CS-541
Wireless Sensor Networks

Lecture 5: Network standards for Personal and Body-area networks

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Objectives

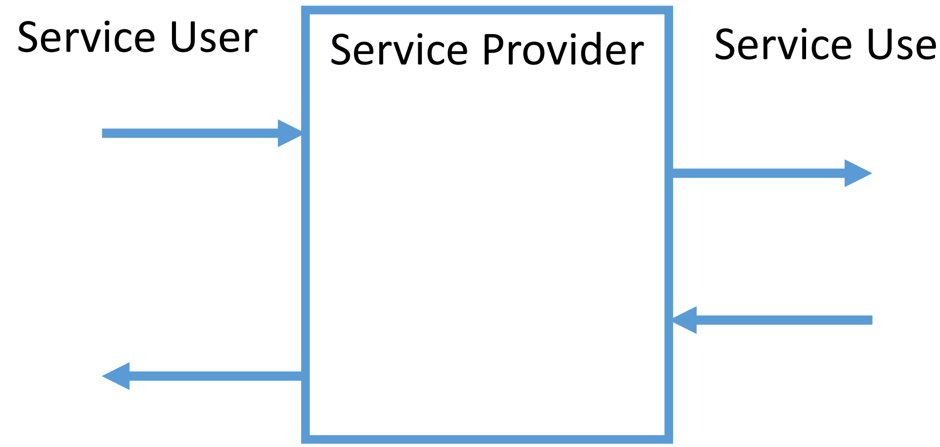
IEEE Standards family for Wireless Personal and Body Area Networks

- IEEE 802.15.1
- IEEE 802.15.4
- IEEE 802.15.6
- LoRAWAN Specification

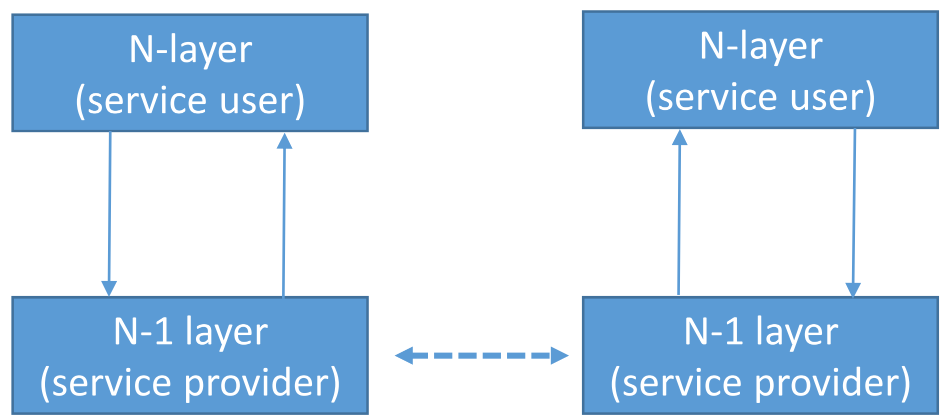
Network Standards

- Consensus on technical specifications
- Open (i.e. non-proprietary) solutions
- Cost-effective/Flexible/Interoperable solutions
- Increase the range of features and reduce the cost production

Network Standards



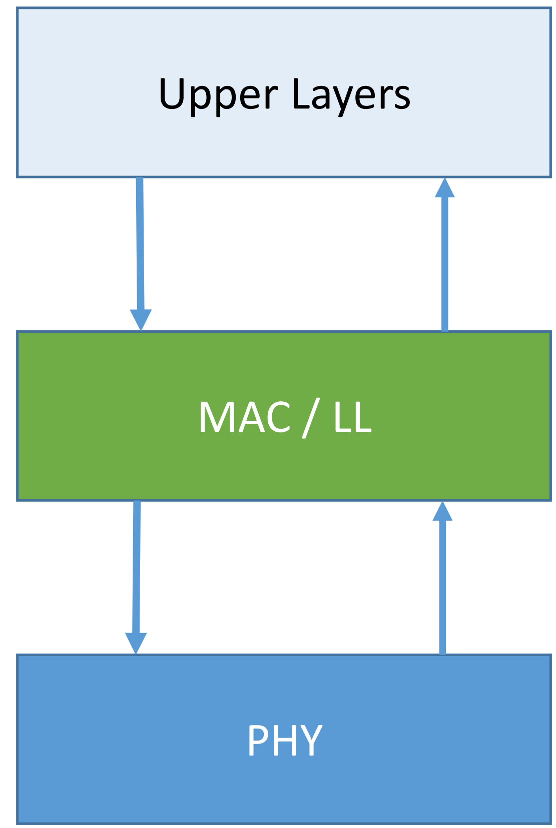
- Architecture
- Services of a layer: capabilities it offers to the users of the upper layers
- Information flow -> passing a *service primitive* (convey the required information)
  - *When Generated*
  - *Effect on receipt*
- Frame Format
- Constants and Attributes



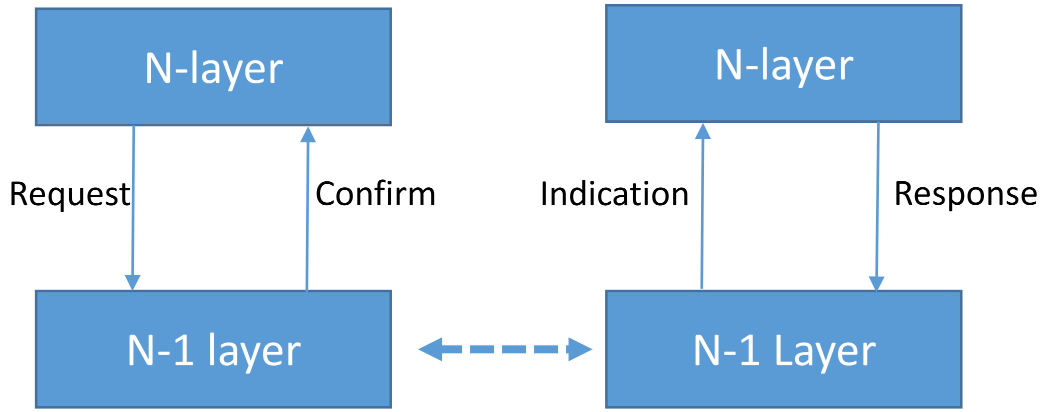
IEEE Standards

The standards family for Short Range WSN: IEEE 802.15

- Topologies and network roles for WSN
- PHY: frequency and channels, spectrum handling, modulation, bit rate
- MAC: operational modes, timing aspects, topologies
- Protocol Data Units
- Service Primitives (interactions between different layers and between different nodes)



Service Primitives supported by IEEE 802.15.x



Request: The request primitive is passed from the N-th layer to the (N-1)-th layer to request that a service is initiated. *e.g. a node creates a MAC packet @ the MAC layer → PHY Layer*

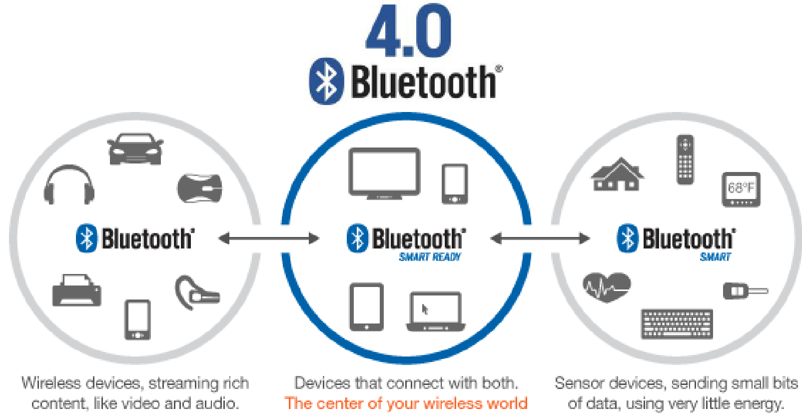
Indication: The indication primitive is passed from the (N-1)-th layer to the N-th layer to indicate an internal event *e.g. a node receives a frame @ the PHY Layer and passes it on the MAC layer*

Response: The response primitive is passed from the N-layer to the N—1 layer to complete a procedure previously invoked by an indication primitive. *e.g. a node @ the MAC layer generates a response for a MAC frame it received -> PHYLayer*

Confirm: The confirm primitive is passed from the N—1 layer to the N-layer to convey the results of one or more associated previous service requests. *e.g. a node @ the PHY receives the response -> MAC Layer*

Standard	Description	1st Release & Revisions	Comments
IEEE 802.15.1 (Bluetooth)	**MAC and PHY Layer Specifications for Wireless Personal Area Networks (WPANs)**	**2002 / 2005**	**Bluetooth Core Configuration v4.0 and Bluetooth Low Energy (2009)**
IEEE 802.15.2	Coexistence of Wireless Personal Area Networks With Other Wireless Devices Operating in Unlicensed Frequency Bands	2003	In hibernation since 2011
IEEE 802.15.3	MAC and PHY Layer Specifications for High Rate Wireless Personal Area Networks (HR-WPANs)	2003	802.15.3b: MAC layer amendment 802.15.3.c: Millimeter-wave-based Alternative PHY extension Due to WiFi popularity it is not used in real-life
IEEE 802.15.4	**MAC and PHY Layer Specifications for Low-Rate Wireless Personal Area Networks (HR-WPANs)**	**2003/2006/2011**	**The most popular and well-studied standard for WSN applications (7 extensions)**
IEEE 802.15.5	Mesh Topology Capability in Wireless Personal Area Networks	2009	
IEEE 802.15.6	**Wireless Body Area Networks**	**2012**	

IEEE 802.15.1

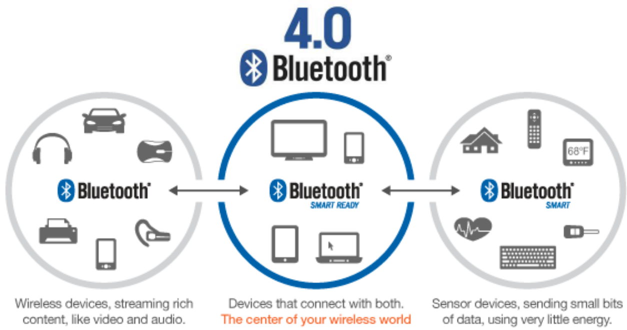


BT Basic/Enhanced Data Rate

- 2.45 GHz ISM frequency band
- 79 Channels (USA, Europe) or 23 (Japan) RF channels. 1 MHz channel width
- Frequency Hopping (FH) - Frequency-Hopping/Time-Division-Duplex (FH/TDD) - Adaptive Frequency Hopping
- Devices are organized in piconets
- The master of the piconet provides the clock and the frequency-hopping pattern (ordering of the frequencies)

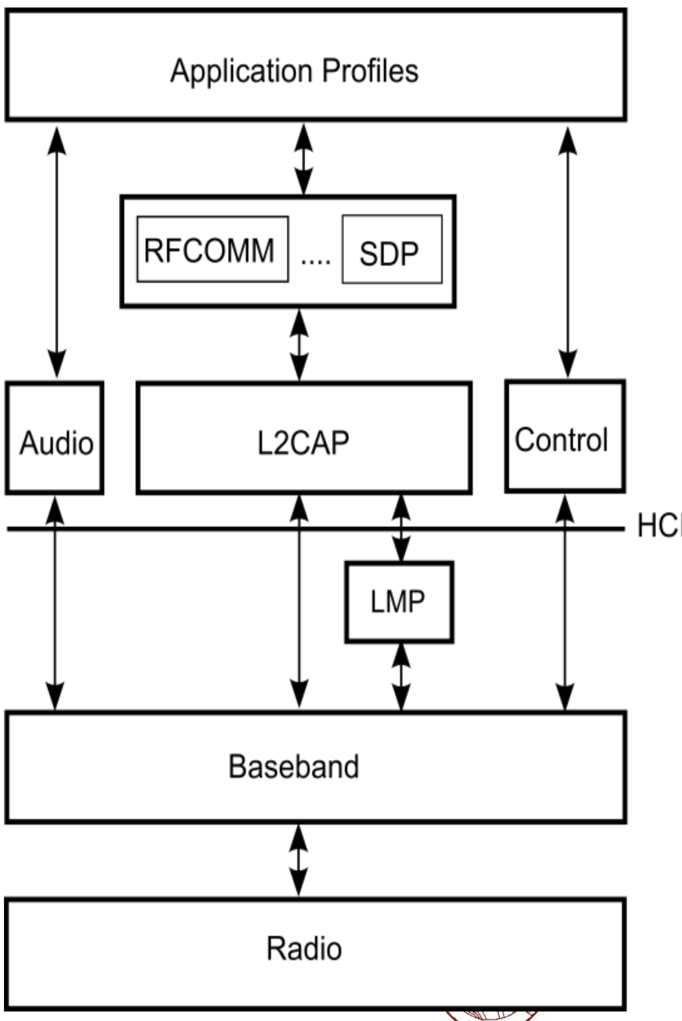
BT Low Energy

- 2.45 GHz ISM band
- 40 RF channels. 2 MHz channel width.
- AFH mechanism: FDMA and TDMA
- @FDMA: the 40 physical channels are divided into 3 advertising channels and 37 data channels.
- Devices are organized in piconets.
- The master of the piconet determines the hop interval and the hopping pattern for accessing the 37 physical channels. @TDMA: polling-based data transmission between the master and the slaves of the piconet.



IEEE 802.15.1

BT Basic/Enhanced Data Rate



RFCOMM and Service Discovery Protocol: Representative examples of the upper layers of the Bluetooth stack for higher-level functionalities and interfaces to application profiles.

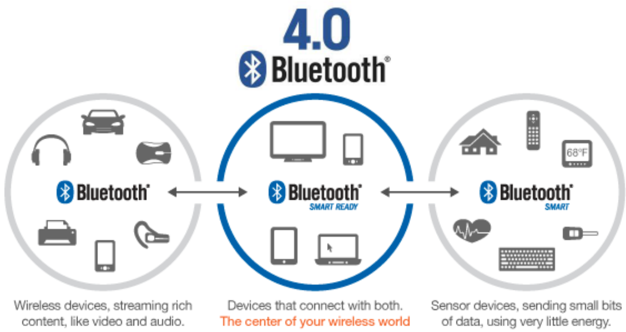
L2CAP: Utilises HCI to provide data services to the upper protocols.
Data services: multiplexing, segmentation and reassembly capabilities.

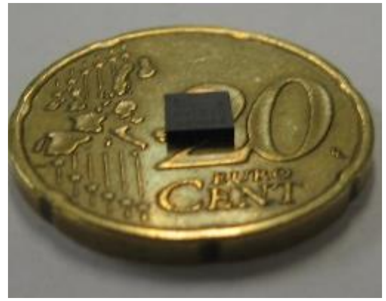
Host Controller Interface (HCI): Uniform set of interfaces for accessing the upper layers of the Bluetooth stack.

Link Manager Protocol (LMP): Control operations for the baseband and physical layers.

Baseband: Packets formats & defines the physical links that can be formed between a master and a slave device.
Physical links are only formed a master and a slave. **A master can support up to 7 active links with slave devices.**

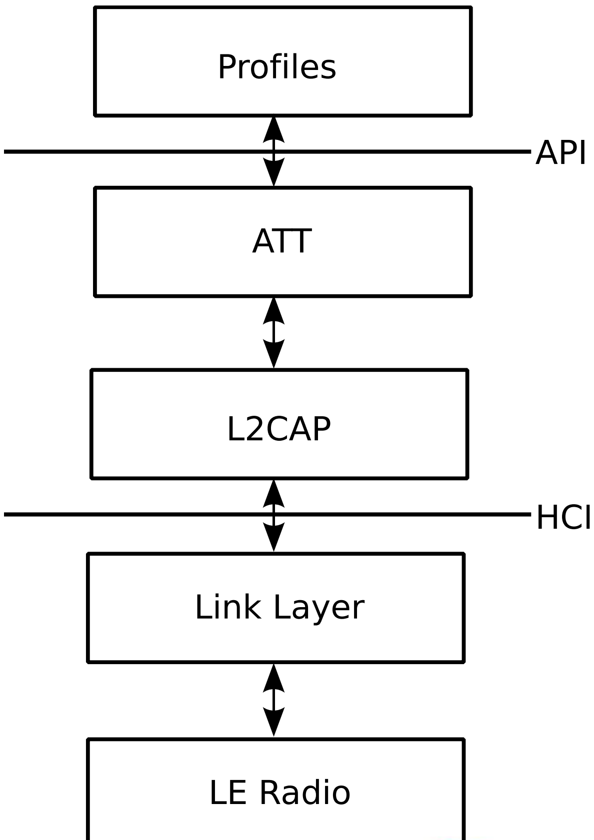
BT Radio: Channel characteristics
Physical channels: (a) inquiry scan, (b) page scan, (c) basic, (d) adapted piconet.
Inquiry & Page scan: Device discovery and connection
Basic and adapted piconet: Normal operation





IEEE 802.15.1

BT Low Energy



Attribute Protocol (ATT): exposition of the attributes of the LE device to its peer devices.

L2CAP: provides channel-based abstraction between the lower and upper layers of the LE devices.

LL: logical topology
Asynchronous traffic support (control commands + data packets)

LE: **There exists no theoretical limit on the number of LE active links that can be supported within a piconet. -> >> 7 active master-slave links per piconet**

IEEE 802.15.1

Comparison between BT and BT LE

Bluetooth BR/EDR

++Short-range cable replacement.

--Automatic network formation is not supported (single point failure)

--Starting up a connection ~ 5sec

--Blocking operations (e.g., once a Bluetooth inquiry is initiated to look for other Bluetooth devices, it disrupts every on-going communication, such as transmission of an ECG data stream.

--No support for multicasting

Bluetooth LE

++Simplified protocol stack

++Active links are maintained only for as long as data need to be exchanged between two devices. (low-energy)

++Starting up a connection ~6ms

--Not support data streaming: Designated for sending small chunks of data

IEEE 802.15.4

Standard	Description	Initial Release / Revision Date	Amendments
IEEE 802.15.4	PHY and MAC Layer for Low Rate Wireless Personal Area Networks (LR-WPAN)	2003 /2006/ 2011	802.15.4.a (2007): PHY Layer Extension to **Chirp Spectrum Techniques** and UWB systems
			802.15.4c (2009): Alternative PHY Extension to support one or more of the Chinese 314-316 MHz, 430-434 MHz, and 779-787 MHz bands
			802.15.4d (2009): Alternative PHY Layer Extension to support the Japanese 950 MHz Bands
			802.15.4e (2012): MAC sub-Layer
			802.15.4f (2012): Active Radio **Frequency** Identification (RFID) System PHY
			802.15.4j (2013) – Alternative PHY Extension to support Medical Body Area Network (MBAN) services operating in the 2360-2400 MHz band

IEEE 802.15.4 → Personal Area Network

Types of Devices

- Full-Function Device (FFD)
  - Capable of acting as the network’s coordinator
  - Undertaking complex network functionalities
- Reduced-Function Device (RFD)
  - Extremely low bandwidth demands $\propto$ application specs (e.g. passive RFID)

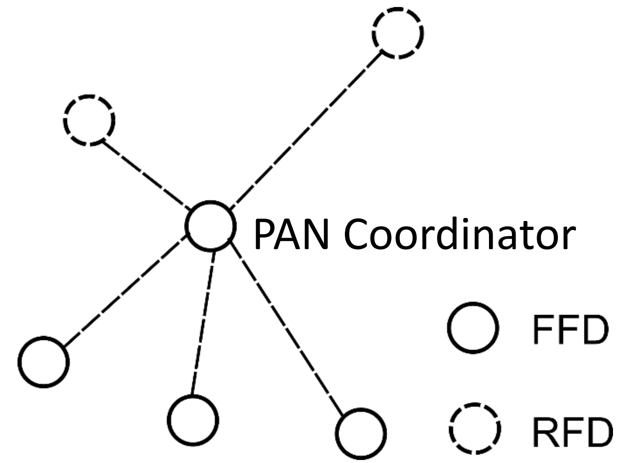
A PAN Coordinator

- Associates a PAN with an ID. Networks with different IDs cannot communicate directly with each other.
- Allows nodes to join, leave the PAN. If necessary initiates, terminates, routes the communication (RFD)
- Usually is plugged into power source (Vs RFDs and FFDs)

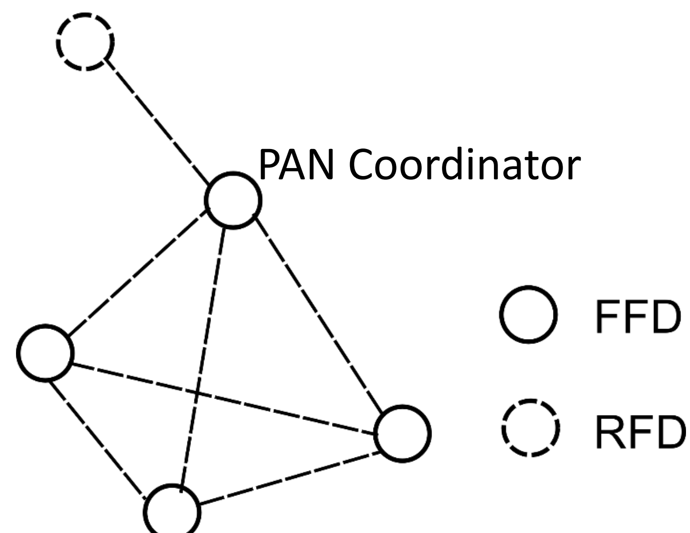
IEEE 802.15.4

Types of logical topologies

- **Star**: each device (FFD or RDF) communicates with the PAN coordinator only
  - Suitable for small-scale networks that operate within a limited space
  - home automation, computer peripherals, peripherals, games, and smart health care



- **Peer-to-peer:** FFD devices can communicate with each other, as long as they are within communication range.
  - More flexible than star, suitable for larger-scale networks that need distributed coordination between peers without the necessity of a central unit.
  - Multi-hopping, Cluster Trees, and Mesh networking
  - Environmental & Wild Life, Smart Cities, Industrial, etc.

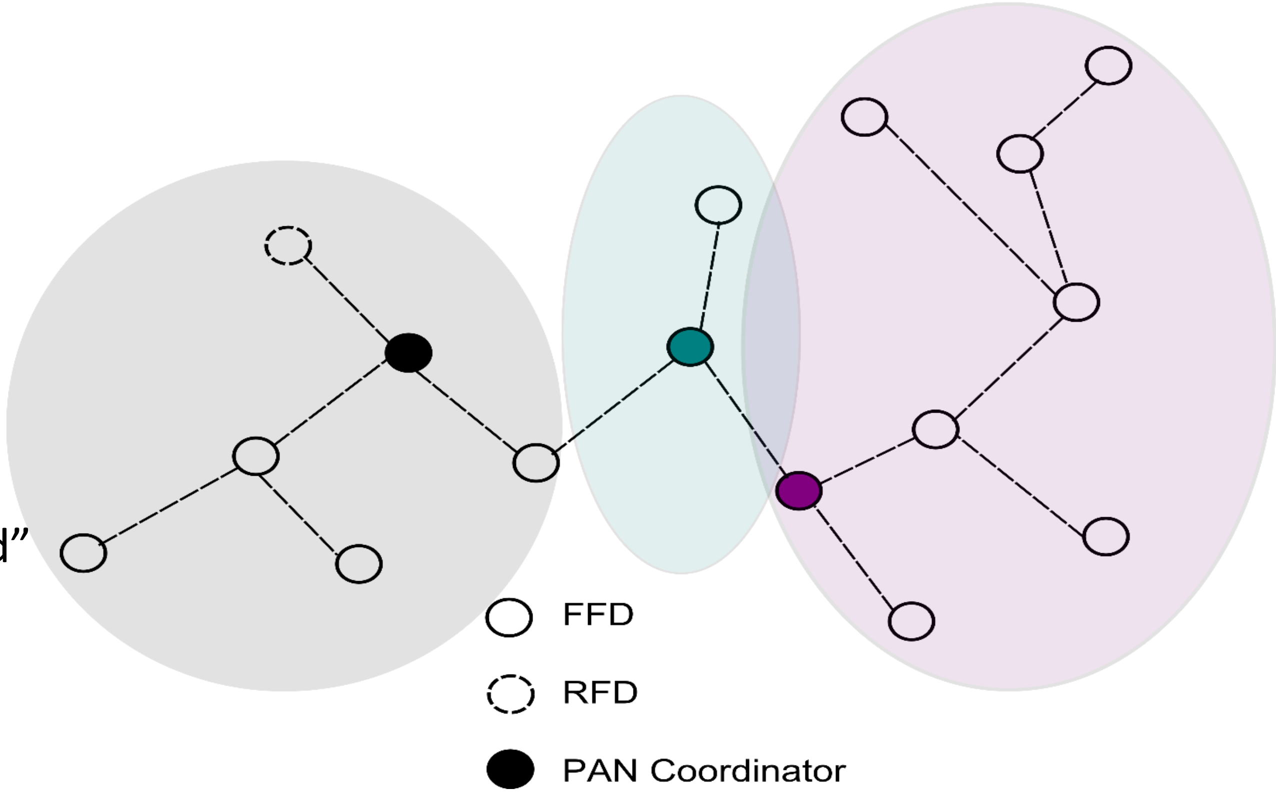


IEEE 802.15.4

Types of logical topologies

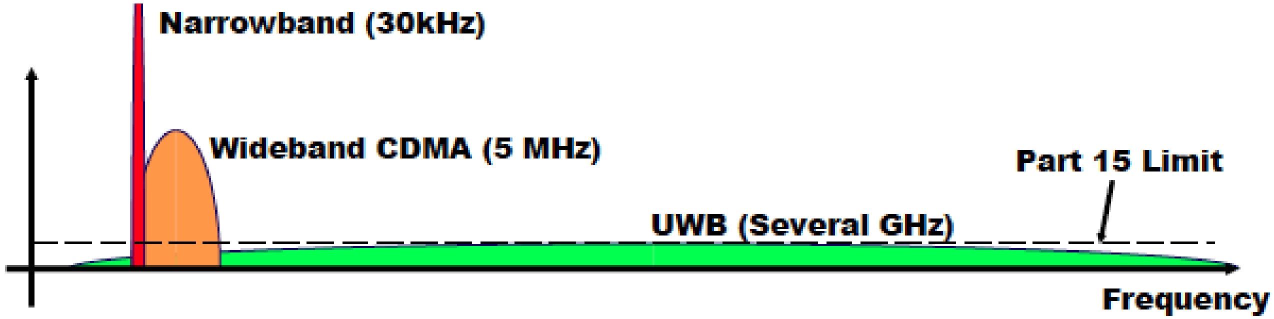
Cluster Tree

- Always only a single path between two devices.
- Devices are aware of their “parent” node and any “child” nodes.
- Reducing routing complexity



Band (MHz)	Region	Number of Channels	Modulation	Data Rate (Kbps)	Support
868 - 868.6	Europe	1	BPSK	20	**Mandatory**
			ASK	250	Optional
			O-QPSK	100	
779-787	China	8	MPSK	250	**Mandatory**
			P-QPSK		
902 - 928	USA	10	BPSK	40	**Mandatory**
			ASK	250	Optional
			O-QPSK	100	
950-956	Japan	22	BSPK	20	**Mandatory**
			GFSK	100	
2400 - 2483.5	Worldwide	16	**O-QPSK (DSSS)**	**250**	**Mandatory**
		14	CSS		Optional
			CSS	1000	
249.6 - 749.6 (UWB sub-GHz)	Worldwide	1	BPM and BPSK	110 – 27400 (Varying w.r.t. chip rate)	Optional
3244 - 4724 (UWB low band)		4	BPM and BPSK	110 – 27400 (Varying w.r.t. chip rate	Optional
5944 - 10234 (UWB high band)		11	BPM and BPSK	110 – 27400 (Varying w.r.t. chip rate	Optional

IEEE 802.15.4



UWB

Uses more bandwidth than the minimum required for the signal transmission (SS)
BUT
It employs baseband transmission -> there is no intermediate or radio carrier frequencies. (reducing the complexity of the receiver circuity)
Uses pulse position modulation (PPM).

+++ Resilience to multi-path fading.
+++ Implementation costs are significantly lower than DSSS systems.
+++ UWB improves the advantages of spread-spectrum techniques since much wider spectrum bands are used for transmission.

-- small communication ranges (< 10 m), which limits its applicability for WSN deployment.
-- Carrier Sensing MAC is not applicable

How to calculate time required for a packet to reach its destination at the PHY layer given the band range and type of modulation?

e.g.

PHY header 6 Bytes	**PHY Payload (20bytes)**

@2.4GHz -- O-QPSK ??

@ 868MHz – BPSK ??

IEEE 802.15.4

PHY tasks

Receiver Energy Detection (ED)

- Use by an upper layer as part of a **channel selection** algorithm.
- An estimate of the received signal power within the bandwidth of the channel.
- No attempt is made to identify or decode signals on the channel.

Link Quality Indicator (LQI)

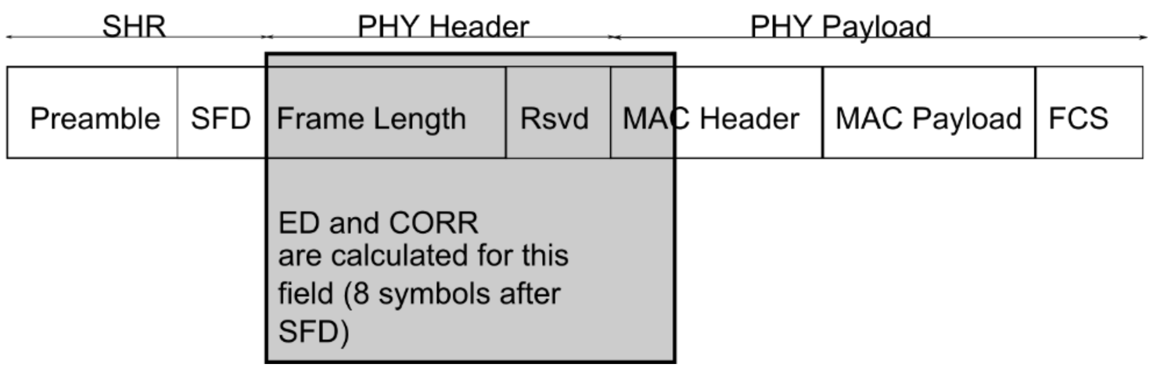
- The characterization of the strength and/or the quality of a received packet.
- The measurement may be implemented using receiver ED, a SNR estimation, or their combination.
- The minimum and maximum LQI values (0x00 and 0xff) associated with the lowest and highest quality compliant signals detectable by the receiver

IEEE 802.15.4

PHY tasks

ED → A measurement of the channel

- Usually used as the **Received Signal Strength Indicator** (RSSI), although RSSI is NOT explicitly defined in the standard (opposed to 802.11);
- Direct measurement (linear relationship between ED and Received Power)

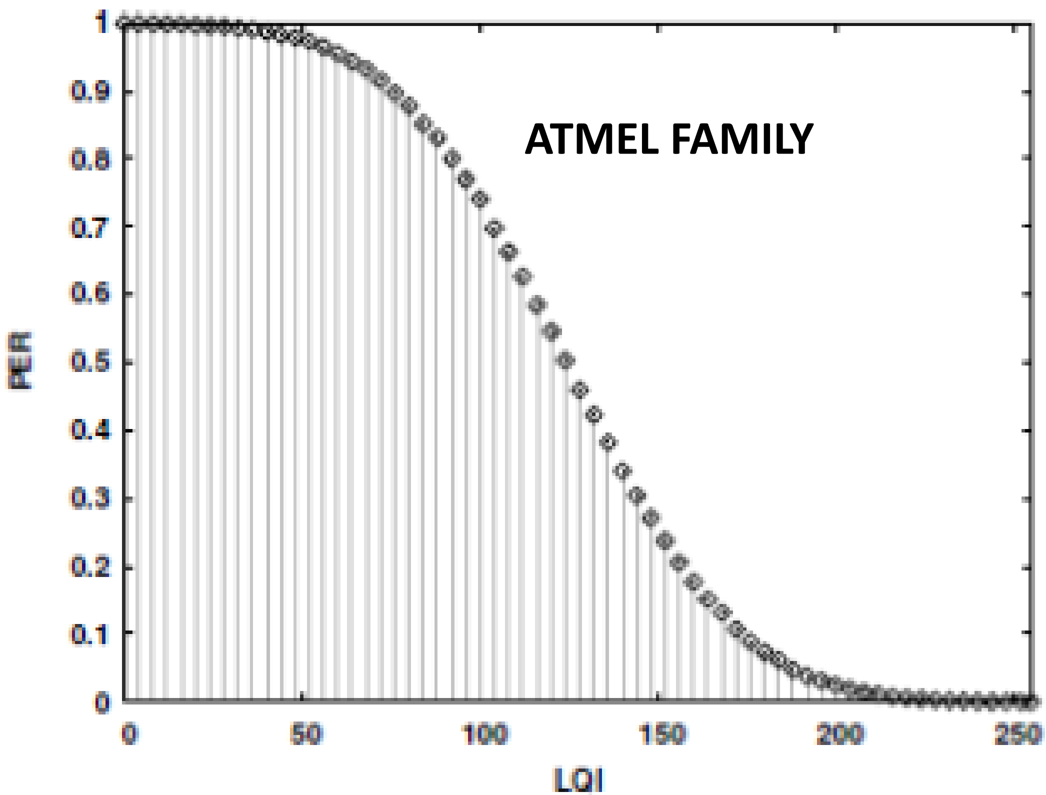


LQI → A measurement of the frame;

- Associated with the Chip Error Rate (Symbol Error Rate and Packet Error Rate).
- Statistical measure (correlation value) related to symbols within frame.

IEEE 802.15.4

IEEE 802.15.4 – PHY tasks. Vendor's rules of thumb



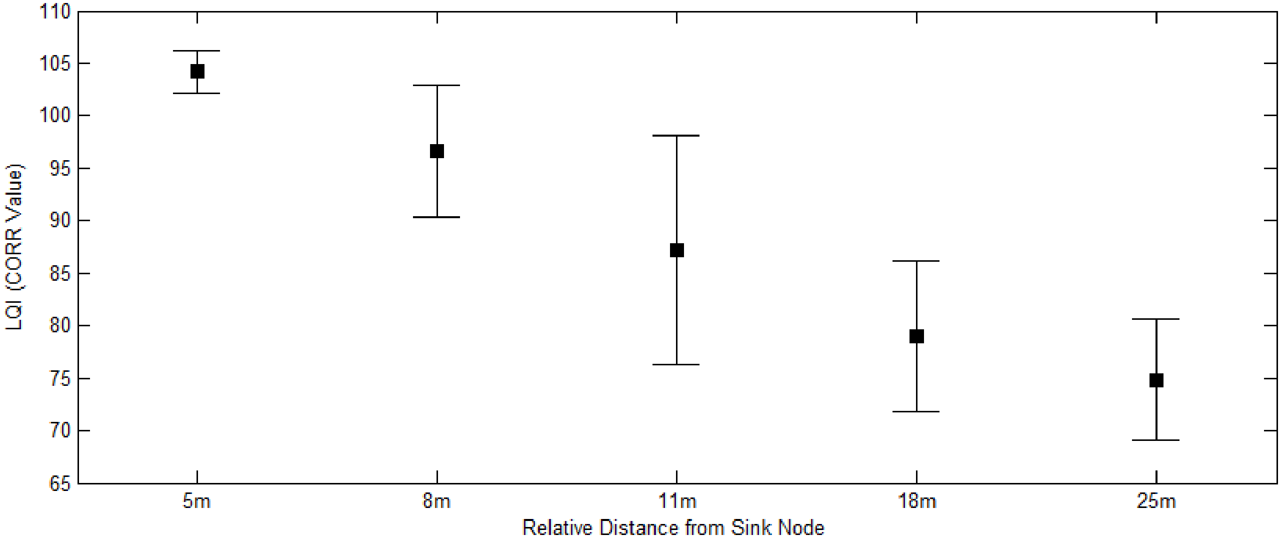
LQI ∝ PER ∝ Throughput

RSSI/ED ∝ tx power and link margin

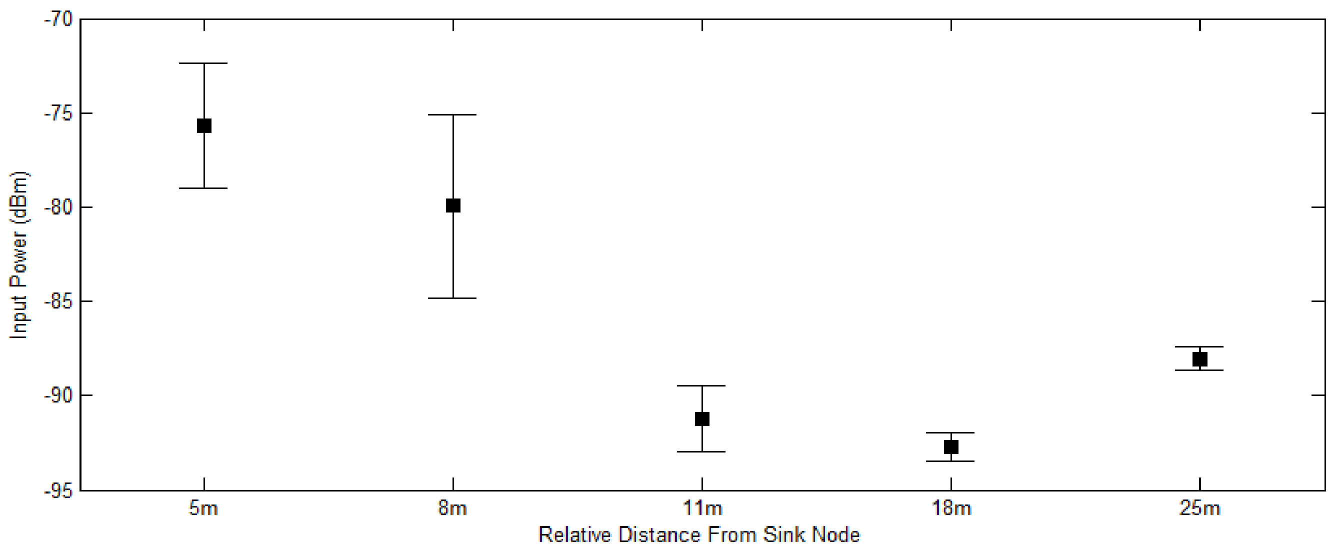
High LQI → Use RSSI /ED to differentiate between links

Low LQI → Link should be disca-rded. A high RSSI / ED could be strength of an interfering signal

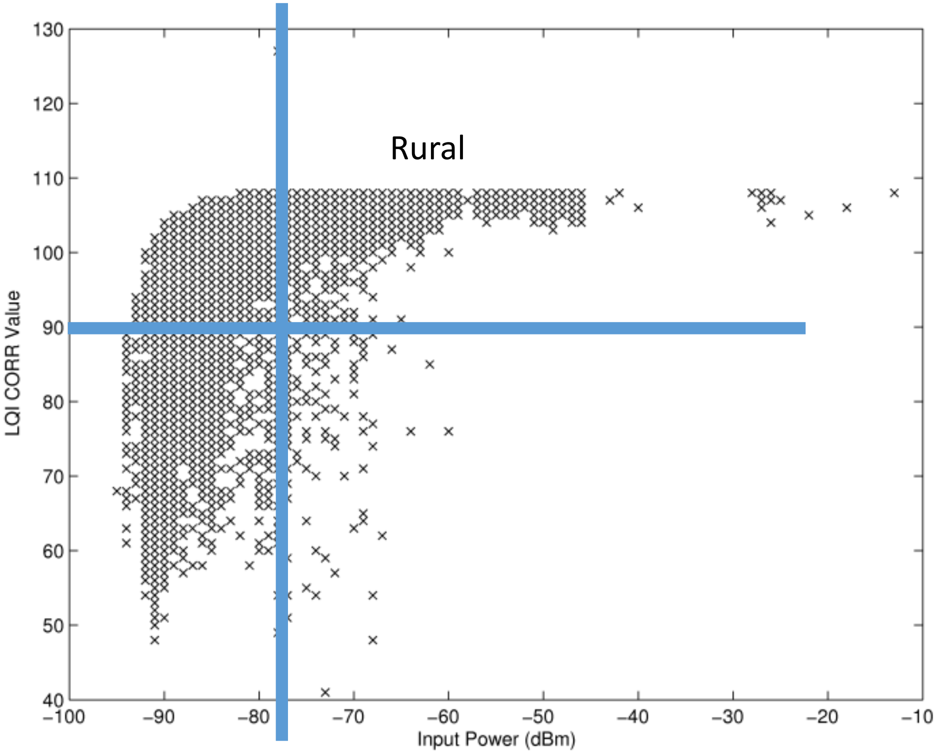
IEEE 802.15.4

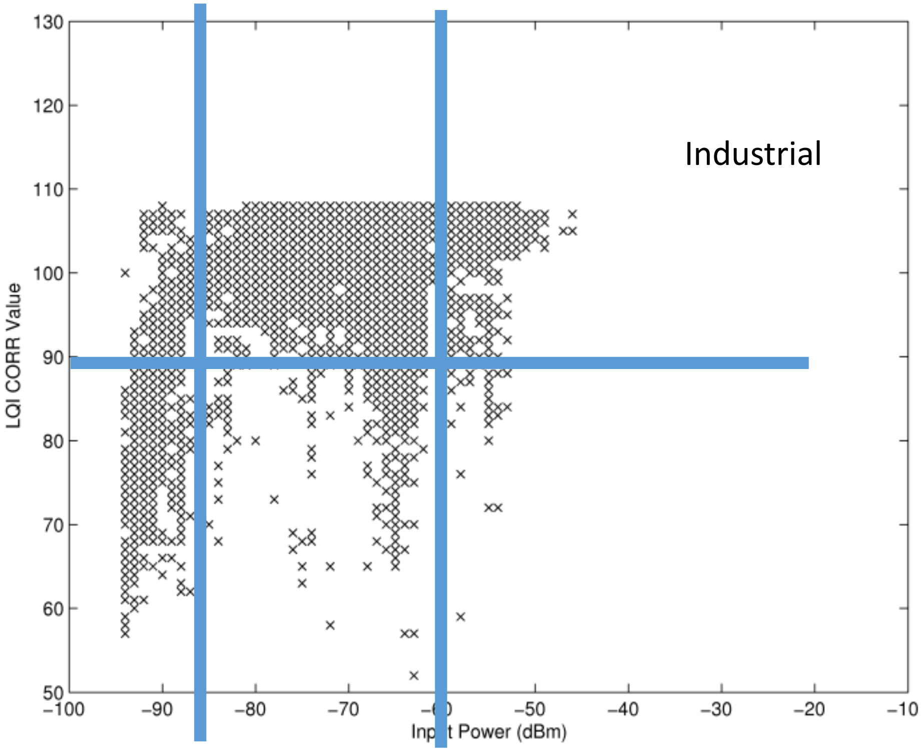


Industrial



IEEE 802.15.4



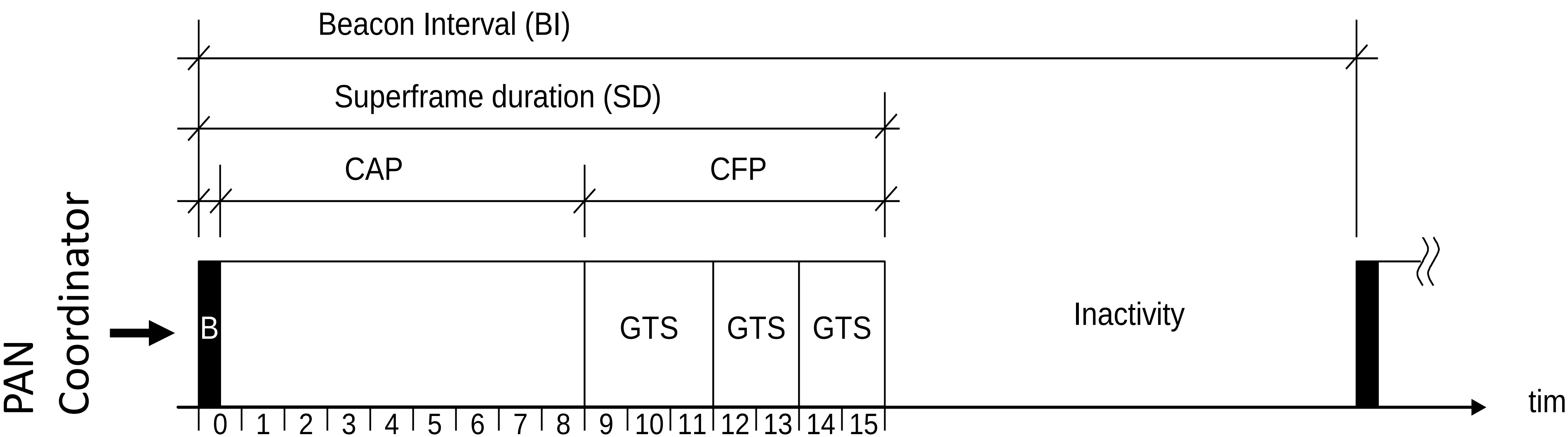


- RSSI Vs LQI: cuttoff threshold of RSSI that affects the LQI (=> chip error rate)
- However: different environment has also different RSSI – LQI relationship
- **@ industrial environment: higher LQI variation Vs @ home / working environments, where LQI presents lower variations**

IEEE 802.15.4

MAC Sublayer Spec

- Beacon Interval: Superframe Duration & Inactivity
- Superframe Duration: Contention Access Period and Contention Free Period



Non-beacon enabled mode

Best effort traffic

Peer-to-peer topologies

Unslotted CSMA/CA

Beacon Enabled mode

Hybrid scheme (best effort & guaranteed access)

Slotted CSMA/CA

Star and peer to peer topologies

Up to 7 slots on TDMA (GTS)

Sync with PAN Coordinator

IEEE 802.15.4

MAC Sublayer Spec

(Slotted / Unslotted) CSMA-CA –> NO RTS/CTS mechanism

- Backoff exponent
- **Clear Channel Assessment**
- If channel is idle => transmission
- Else increase backoff exponent and try again

Slotted CSMA-CA

- Basic steps of unslotted CSMA-CA
- The start of the first backoff period of each device is aligned with the start of the beacon transmission.
- The channel has to be clear for a number of backoff periods before the transmission commences

IEEE 802.15.4

MAC Sublayer Spec

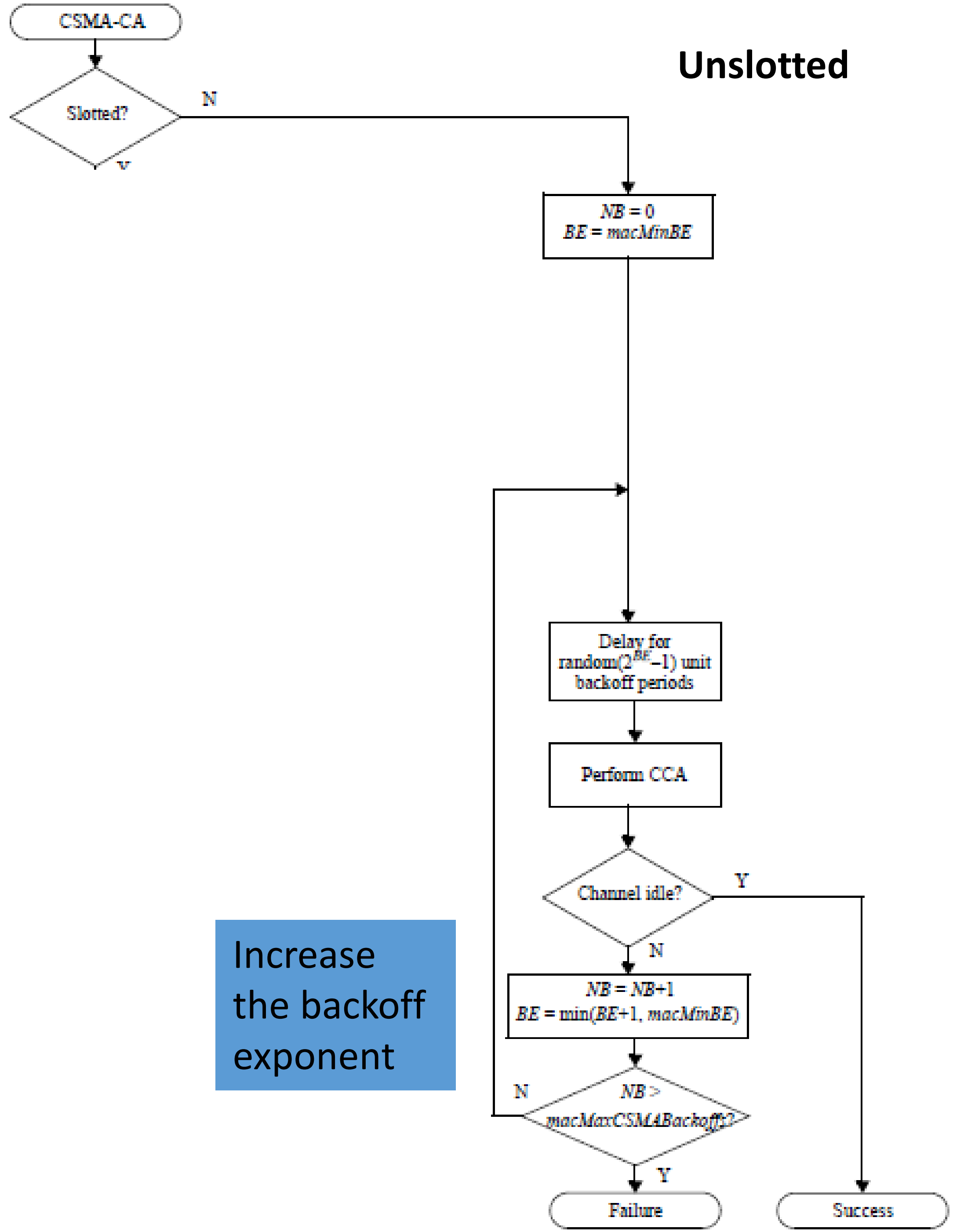
NB : #backoffs

CW: size of the current congestion window

BE: current backoff exponent.

Constants, parameters and operational thresholds are defined in the standard

Unslotted



Increase the backoff exponent

IEEE 802.15.4

MAC Sublayer Spec

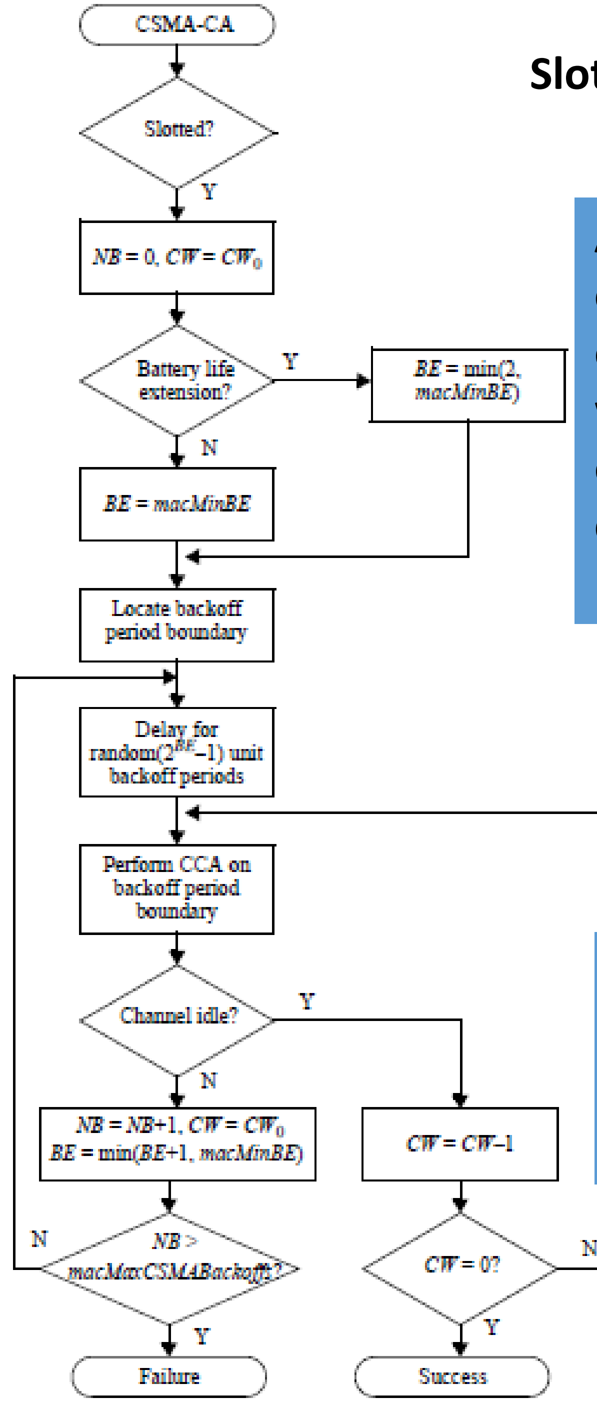
NB : #backoffs

CW: size of the current congestion window

BE: current backoff exponent.

Constants, parameters and operational thresholds are defined in the standard

Slotted



Adapt value of backoff exponent w.r.t. to energy conservation profile

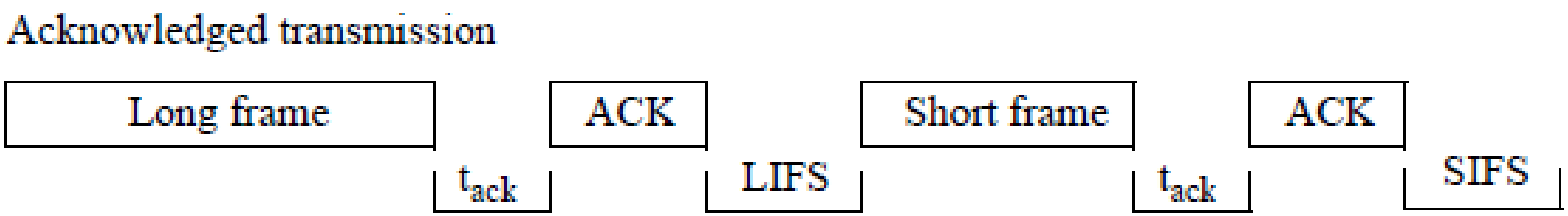
Check for a number of Contention Windows

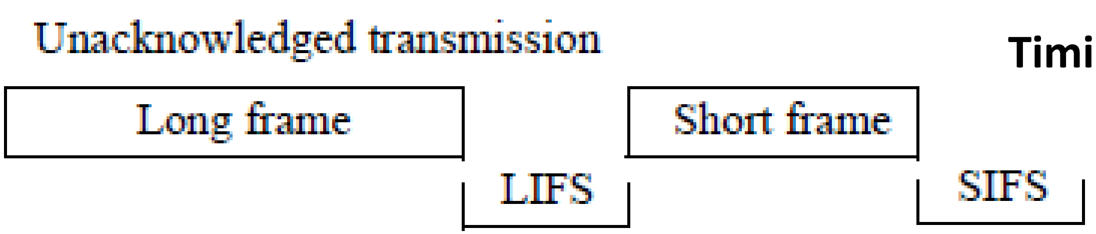
IEEE 802.15.4

MAC Sublayer Spec

TRX cannot process old data and receive new at the same time.

Interframe spacing: time period separating the transmission of two successive frames from the same device
Length of the IFS period depends on the type of the frame that has just been transmitted.





Timings are also defined in the standard

IEEE 802.15.6

- IEEE 802.15.6: **Medical** Body Area Networks (2012)
  - For wearable and implantable devices

MAC

PHY NB (402MHz-2.4GHz)	PHY UWB (3.1GHz – 10 GHz)	PHY HBC
Short range – High data rates (e.g. ECG) Built-in Security Highly reliable wireless connection Low current consumption (<10mA)	High reliability, Low complexity, Ultra-low power operations	Human body as the transmission medium Electric fields instead of electromagnetic waves The user simply touches the devices, and the devices are connected to each other @21 MHz frequency band (164 kbps to 1.3125 Mbps) **EFFECTIVELY INACTIVE**

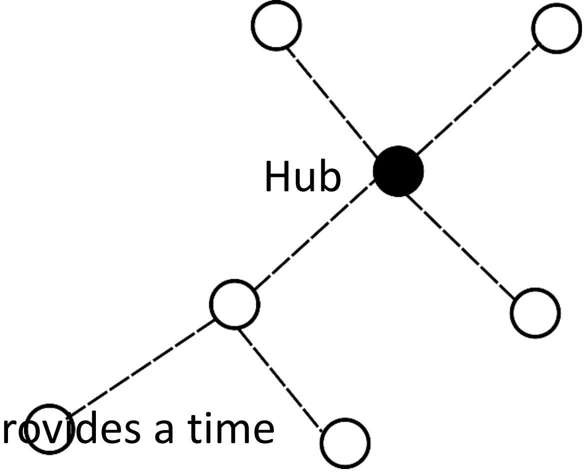
IEEE 802.15.6

@PHY

- Narrowband

Band (MHz)	Region	Number of Channels	Modulation	Data Rate (Kbps)	Support
402-405	Worldwide	10	π/2-DBPSK	75. 9	Mandatory
			π/2-DBPSK	151.8	
			π/4-DQPSK	303.6	
			π/8-D8PSK	455.4	Optional
420-450	Japan	12	GMSK	75.9	Mandatory
				151.8	
				187.5	Optional
863-870	Europe	14	π/2-DBPSK	101.2	Mandatory
902-928	US, Korea	60	π/2-DBPSK	202.4	
950-958	Japan	16	π/4-DQPSK	404.8	
			π/8-D8PSK	607.1	Optional
2360-2400	US	39	π/2-DBPSK	121.4	Mandatory
			π/2-DBPSK	242.9	
2400-2483.5	Worldwide	79	π/2-DBPSK	485.7	
			π/4-DQPSK	971.4	Optional

IEEE 802.15.6



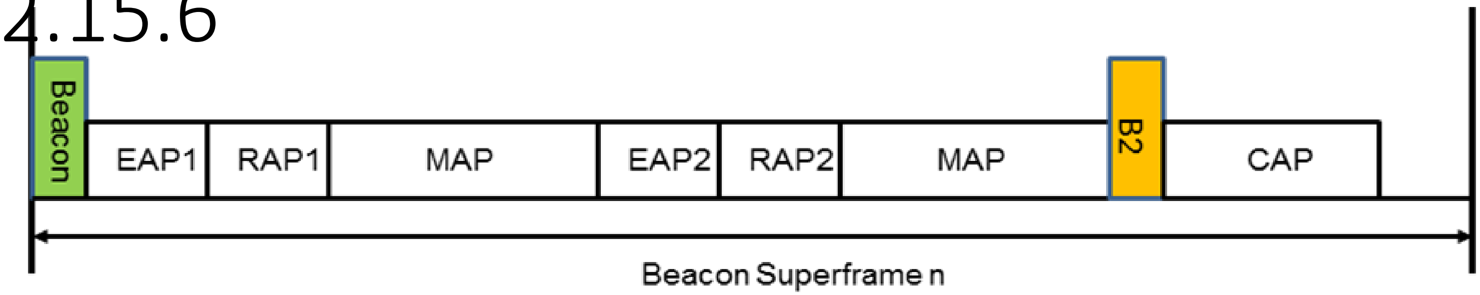
@MAC

Star / Extended Star topologies only

When the BSN operates in either of the first two modes, the hub provides a time reference and corresponding time division to the operational nodes

Medium Access Policy	Type	Beacon with superframes	Non-beacon with superframes	Non-beacon without superframes
Scheduled Access	Contention – Free (Pre-negotiated dedicated time slots)	X	X	-
Improvised / Unscheduled Access	On demand slot allocation and data transaction based on Polling / Posting and Round-robin	X	X	-
Random Access	Slotted CSMA/CA (NB PHY) / Slotted Aloha (UWB PHY)	X	-	X

IEEE 802.15.6



EAP : Exclusive Access Phase RAP: Random Access Phase
MAP: Managed Access Phase CAP: Contention Access Phase

Beacon with superframes: All 3 different policies (with predefined sequence)

EAP, RAP and CAP: Slotted CSMA/CA (NB PHY) or slotted Aloha (UWB PHY). **Hub uses MAP in order to provide contention-free time allocation intervals.**

Non-beacon w. superframes: MAP only

Non-beacon without superframes: slotted CSMA/CA or slotted Aloha.

EAP: Medical emergency event reports
RAPs / CAP: regular data traffic.
MAP: Scheduled / improvised access that al-low event- or poll-driven data transmission from / to the hub.

IEEE 802.15.6

Example

	12 lead ECG	6 lead ECG	SpO2	Temp.	Blood pressure	Weight scale
Scheduled Access	✓	✓	✓	✗	✗	✗
Improvised Access	✓	✓	✓	✗	✗	✗
Random access	✗	✗	✗	✓	✓	✓

IEEE 802.15.6

Why not use Bluetooth LE?

802.15.6 Narrowband and BLE are designed for different use cases.

Bluetooth LE

Infrequent sending of small amounts of data via a mobile phone and/or to a web service.

Not designed for:

- streaming or applications requiring higher data rates (>20kbps)
- applications requiring high reliability (BLE has no FEC, operates in noisy 2.4GHz band)

802.15.6 Narrowband

Focussed on medical applications requiring short range bidirectional wireless data transfer. Typically at least one end of the wireless link is on or in the human body.

It is designed to:

- provide a highly reliable wireless connection (FEC & operation in quiet MBAN band)
- support streaming

Proceedings of the workshop on Wireless Body Area Networks, Body Sensor Networks Conference 2012, London, UK

Comparison

	Bluetooth LE	IEEE 802.15.4			IEEE 802.15.6
PHY Layer supported	2.4 GHz (FHSS / AFH)	2.4 GHz DSSS / 2.4 GHz CSS	UWB: sub GHZ / 3-10 GHz	2.36 – 2.4 GHz (802.15.4j)	NB / UWB / HBC
Data rate	1 Mbps	250 Kbps / 1 Mbps	Varying w.r.t to chirp rate (110 Kbps – 27400 Kbps)	250 Kbps	75.7 – 971.4 Kbps / 202.5 Kbps – 15600 Kbps / 164 Kbps – 1312.5 Kbps
Range	10-30 m	~10-30 m	few meters-30 m (depending on PHY and data rate)	~10-30 m	<10 m (depending on the PHY)
Network topology	Star	Star, peer-to-peer			Star / Extended Start

LoRa Alliance™
Wide Area Networks for IoT

LoRAWAN

Standard for **Long Range WSN**

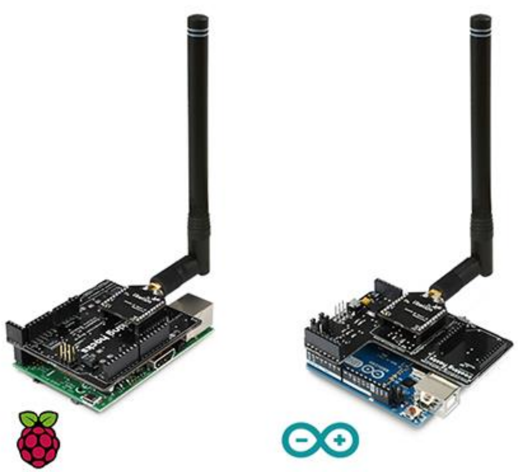
- 3-5km urban areas
- 10-15km rural areas

Uses the CSS modulation@ lower bands of the ISM

- **PHY Layer: Proprietary**
- **MAC is open – yet simplified (e.g., ALOHA)**

- EU: 433MHz & 868Mz
- US: 915MHz
- AS: 430Mz

End-to-end encryption by default



LoRAWAN

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Wide Area Networks for IoT

Standard for **Long Range WSN**

FEC -> Error detection / correction mechanism:
m bits of information / n bits of transmission

- Adaptive Data rates: 0.25 – 50kbps
- Trade-offs between range and data-rates
- Transmission mode w.r.t. bandwidth, coding rate and spreading factor

Number of chips utilized for the transmission by the SS mechanism
Chip: shorted modulated signal

LoRa Mode	Bandwidth	Coding Rate	Spreading Factor	Sensitivity (dB)
LM1 (max range)	125	4/5	12	-134
LM2	250	4/5	12	-131
LM3	125	4/5	10	-129
LM4	500	4/5	12	-128
LM5	250	4/5	10	-126
LM6	500	4/5	11	-125.5
LM7	250	4/5	9	-123
LM8	500	4/5	9	-120
LM9	500	4/5	8	-117
LM10 (min range)	500	4/5	7	-114

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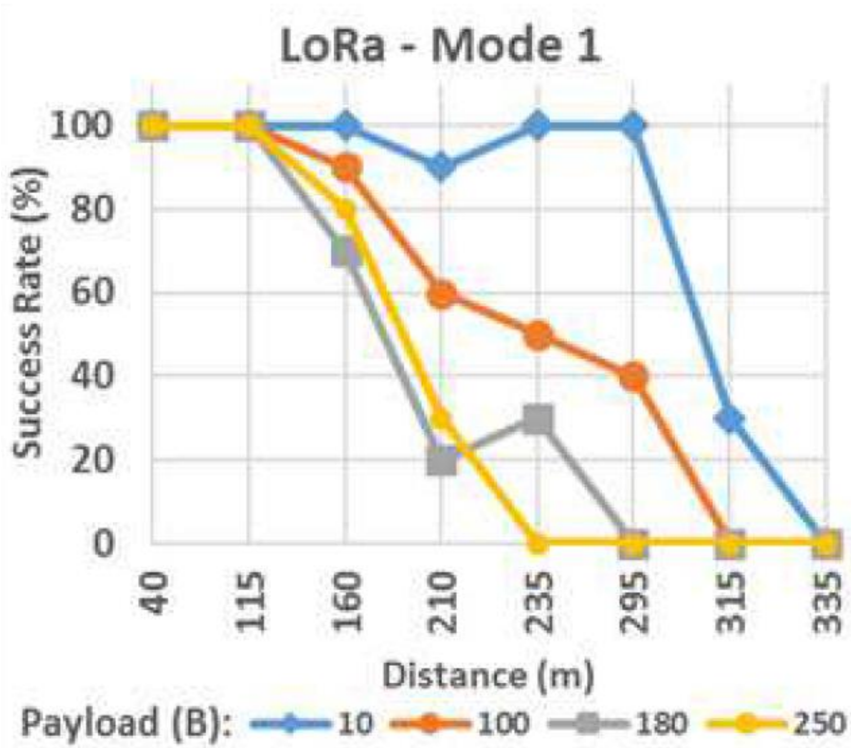

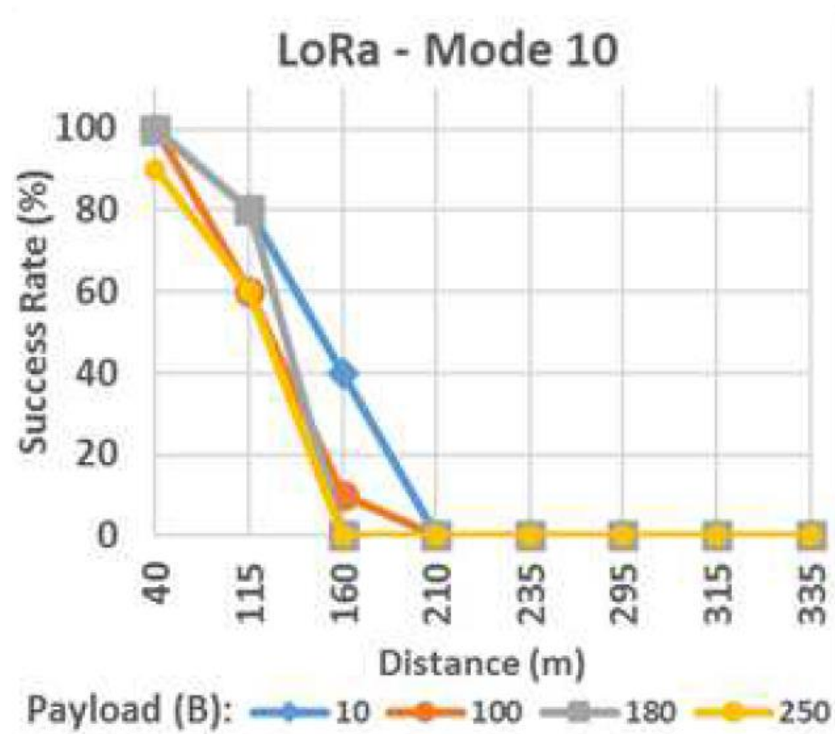

Kartakis and McCann, "Communication Optimization and Edge Analytics for Smart Water Grid", in Smart Water Grids: a CPS approach (ch. 3), March 2018.

NOT suited for:

- High data-rate and/or very frequent transmissions (e.g., each 10 seconds).
- Highly populated networks w.r.t. to traffic demand.
- Self-powered nodes (e.g., battery-based)

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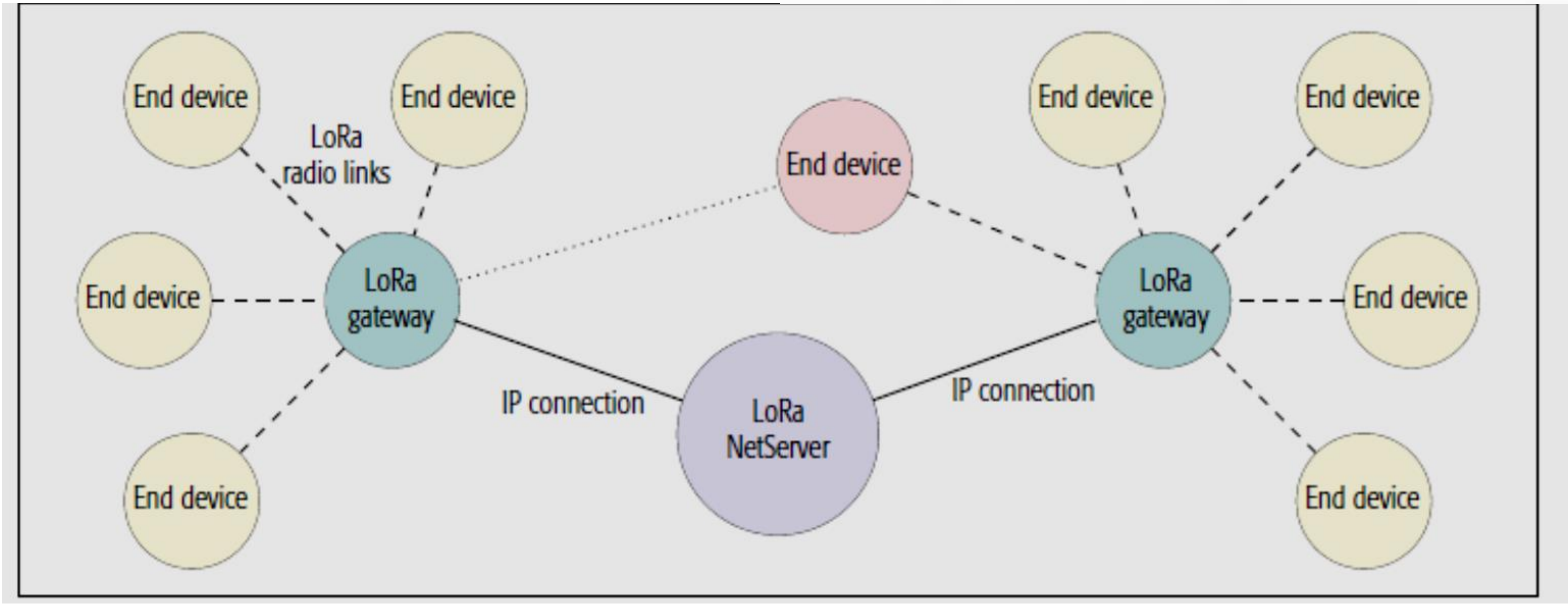

Star of Stars Topology **Intelligence on the NetServer**

Gateways: relay messages between the end devices and the NetServer
End devices are not required to associate with a certain gateway to get access to the network, but only to the NetServer.
Gateways: transparent relay/bridge
Gateways: up to 9 nine LoRa channels (channel: specific sub-band & spreading factor)

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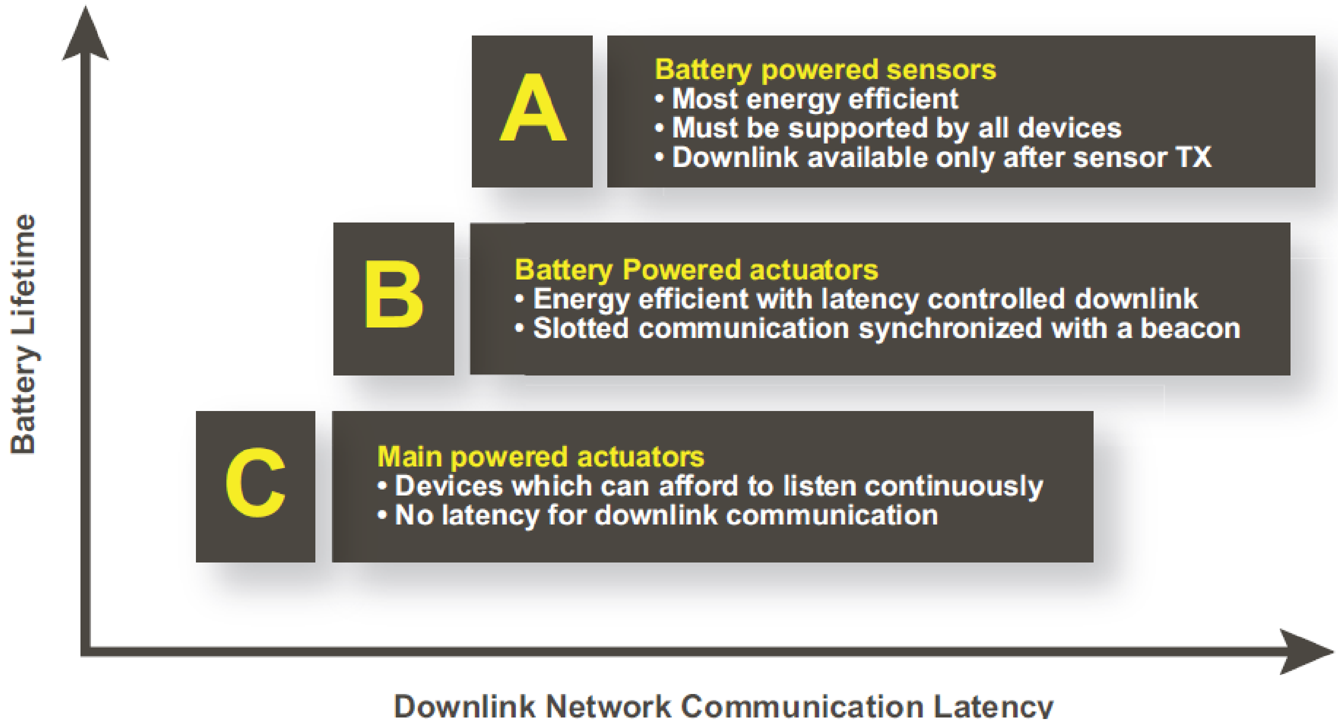

Class A (for *All*): transmissions are always initiated by the end devices (asynchronous)
Class B (for *Beacon*): synchronize with the NetServer – receiving downlink data or command packets in specific time windows, irrespective of the uplink traffic.
Class C (for *Continuously listening*): keep the receive window always open

References and Material for Reading

802.15.1-2005 - IEEE Standard for Information technology-- Local and metropolitan area networks-- Specific requirements-- Part 15.1a: Wireless Medium Access Control (MAC) and Physical Layer (PHY) specifications for Wireless Personal Area Networks (WPAN)

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802.15.4-2011 - IEEE Standard for Local and metropolitan area networks--Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)

802.15.6-2012 - IEEE Standard for Local and metropolitan area networks - Part 15.6: Wireless Body Area Networks

Proceedings of the workshop on Wireless Body Area Networks, Body Sensor Networks Conference 2012, London, UK

Body Sensor Networks, G.Z. Yang Editor, 2014, Springer, Ch. 5

Centerato et. al, Long-Range Communications in Unlicensed Bands: The Rising Stars in the IoT and Smart City Scenarios, IEEE Wireless Communications, Oct. 2016.

Kartakis and McCann, "Communication Optimization and Edge Analytics for Smart Water Grid", in Smart Water Grids: a CPS approach (ch. 3), March 2018.