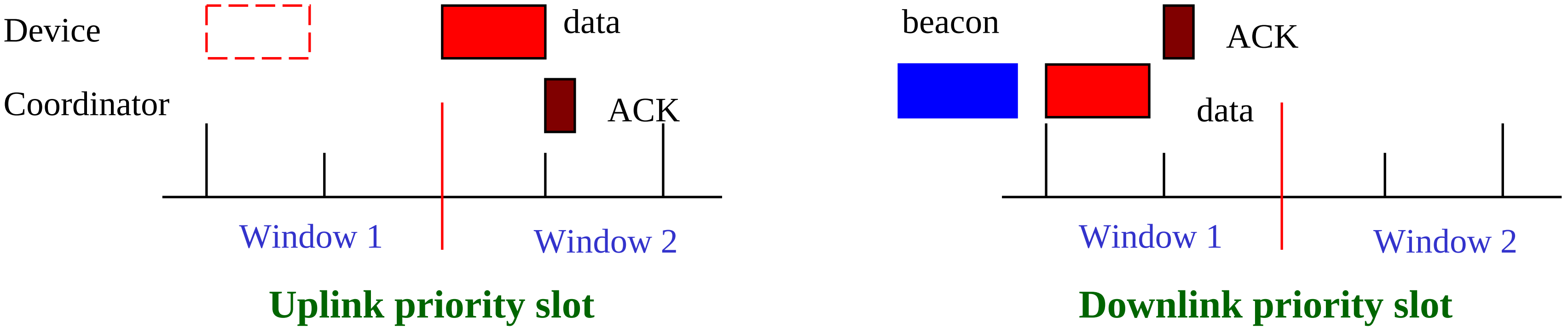


Priority slot

- Priority slot is the slot immediately after beacon in the BAN superframe
  - Two communication windows in 4 minislots
  - Priority slot is allocated by beacon
  - Priority slot is optional
- Priority slot guarantees the upper limit of the priority traffic delay
  - Priority slot can be uplink or downlink as indicated by beacon



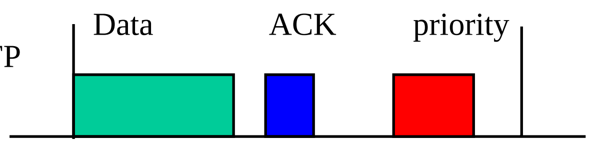
- Beacon broadcasts direction of priority slot and pending priority traffic in beacon
- Uplink priority slot
  - Coordinator enters receiving state in if there is no pending priority traffic
  - Device can randomly select a window
- Downlink priority slot
  - Coordinator transmits pending priority traffic and wait for ACK
  - Tow priority traffics in two windows
- If priority slot fails, go to embedded priority period



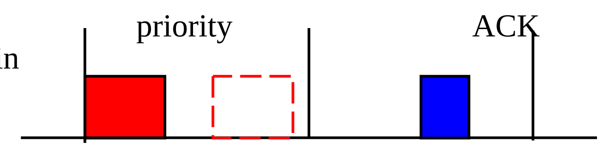
Embedded priority period

Case 1: free GTS

Case 2 in CFP



Case 1: slots in CAP



- Case 1: a free slot
  - All minislots in CAP except ACK are free slots
  - Unallocated GTS
- Case 2: a busy GTS
  - the free period in GTS if it is long enough
    - Due to equal slot division, there may be some free space after ACK
    - Allocated GTS should be protected
- After transmit priority traffic, the device waits for ACK
  - ACK to priority traffic take the next transmission chance

Detection of channel free period in case 2

- Coordinator assisted detection
  - Coordinator broadcasts BUZZ signals once the GTS is free
  - Device with priority traffic listens the BUZZ signal in all GTS
  - The BUZZ signals depend on PHYs
  - The need of cooperation between coordinator and device
- Device detection
  - Device actively conducts channel sensing to detect free space in a GTS
  - "Hidden node" issues of channel sensing

§3 BAN group superframe

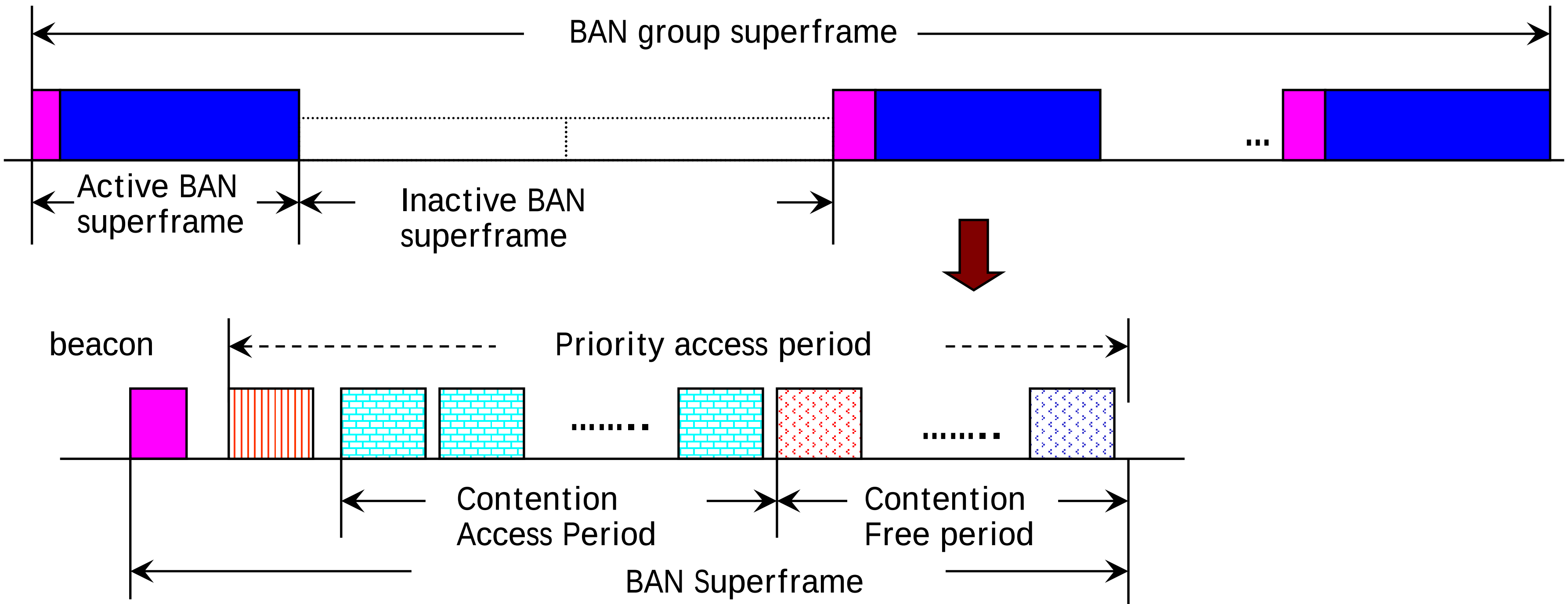
§3.1 Group Superframe

Motivations

- Dynamic BAN
  - Network scalability
    - Up to 256 devices in a piconet, and typical network size is about 10
  - Traffic duty cycle
    - Low duty cycle <0.1%
    - Medium and heavy duty cycle for non-medical traffic
  - Data rate of real time traffic
    - Audio *vs.* video, ECG *vs.* EMG
- How to guarantee the QoS and maintain the low power consumption?

BAN group superframe

- A BAN group superframe consists of *N* superframes
  - Each BAN superframe can be active or inactive
    - No beacon in the inactive BAN superframe
  - The interval between adjacent active beacons is defined by beacon order



Benefit of BAN group superframe

- To provide data rate and QoS support
  - Totally there can be up to N*Nf GTS in a BAN group superframe
  - More than one slot in a BAN group superframe can be allocated to a link
- To provide dynamic duty cycle support
  - Scheduled and synchronized active and inactive period
  - Power saving by distributed optional beacon listening
    - Device may skip some beacons per its duty cycle
  - Easy for multihop support and radio resource computation
- To provide a hardware clock to upper layer
  - BAN superframe can be time unit
- Inactive BAN superframe can be used to enable multi-hop and multiple BAN coexistence

Why it is better than a long BAN superframe?

- Short and practical beacon frame
- Extension to 802.15.4
  - Easy for chip maker
- Clock offset after beacon in the BAN superframe
  - Some devices may enter inactive mode after the beacon until its slots
- More flexibility

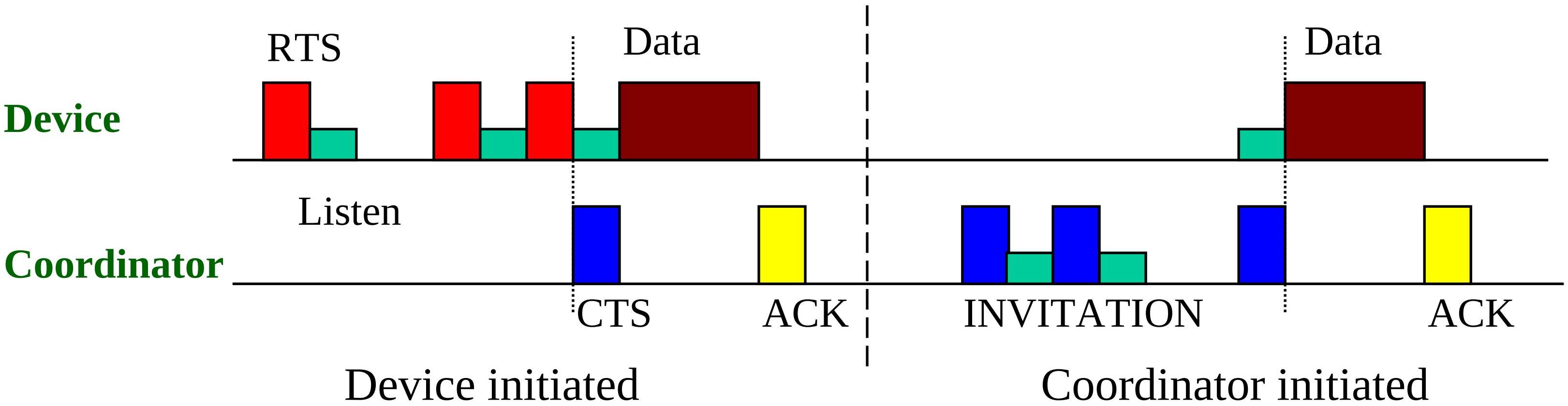
§3.2 Non-beacon mode

Two motivations

- Some FCC rules
  - Implanted medical device in MICS band can transmit immediately in case of some medical events
- For very low duty cycle devices, periodical listening to the beacon is power consuming

Non-beacon mode communication

- Who can use non-beacon mode?
  - Medical events from medical sensors
  - Device with very low duty cycle traffic
- Channel access in non-beacon mode
  - Pure ALOHA or CDMA (depend on PHY) based handshake due to clock offset after long time sleep
  - The handshake should also consider power consumption
    - Coordinator initiated method
    - Device initiated method



- Non-beacon mode should be used in inactive BAN superframe
  - Devices in non-beacon mode do not need to listen beacon before communication
  - Coordinator enters receiving state in inactive period periodically or upon command from application layer
    - Coordinator and Devices should negotiate the non-beacon mode time if coordinator is not always ready for reception
    - Coordinator and devices are pseudo-asynchronous (in application layer)
  - Non-beacon communication shall be finished before active BAN superframe to avoid collision with beacon mode
    - There should be enough guard time to combat clock offset
    - Coordinator can stop non-beacon communication during handshake

Coexistence between beacon mode and non-beacon mode

- After long time sleep, devices in non-beacon mode may lose the clear border of inactive BAN superframe.
  - Packets in non-beacon mode may collide with packets in beacon mode
- The collisions are low probability because the total traffics in non-beacon mode are low duty cycle
  - <0.1% duty cycle per device
- Devices in non-beacon mode have more or less BAN superframe information
  - Device's clock can be refreshed in the non-beacon mode communication, e.g. through MAC command

Non-beacon mode *vs.* beacon mode

	Beacon mode	**Non-beacon mode**
Who	Normal traffic	Medical event from sensor, or very low duty cycle traffic
When	Active BAN superframe	inactive BAN superframe
How	Slotted ALOHA and TDMA	Pure ALOHA (narrow band PHY) or CDMA (UWB PHY), handshake
Mode switch	Coordinator informs device the period of active and inactive superframes. Coordinator and device negotiate the time of non-beacon mode. Coordinator enters reception state at the negotiated time.	
	Default mode, when battery is draining	When communication fails

	Beacon mode	Non-beacon mode
Direction	Uplink and downlink	Uplink only
Advantage	Guaranteed QoS	Low power consumption
Clock	Accurate MAC clock maintained by beacon listening	Coarse clock in application layer
Coexistence	Low probability of packet collision	
	MAC clock	Cooperation between device and coordinator

- Non-beacon mode is a "minimum function set" for medical applications in the case of beacon jamming attack
- Reliability and QoS in non-beacon cannot be guaranteed
  - Asynchronous clock, pure ALOHA and possible poor channel quality
  - Resource limited sensors

§3.3 Power-efficient beacon

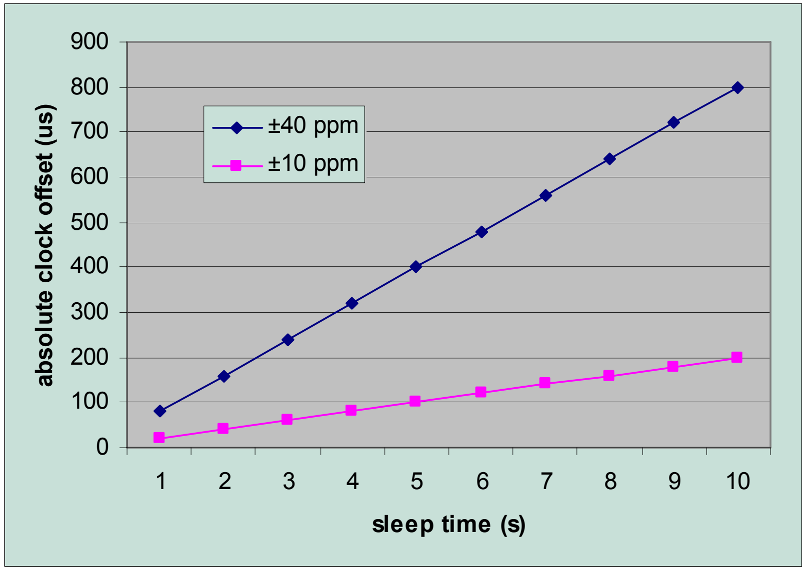
Motivations

- When and how to wakeup an inactive device with the least power consumption?
  - Dynamic duty cycle of BAN devices
- The clock is maintained by beacon listening
  - Typical clock accuracy is ±40ppm

Sleep time

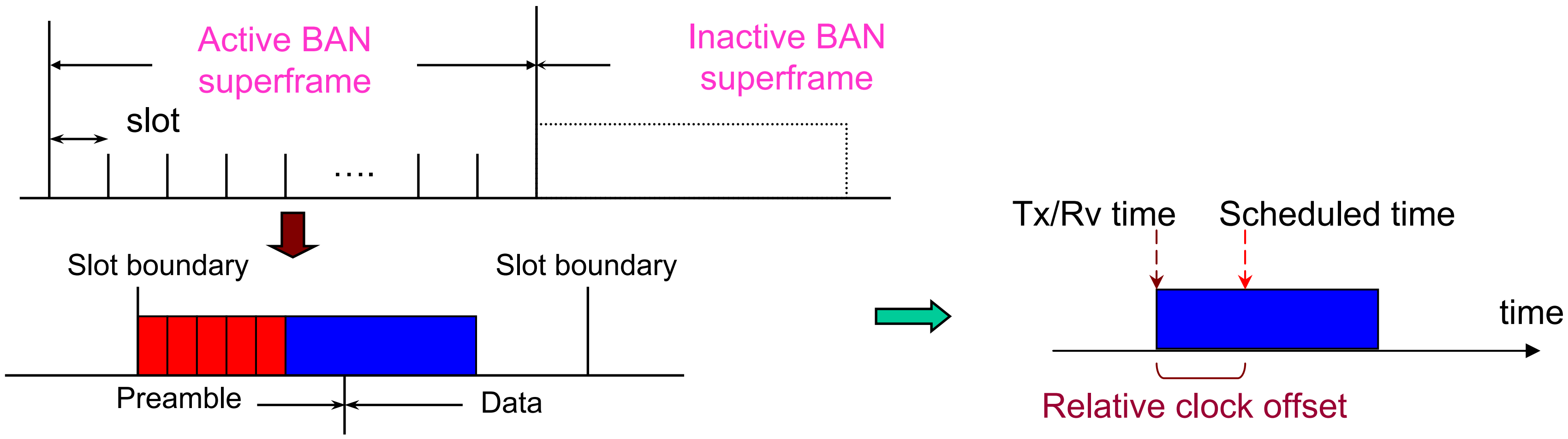
$$\Gamma = 2|\theta| L$$

Clock accuracy: drift in unit time



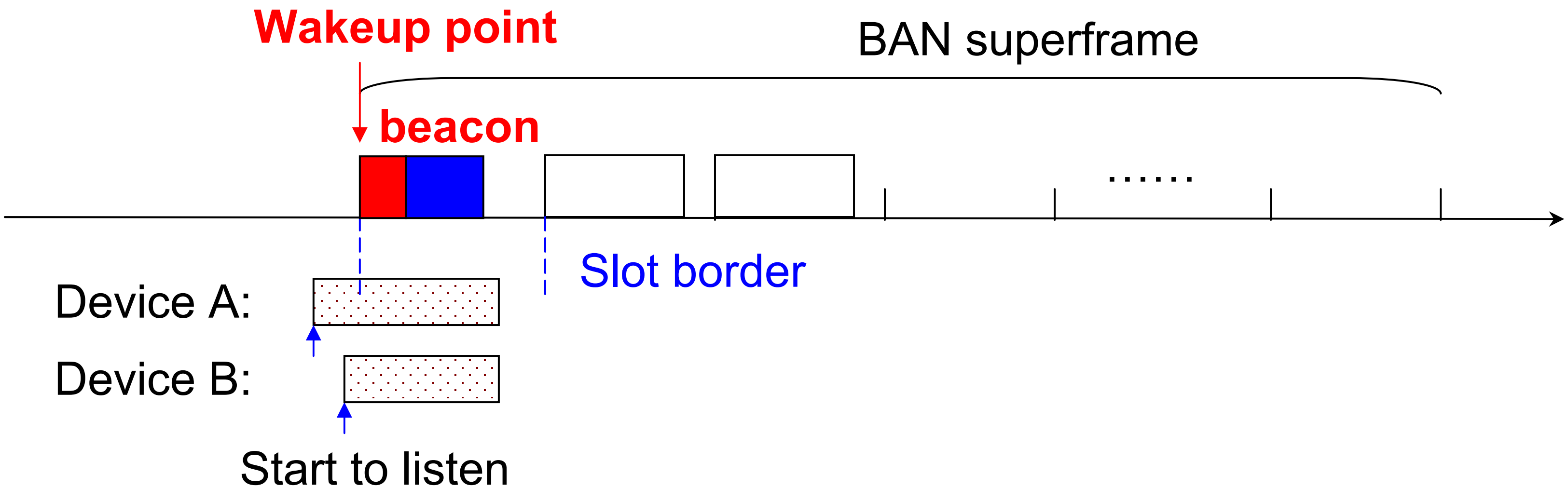
Beacon in BAN superframe

- Except bit-wise synchronization, the beacon carries slot information of superframe
  - Where is the start or end of a slot?
- How to cooperate beacon transmit/listen and maintain the slot information in an energy efficient way?
  - Beacon starts at slot Beginning (B-B)
  - Beacon ends at slot End (B-E)



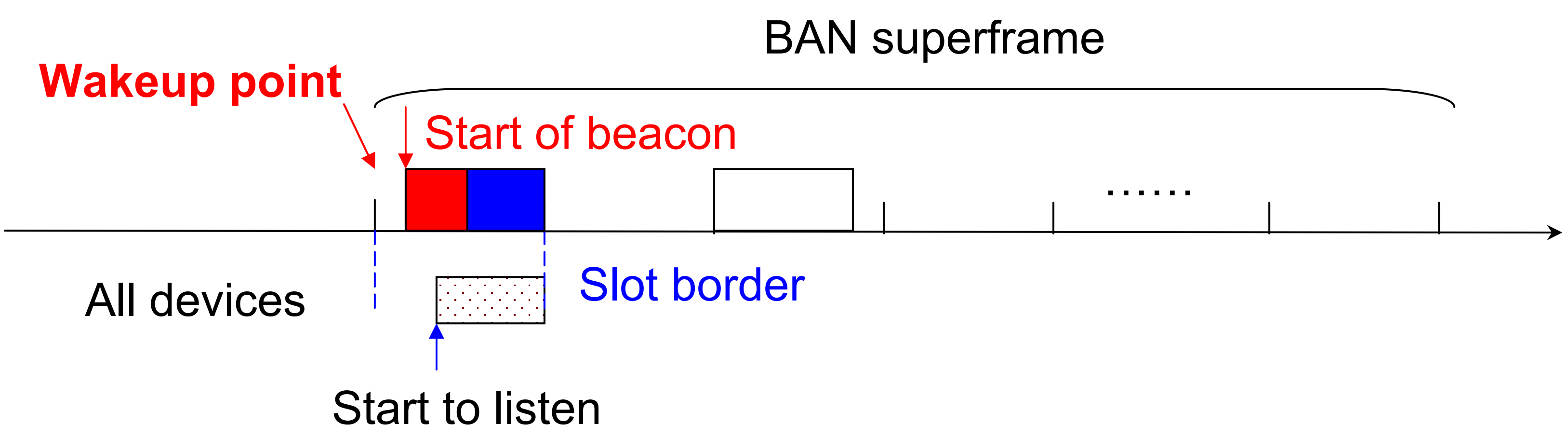
Beacon starts at slot beginning (B-B)

- It is the device's duty to consider the clock offset
  - Slot is described by the start of beacon
- Device operation
  - Coordinator broadcast beacon at scheduled time per its clock
  - Node must listen before the scheduled time

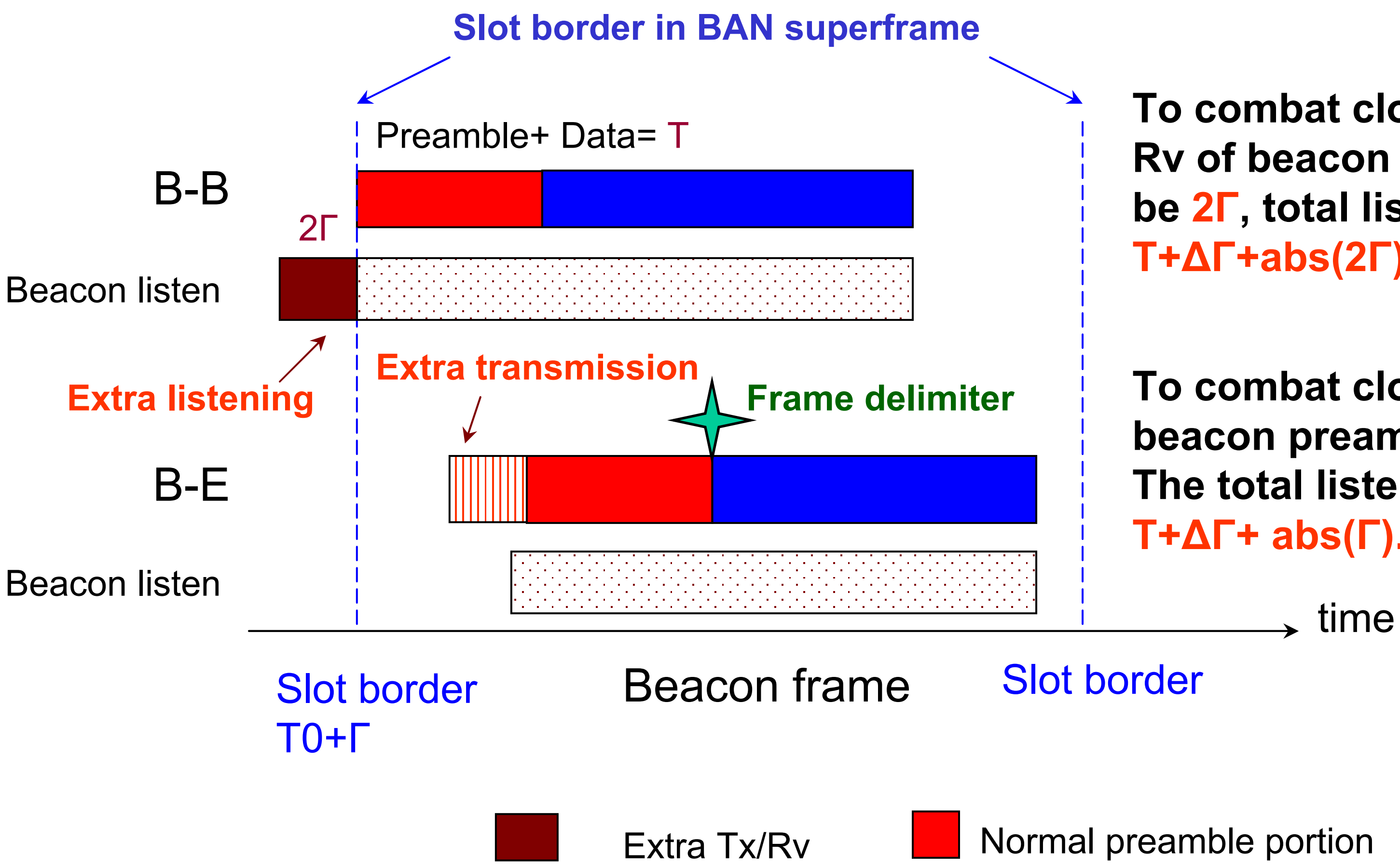


Beacon ends at slot end (B-E)

- It is the coordinator's duty to consider clock offset
  - Slot is described by the end of beacon
- Devices operation
  - Coordinator must transmit before the scheduled time. But the beacon must be end at the slot boarder
  - Device wakeup per its clock for beacon listening



Where are the differences?



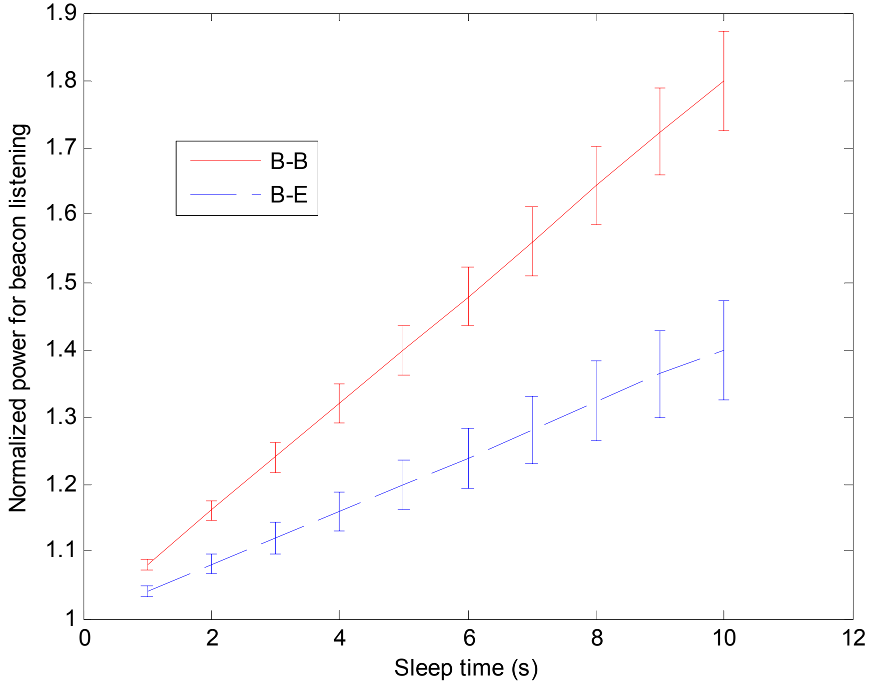
To combat clock offset, extra Rv of beacon preamble must be 2Γ, total listen time is T+ΔΓ+abs(2Γ).

To combat clock offset, total beacon preamble is T+abs(2Γ). The total listen time T+ΔΓ+ abs(Γ).

	B-B	B-E
Transmit of beacon preamble	Constant preamble	Additional preamble symbols
Listen of beacon preamble	Wakeup before the beacon preamble	Wakeup during the beacon preamble
Slot boundary	At the beginning of beacon	At the frame delimiter with a constant delay
Maximal device sleeping time	No limitation	Be limited by slot duration, frame delimiter and clock accuracy
Beacon payload	No limitation	No limitation
Power	More power to listen at device	More power to transmit at coordinator

B-E can save more power

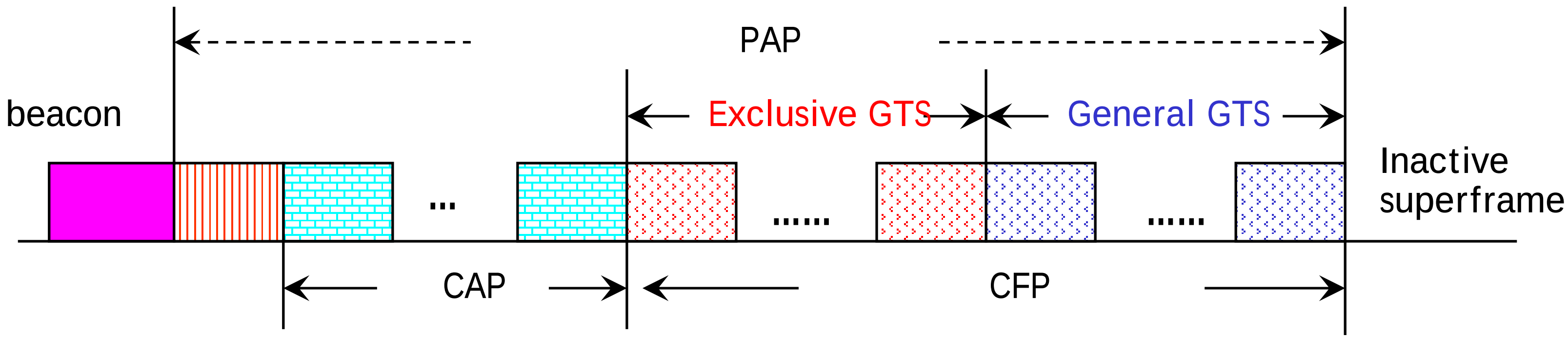
- Numeric result
  - 2ms beacon
  - Uniform distribution of clock drift in ±80 ppm
  - Sleeping time: 1~10 s
  - 10 sensors in a piconet
- B-E is better for dynamic and very low duty cycle of devices
  - On average, B-E consume no more extra power



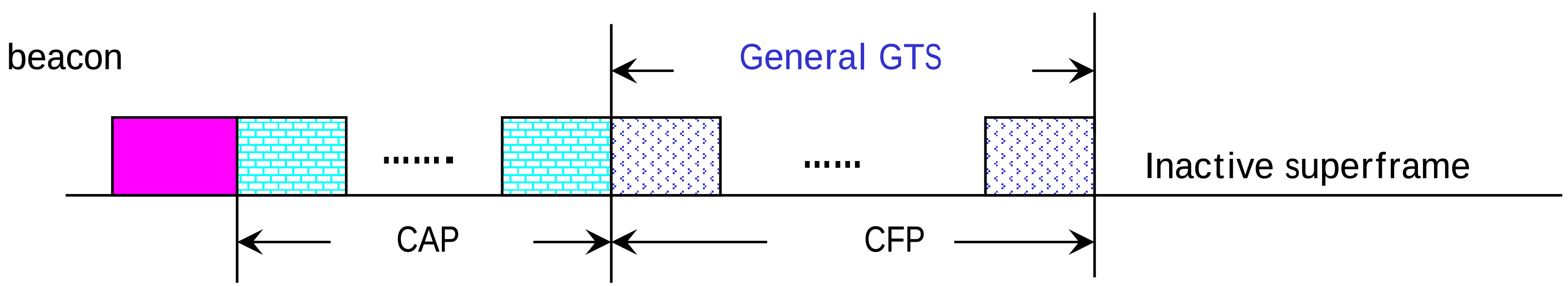
§3.4 Usage cases and coexistence analysis

Different superframe scenarios

Full-featured superframe

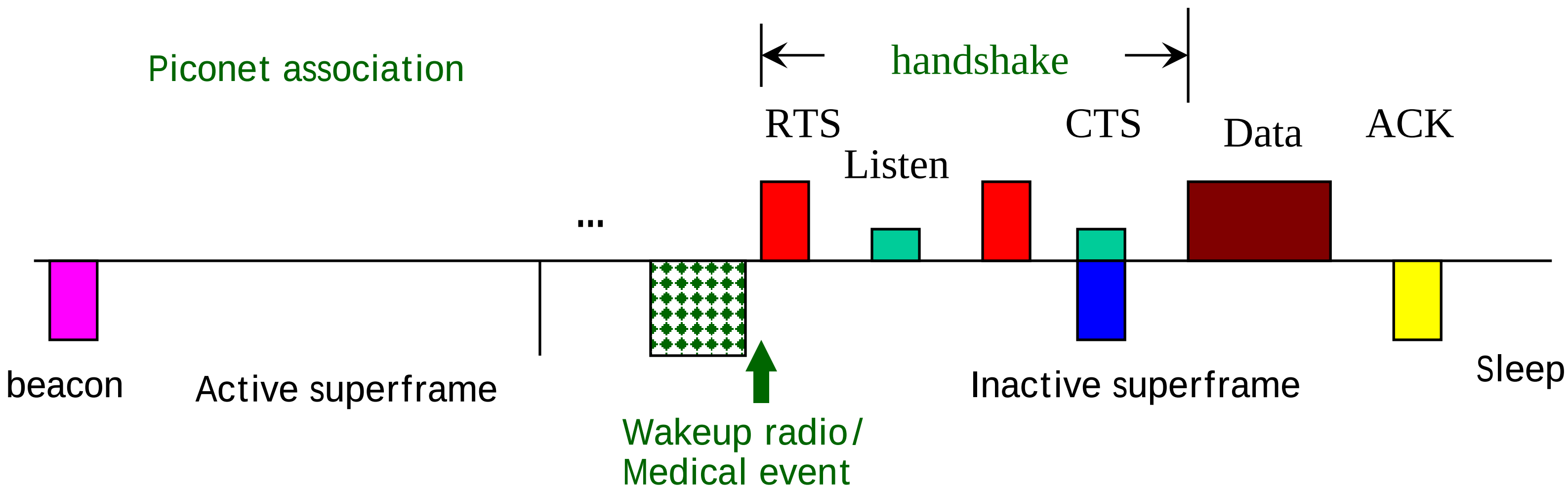


Simplified superframe

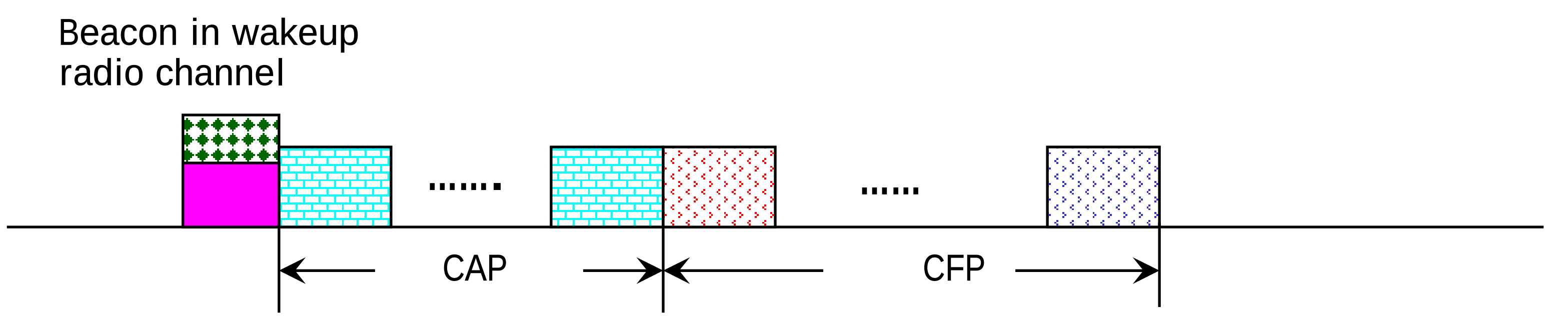


No PAP and exclusive GTS

MICS system and very low duty cycle systems

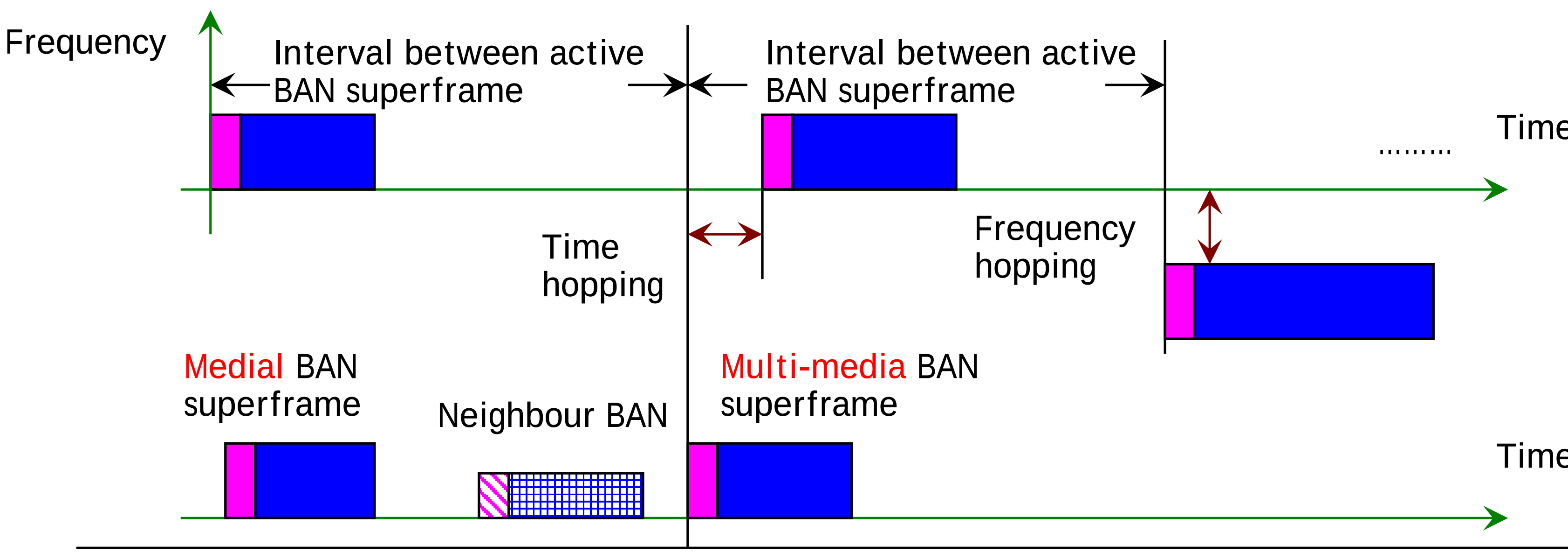


Wakeup radio based systems



Coexistence of multiple BANs

- PHY layer solution
  - Multiple BANs should be in different channels
- Uncollaborative BANs
  - Time hopping (TH) and frequency hopping (HP) of BAN superframe
- Collaborative BANs
  - Medical BAN superframe and multi-media superframe
  - Neighbour BANs can work in the inactive period of each other



Coexistence within a BAN

- In a BAN superframe, radio resource can be measured by GTS
  - Radio resource allocation is controlled by coordinator
- Coordinator can allocate GTS to multi-media links or medical links
  - General GTS and exclusive GTS

§4. Self-evaluation

- MAC transparency
  - TDMA based BAN superframe
- Scalability
  - Group BAN superframe
  - Minislots in CAP
- QoS and dependability
  - GTS in BAN superframe
  - PAP
- Power efficiency
  - Inactive BAN superframe
  - Distributed beacon listen and B-E beacon
  - Non-beacon mode
- Topology
  - Star topology
- Interference and coexistence
  - TH and FH of BAN superframe
  - Inactive superframe
- Easy implementation

Conclusions

- BAN group superframe
  - → for dynamic duty cycle, QoS, network scale, power consumption and diversity of traffic
- TDMA based BAN superframe → QoS friendly
  - PAP → for guaranteed priority traffic
  - Exclusive and general GTS → for radio resource control
  - Power efficient beacon
  - Minislot and group ACK → large capacity
  - Information piggybacked ACK→ for retransmission
  - Equal slot duration → easy implementation
- Non-beacon mode → power consumption friendly
- Coexistent and flexible framework
  - Full featured, simplified, MICS or wakeup radio based superframe

§5. Backup slides

§B1. Performance simulation

Simulation assumption and definition

- A perfect physical channel
- Packet errors are due to packet collision, lifetime and buffer overflow
- Traffic
  - Periodical traffic
  - Poisson distribution of best-effort traffic
- Star topology
- Communication and power consumption includes slot request, ACK and re-transmission
- 50% BAN superframe duty cycle

Simulation parameters

Parameters	Value
Data rate	250 kbps
Slots in BAN superframe	16 , 32
Slot duration	240 symbols
Symbol time	16 µs
PHY Symbols per Octet	2
SIFS	12 symbols
LIFS	40 symbols
Turnaround time	12 symbols
CAP Retries	3
GTS Request command	11 Octets
ACK wait duration (max.)	54 symbols
ACK command	5 Octets
MAC Header	9 Octets
PHY Header	6 Octets

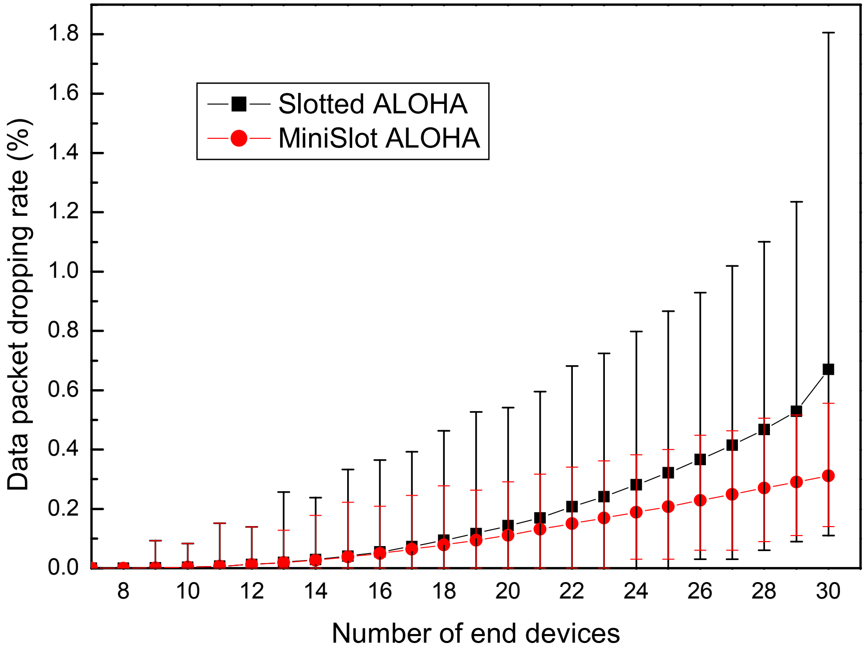
Parameters	Value
Tx power consumption	36.5 mW
Rx power consumption	41.4 mW
Sleep power consumption	42 µW

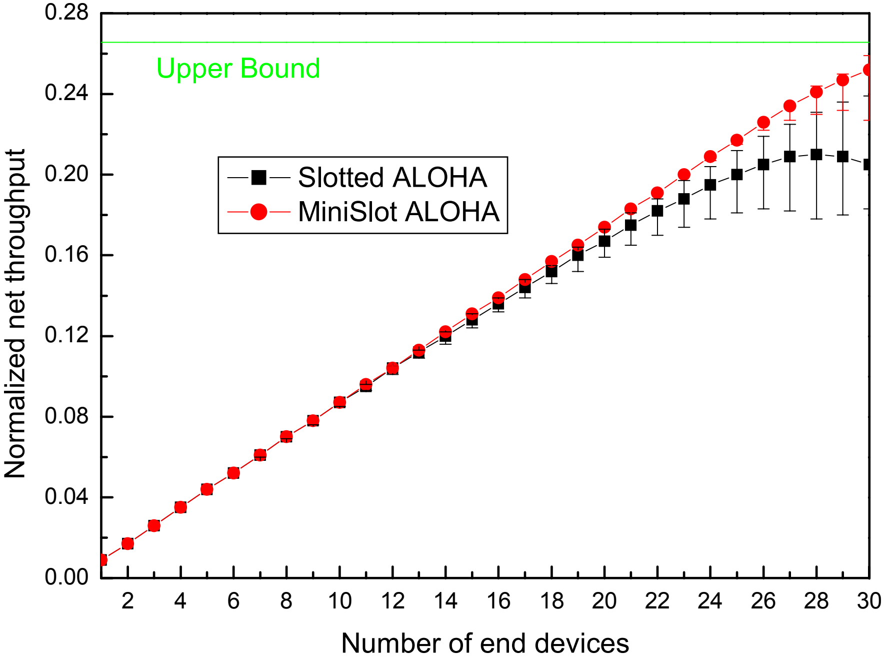
Ref. Chipcon CC2420

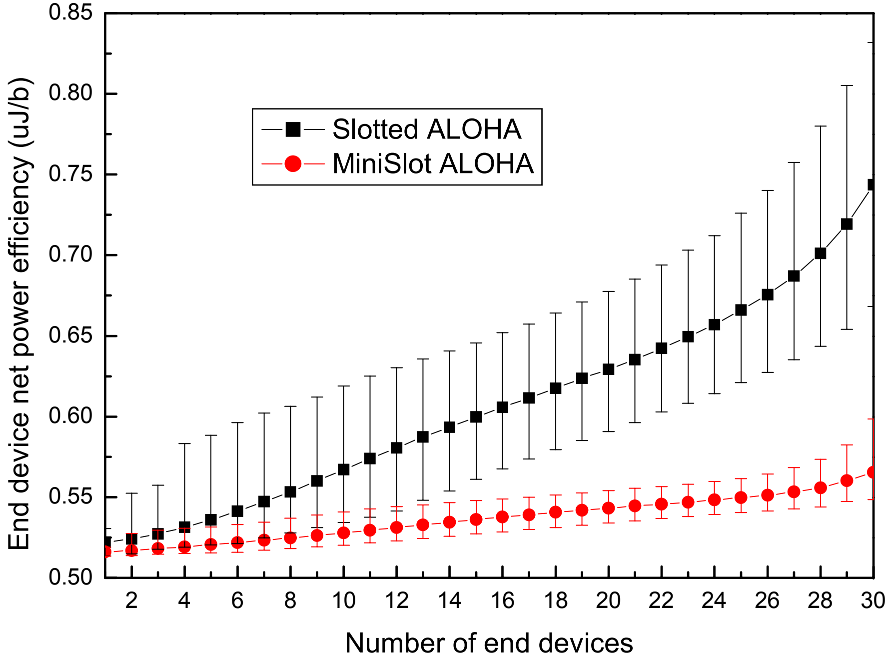
Simulation time	30 s
Simulation running	50,000 times
Confidence level	0.95

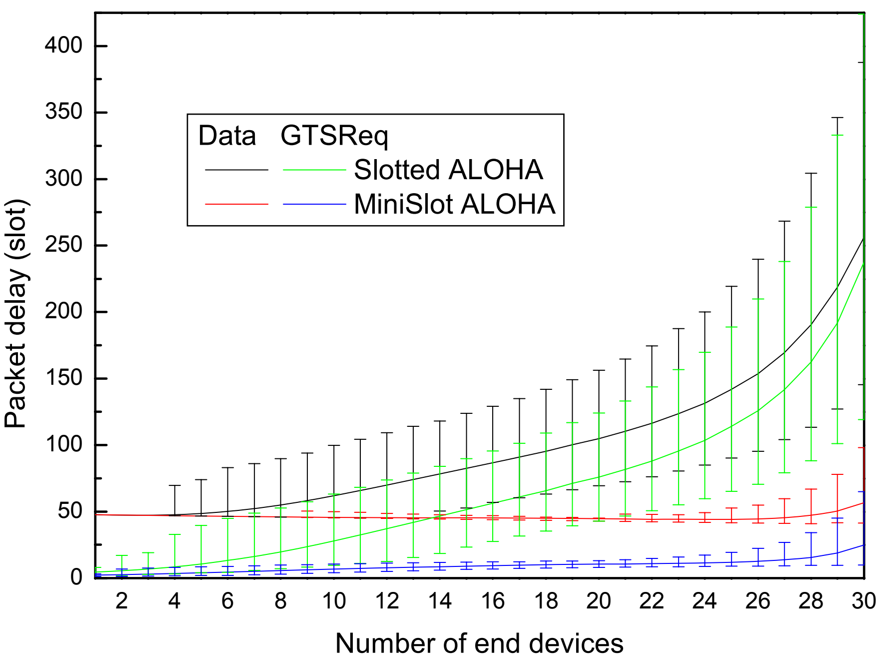
Scenario 1: periodical traffic

- Commands contend in CAP and data transmit in GTS
- Slot request in CAP is dropped after 3 times of retransmissions
- Data rate: 2.176kbps/device



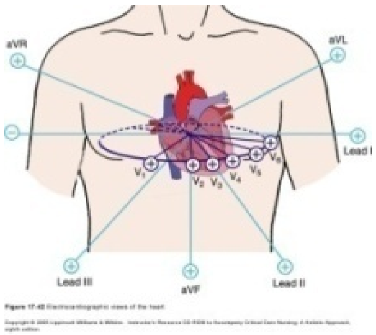






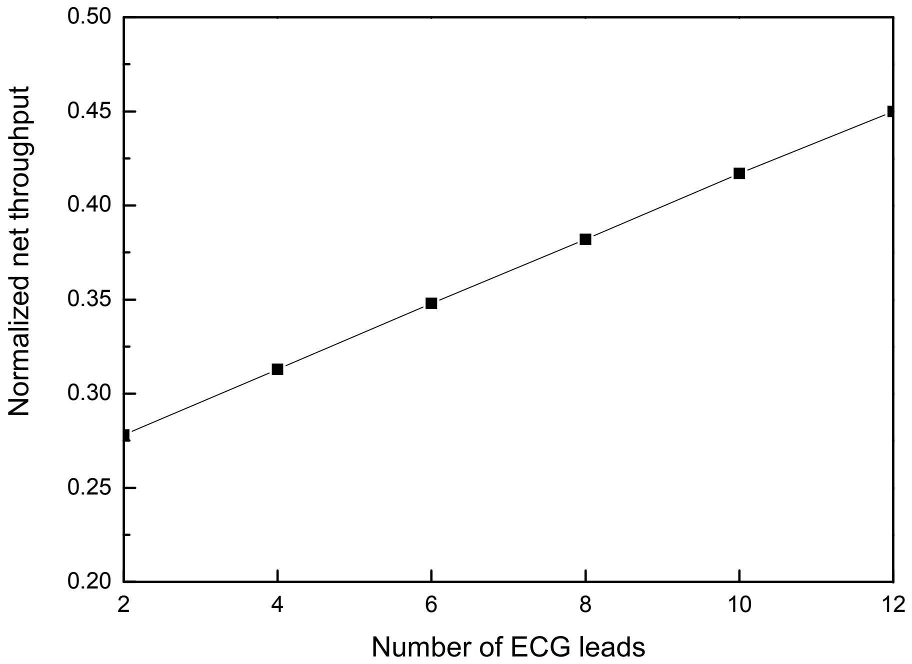
most of delay is due to GTS request.

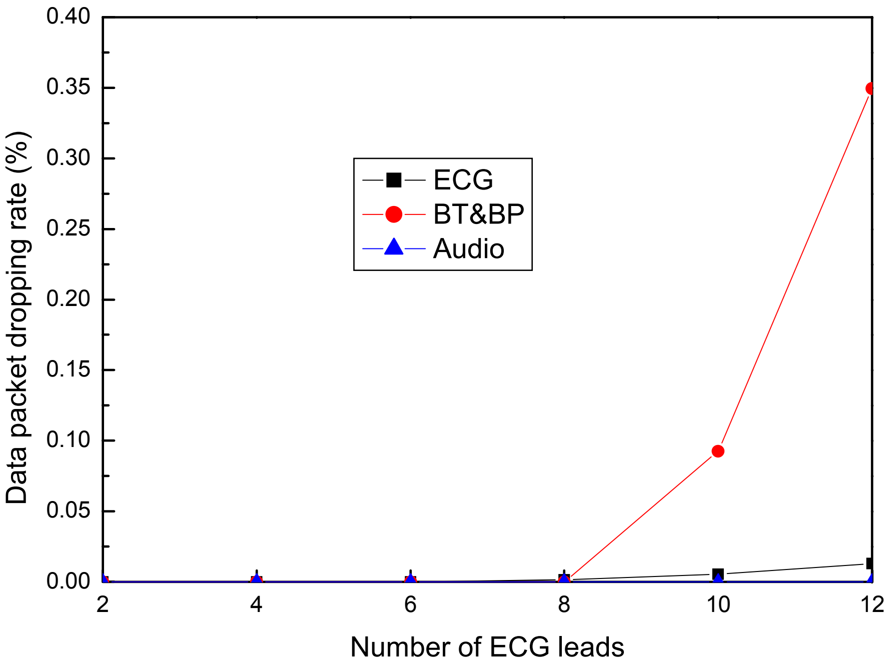
Scenario 2: mixed medical traffic and audio traffic

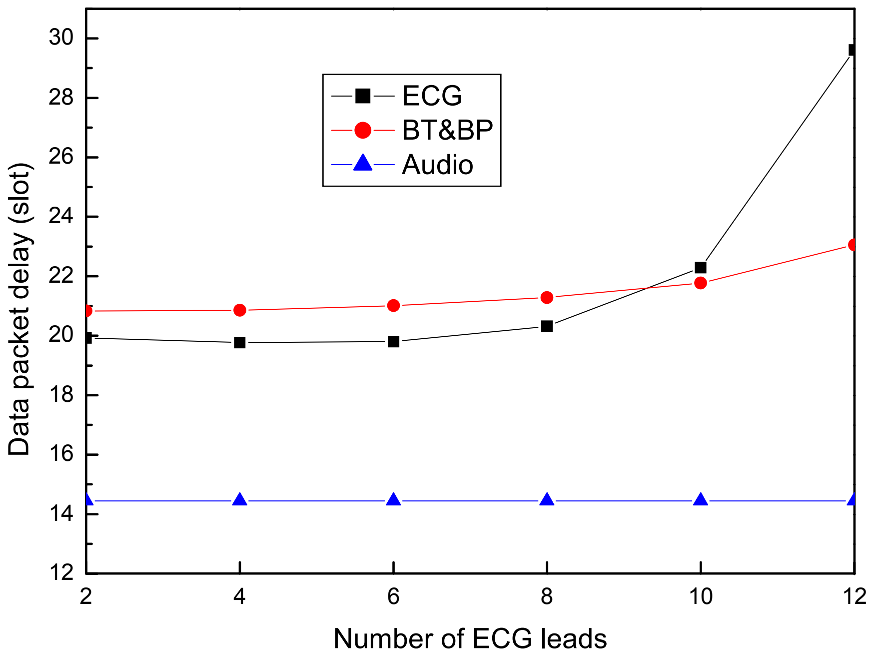


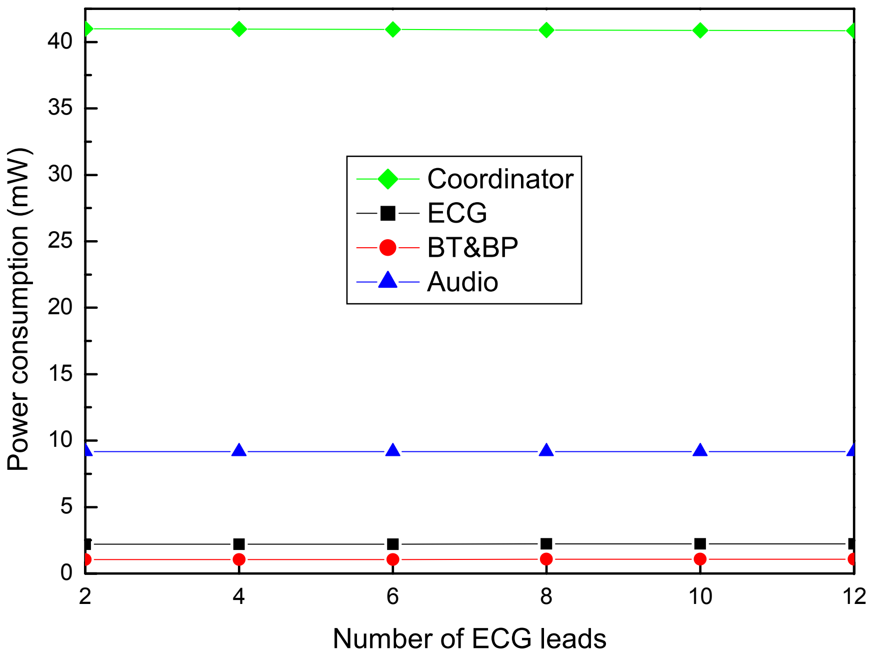
Applications	Leads/ Sensors	Traffic load	Payload (bytes)
ECG	2,4,6,8,10,12	4.352 kbps/lead, 8 packets/s/lead	68
Body temperature (BT)	1	1.6bps, 1packet/5s	1
Blood pressure (BP)	1	3.2bps, 1packet/5s	2
Audio	2	30kbps each	68

- Commands contend in CAP and data transmit in GTS
- A BAN group superframe consists of two single superframes


Normalized net throughput
0.50
0.45
0.40
0.35
0.30
0.25
0.20
2
4
6
8
10
12
Number of ECG leads

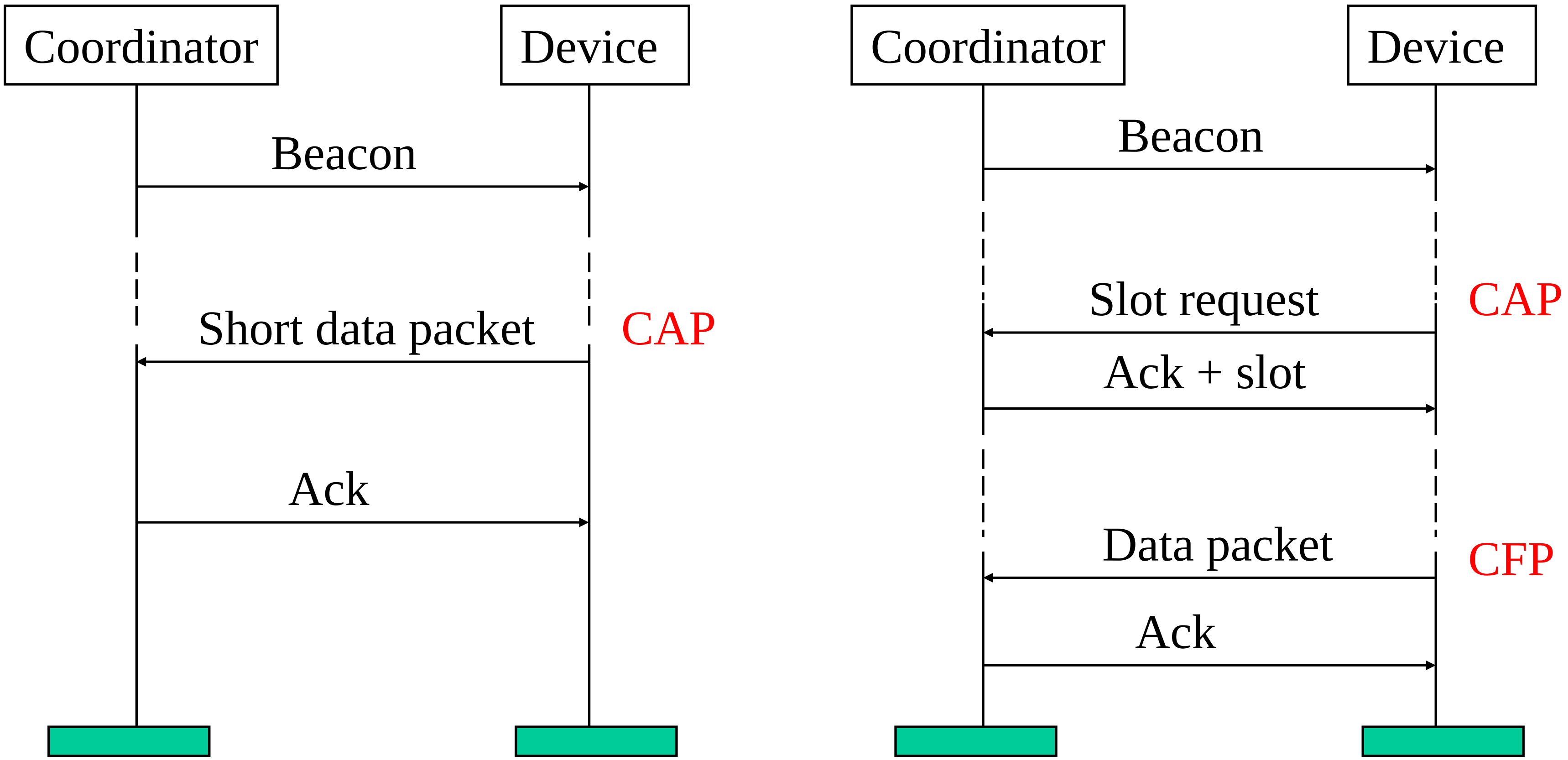

Data packet dropping rate (%)
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
ECG
BT&BP
Audio
2
4
6
8
10
12
Number of ECG leads


ECG
BT&BP
Audio
Data packet delay (slot)
Number of ECG leads
12
14
16
18
20
22
24
26
28
30
2
4
6
8
10
12


Coordinator
ECG
BT&BP
Audio
Power consumption (mW)
Number of ECG leads
0
5
10
15
20
25
30
35
40
2
4
6
8
10
12

§B2. Protocol diagram

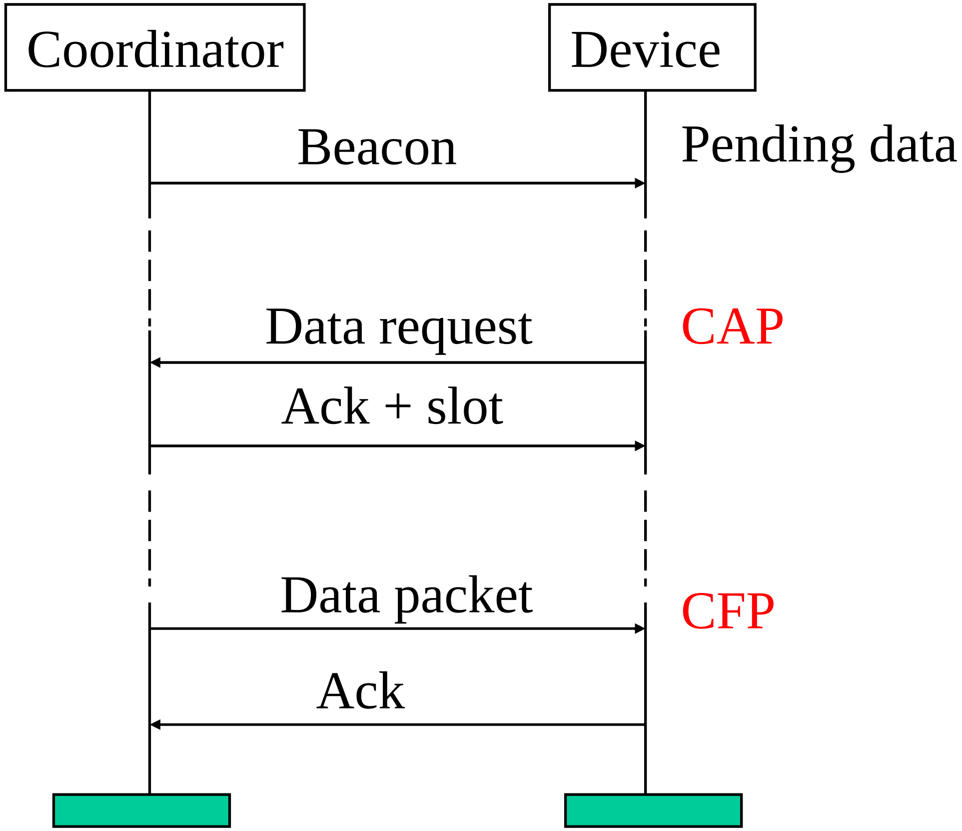
Uplink data in beacon mode



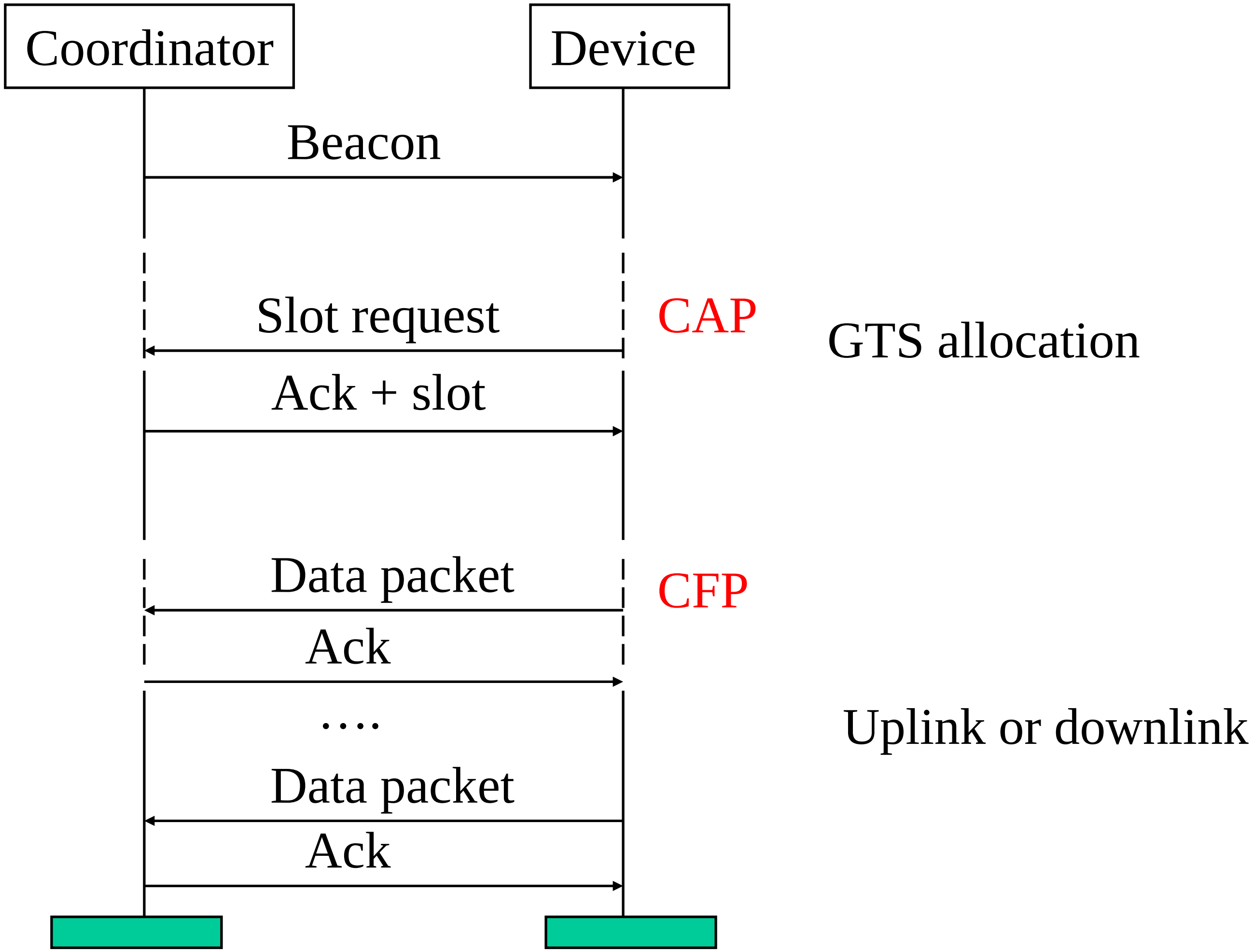
Short data

Long data

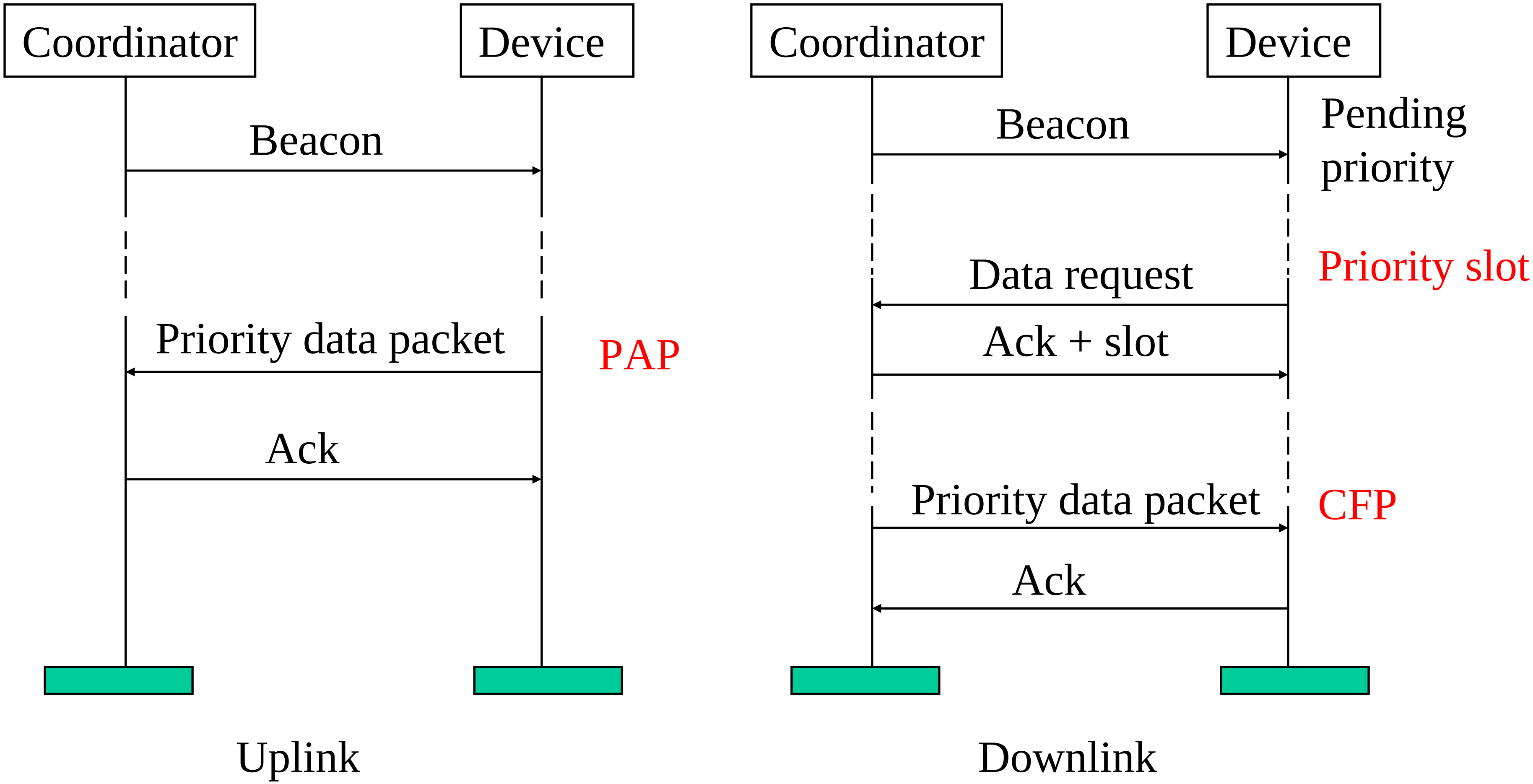
Downlink data in beacon mode



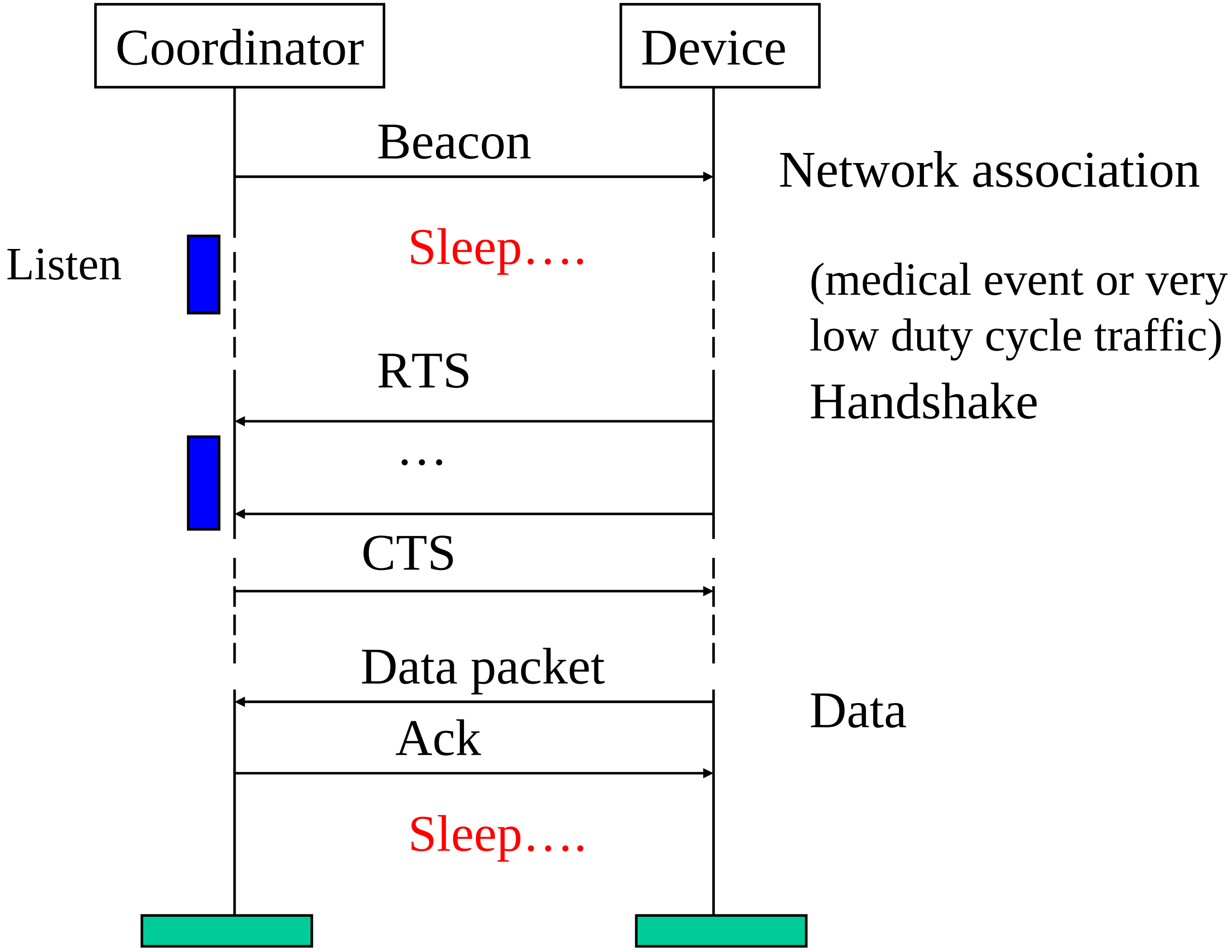
Stream data in beacon mode



Priority data in beacon mode



Data in non-beacon mode



§B3. Major questions to NICT's MAC at Vancouver

Major questions

- Q1: Coexistence between beacon mode and non-beacon mode
- Q2: Beacon listening in non-beacon mode
- Q3: How does non-beacon device know the inactive BAN superframe
- Q4: What is the parameters for the proposed systems?
- Q4: Cooperation mechanism in 2.4GHz
- Q5: Coexistence of medical and non-medical traffic
- Q6: Power consumption of your MAC proposal
- Q7: Can the MAC support tree or mesh topology?
- Q8: Communication between coordinators?
- Q9: Communication between beacon device and non-beacon device