Introduction to Wireless Sensor Networks: Networking Aspects

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Outline

- Part 1: Applications, Standards and Protocols
  - Introduction & Reasoning of Existence
  - Sensing, Processing, and Networking Aspects
  - Standards, Topologies & Protocols
- Part 2: WSN Programming
  - WSN Core and types of nodes
  - Real-time Operating Systems
  - Examples & Hands on Session

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Introduction & Reasoning of Existence

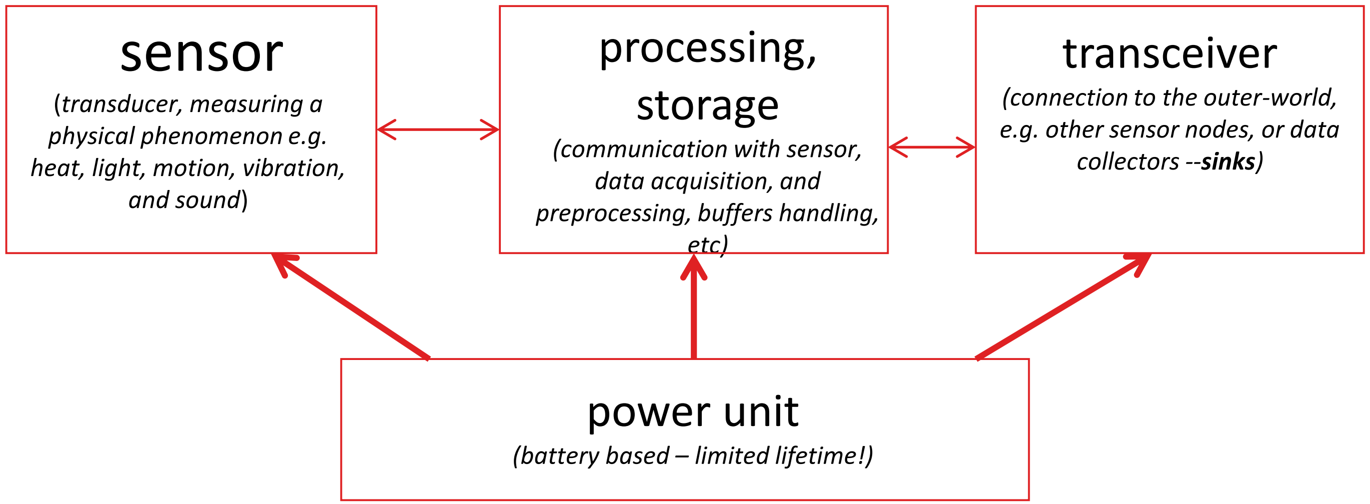
- 10+years old

- 3-in-1 attribute: sensing, processing, communicating

- Secret of success: Miniaturized and cost-effective deployment
  - Research: Full of challenges ∝ Application areas…

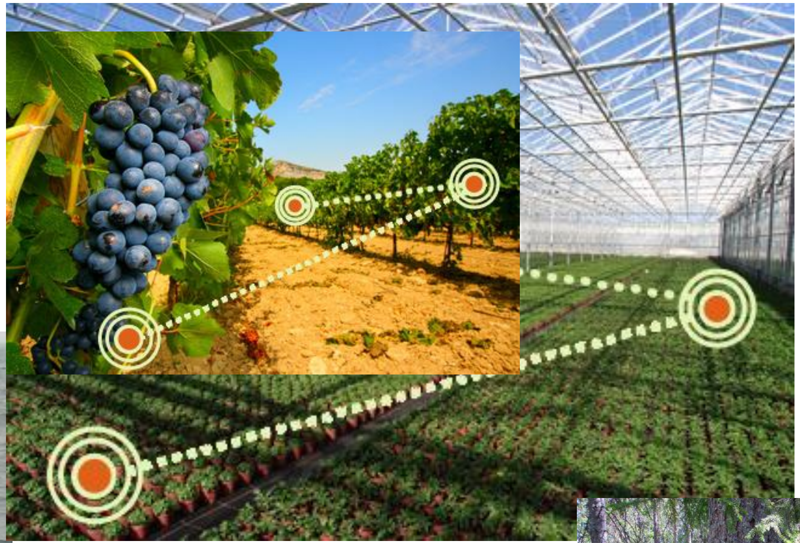
Introduction & Reasoning of Existence

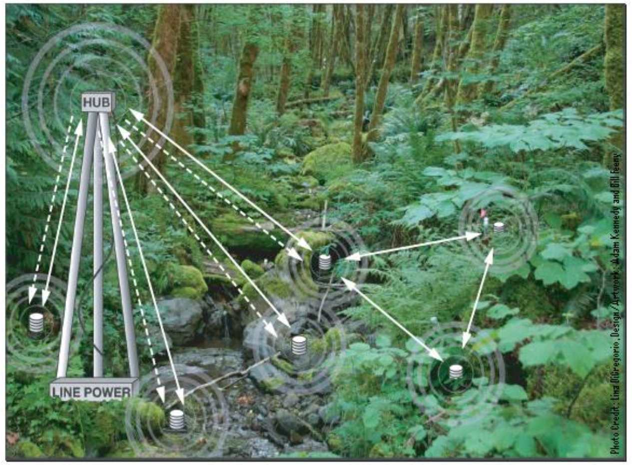
- What is a sensor node
  - Basic unit in sensor network
  - Contains on-board sensors, processor, memory, transceiver, and power supply
- What is a sensor network
  - Consists of a large number of sensor nodes
  - Nodes deployed either inside or close to the phenomenon/parameter being sensed



Introduction & Reasoning of Existence

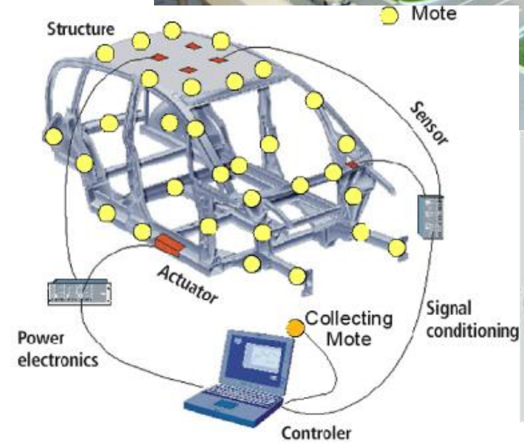
Application Areas (1): Wild-life and environmental monitoring [1-8]

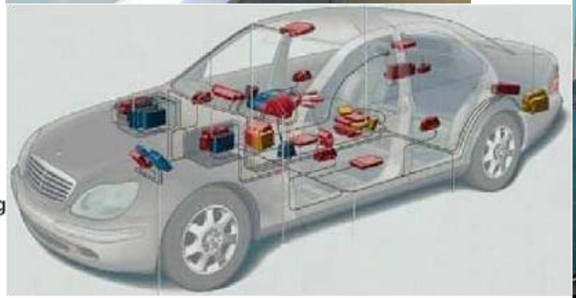




Introduction & Reasoning of Existence

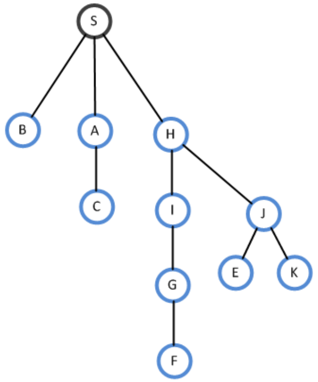
Application Areas (2): Industrial control & Automotive, structural health monitoring, Smart Cities [9-11]

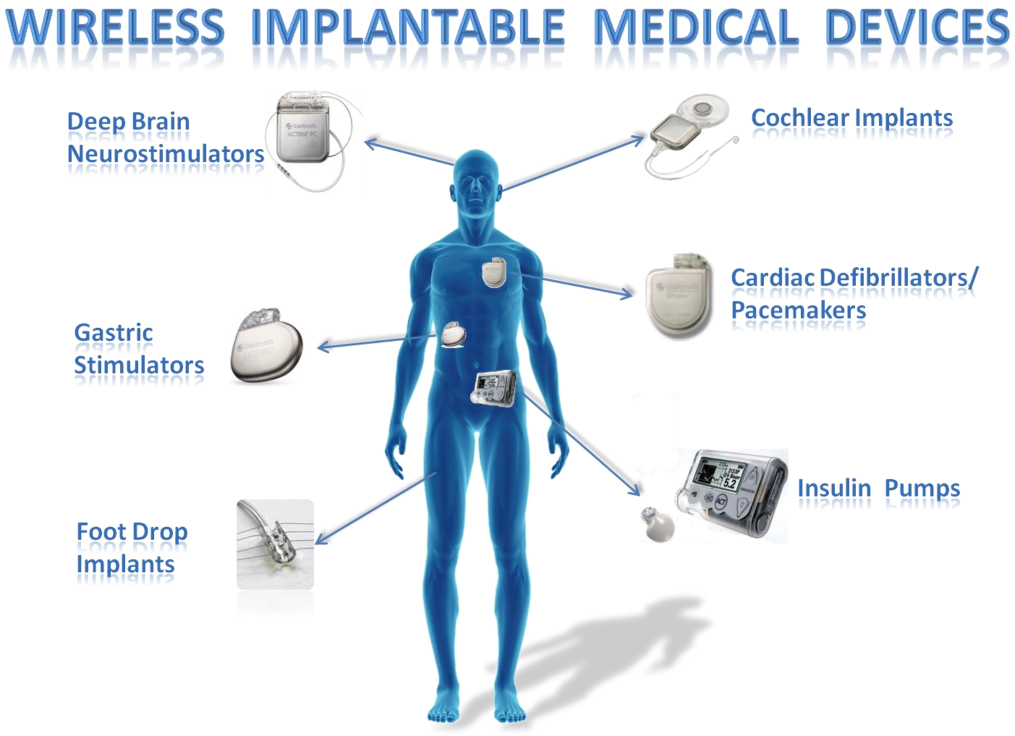




Introduction & Reasoning of Existence

Application Areas (3): Body area networks for sports, healthcare and wellbeing [12]

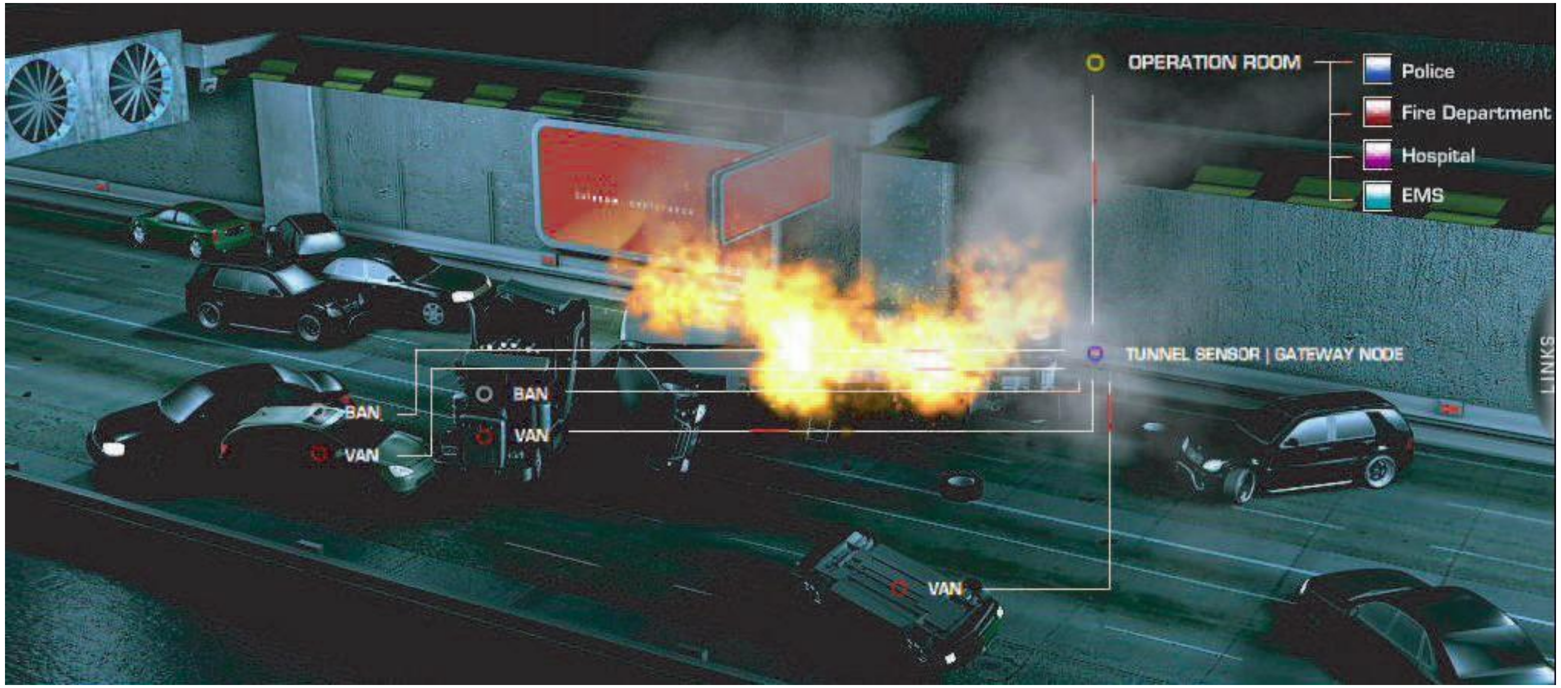




Introduction & Reasoning of Existence

In contrast to data networks:

Necessary means for accessing the "physical" space…



Infrastructure-less information transfer towards support systems and decision makers

Introduction & Reasoning of Existence

Technical Specs (Holistic Aspect)

- Highly scalable (<10 – 1000+)
  - *Depending on the application*

- Lower bit rates than data networks (**nominal max typically 250kbps**) – reduced bandwidth requirements
  - *Easily stretched w.r.t. application area changes & / the network size increases*
  - *Throughput / s.m.* → *Dense networks are not only large-scale networks…*

- Power autonomy (and associated issues…)
  - *Fixed in position? Maybe – Static in operation? No….*

- No need for network infrastructure (unattended, long term monitoring)
  - *Base Station / Gateway support for reaching the outer world.*

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  - Topologies, Standards & Network Protocols
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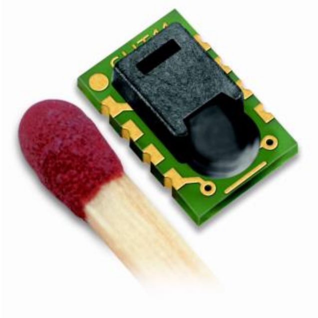
  - A case study of network protocol design and experimental evaluation.

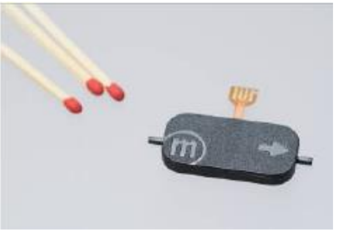
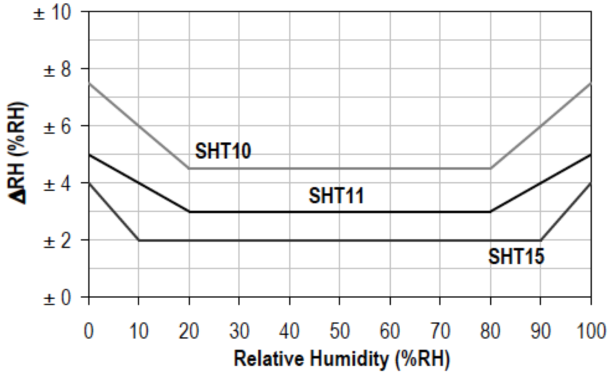
sensing

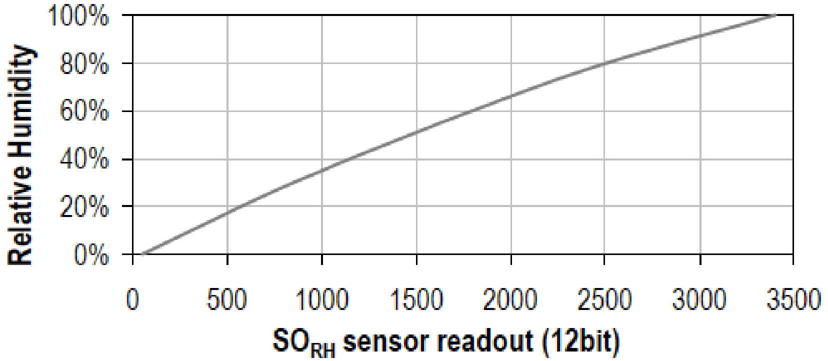
What do we sense?

Depends on the application



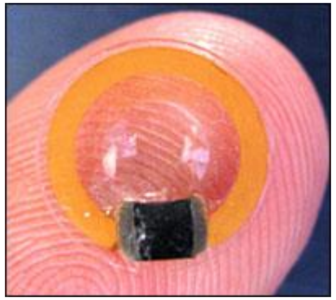




Challenges:

- Accuracy & Operational parameters
  (e.g. how battery fluctuations affect accuracy)
- Size
- Hardware design
- How to make them battery-less….



proces
sing

How do we process it?

Limited (for conventional platforms)

- Trade off: Computational Efficiency Vs Power
- Basic calculations at 16-bit architectures
  - More advanced? Doable but @ reduced speed (software & compiler)

  [e.g. on-node Kalman filter for motion reconstruction (6 inputs – 4 outputs) ~ 5seconds]
- Newer trends in hardware design:
  - increased memory for programming and calculations
- New trend: collaborative & in-network processing
  - + distributed storage -> resolved network issues…

What do we do with it?

networ
king

One of the most active research area in WSNs for the last decade…

- Propagation characteristics & channel modeling
- Protocols design (routing, MAC)
- Energy conservation
- Security
- Topology Control
- ….

networ
king

What do we do with it?

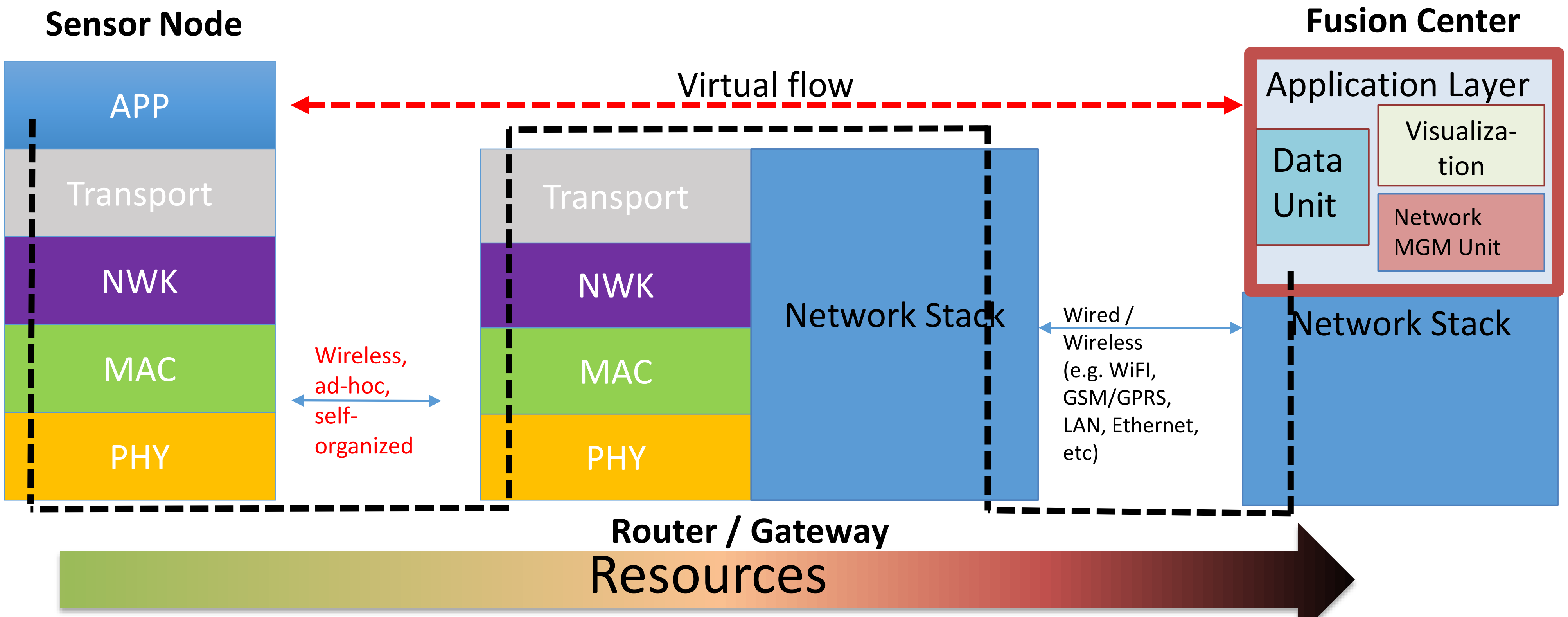
on-node & intra-network: w.r.t. OSI's protocol stack

APP	Sensing, Data Processing
Transport	? Depending on HW capabilities & application demands (lightweight version – limited functionality)
NWK	Open for research (well-studied algorithms in practice)
MAC	Fixed (e.g. TDMA / FDMA) or Contention-based (CSMA) approaches (depends on both the technology and the appl. demands) – Also defined by **standards**
PHY	**Standard-compliant** or "Closed"

No session / presentation layers as in conventional data networks

What do we do with it?

Inter-networking: w.r.t. application demands and outer-world connectivity



Small volume of information (locally available)

- High Volume of information
- Global perspective on the entire system

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The standards

The standards family: IEEE 802.15 [13]

- Topologies and network roles

- PHY - frequency and channels, spectrum handling, modulation, bit rate

- MAC – packet formats, operational modes, timing aspects, topologies

The members of the family [13-14]

Standard	Description	Initial Release / Revision Date	Amendments
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 (2006): Amendment to MAC Sublayer 802.15.3c (2009): Millimeter-wave-based Alternative Physical Layer Extension
IEEE 802.15.4	MAC and PHY Layer Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)	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): Amendment 1: 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 802.15.5	Mesh Topology Capability in Wireless Personal Area Networks	2009	-
IEEE 802.15.6	Wireless Body Area Networks	2012	-

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
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IEEE 802.15.4

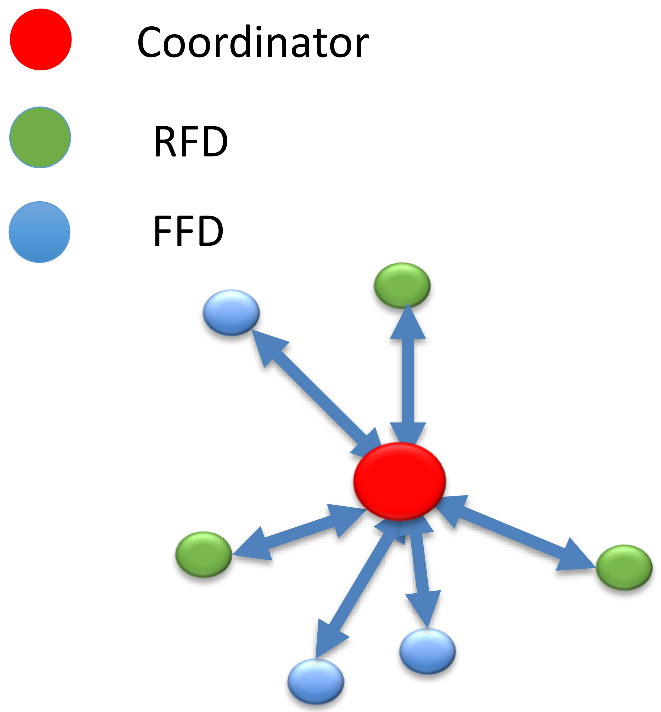
IEEE 802.15.4 Types of Devices [15]

- Full-Function Device (FFD)
  - Capable of acting as the network's coordinator or as a simple device
  - Undertaking complex network functionalities
- Reduced-Function Device (RFD)
  - Extremely low bandwidth demands application specs (e.g. front-end low complexity sensors with no network intelligence, passive RFID, etc)

A PAN Coordinator

- Associates a PAN with an ID. Networks with different PAN 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)

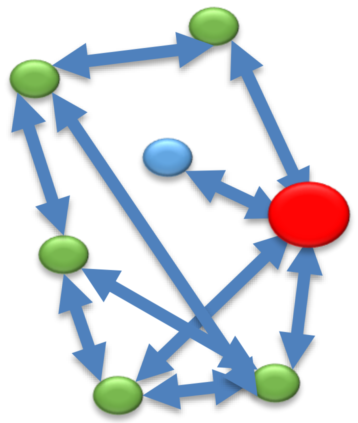
IEEE 802.15.4



Types of topologies [15]

- 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 personal 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.

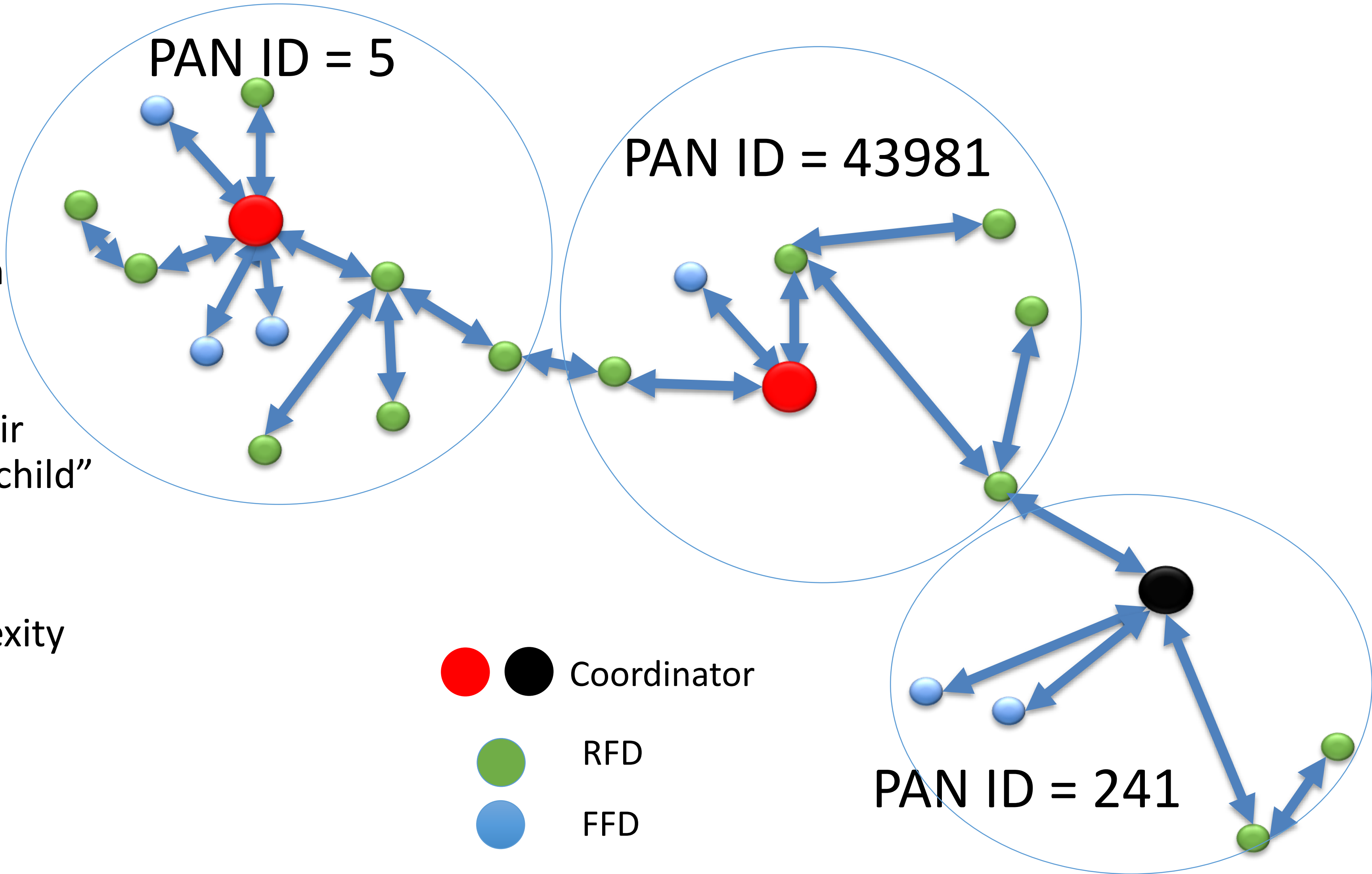


IEEE 802.15.4

Types of topologies [15]

- Cluster Tree

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



IEEE 802.15.4: The PHY map@ 2011 release [14-15]

Band allocation w.r.t. geographical region
Many modulation options

Band (MHz)	Region	Number of Channels	Modulation	Data Rate (Kbps)	
868 - 868.6	Europe	1	BPSK	20	
			ASK	250	
			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-gigahertz)		1	BPM and BPSK	110 – 27400 (Varying w.r.t. chip rate)	Optional
3244 - 4724 (UWB low band)	Worldwide	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

PHY tasks [15, 16-18]

Receiver Energy Detection (ED)

- Use by a network 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)

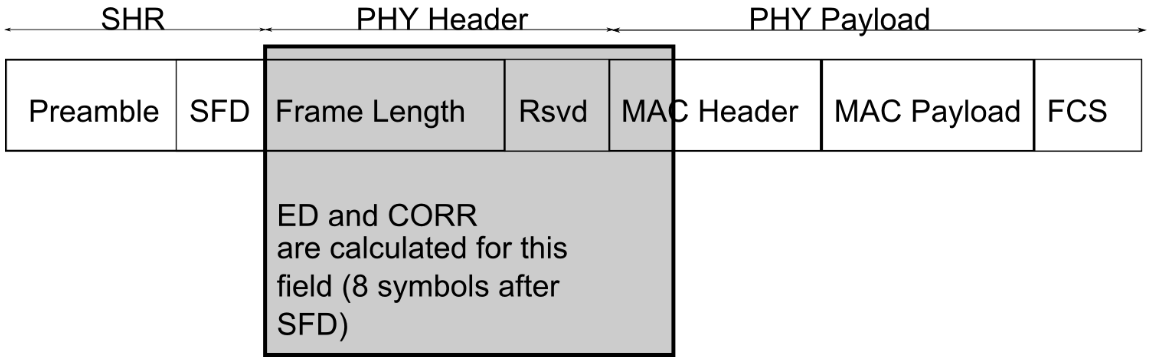
- The characterization of the strength and/or the quality of a received packet.
- The measurement may be implemented using receiver ED, a SNR estimation, or their combination.
- The minimum and maximum LQI values (0x00 and 0xff) associated with the lowest and highest quality compliant signals detectable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

IEEE 802.15.4

PHY tasks [16-18]

ED → A measurement of the channel;

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

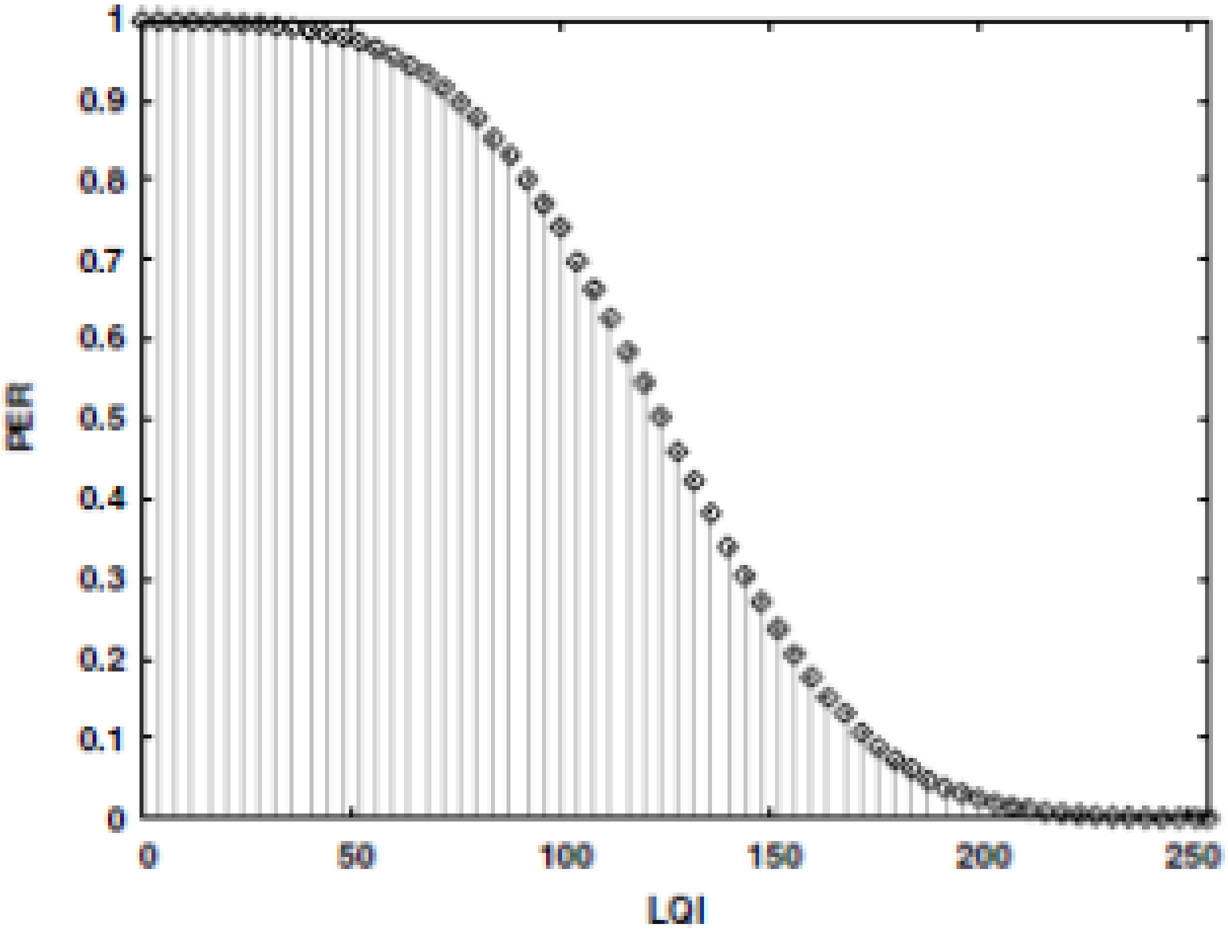


LQI → A measurement of the frame;

- 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

PHY tasks: Vendor’s rules of thumb [16]



LQI ∝ PER ∝ Throughput

RSSI/ED ∝ tx power and link margin

High LQI → Use RSSI /ED to differentiate between links

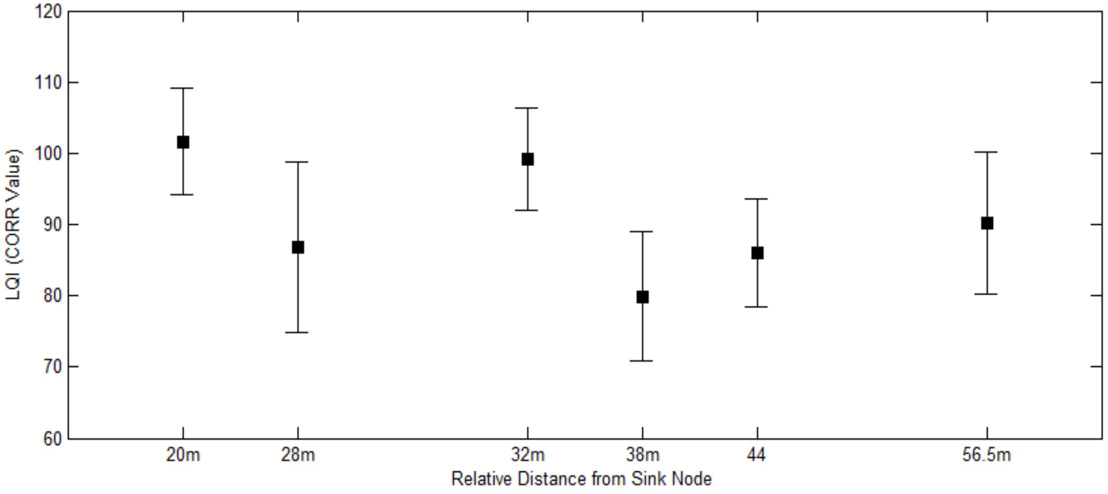
Low LQI → Link should be disca-rded. A high RSSI / ED could be strength of an interfering signal

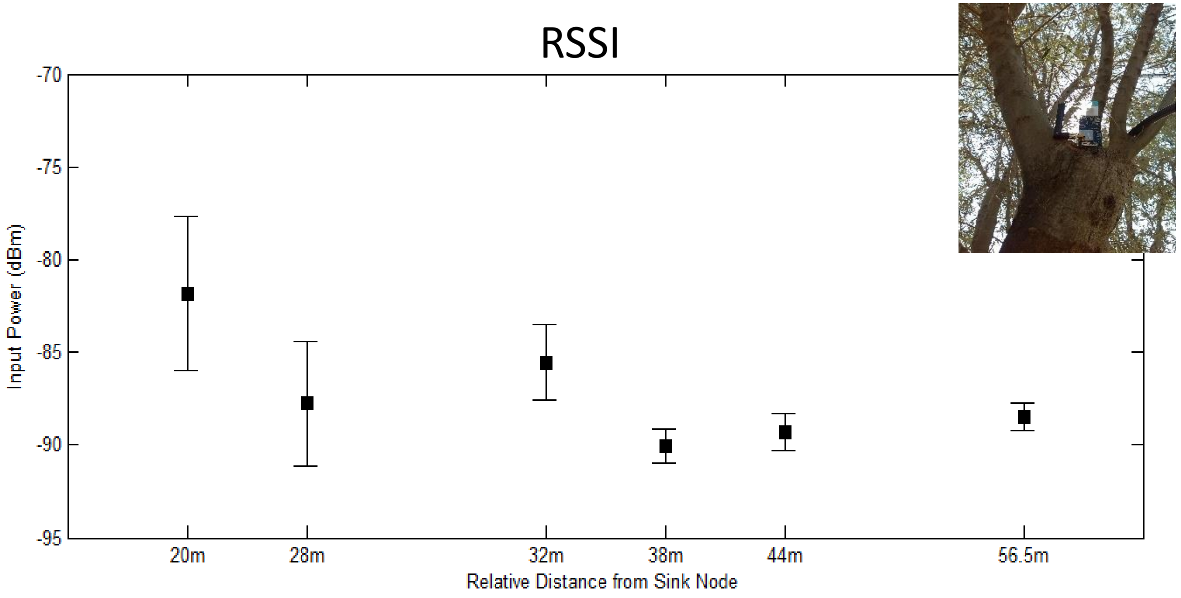
PHY metrics…

LQI

RSSI

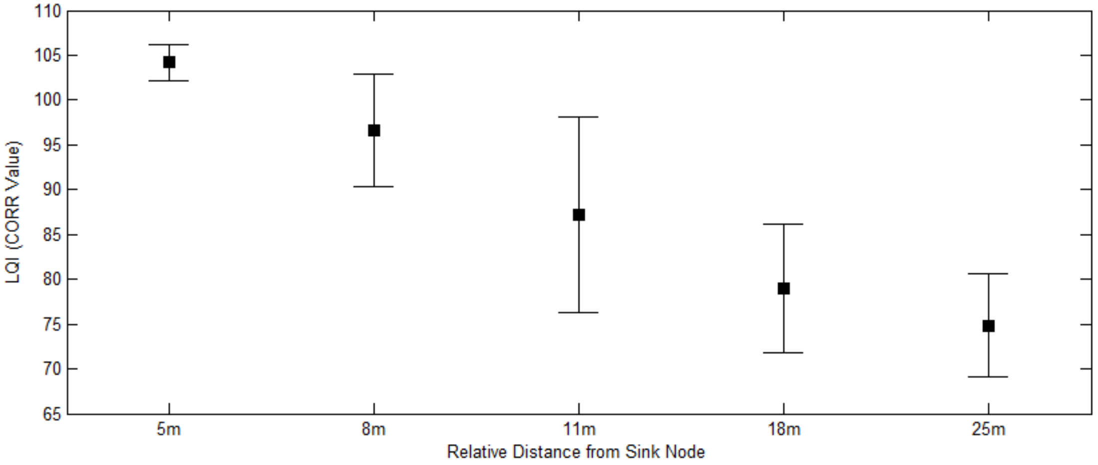
Rural

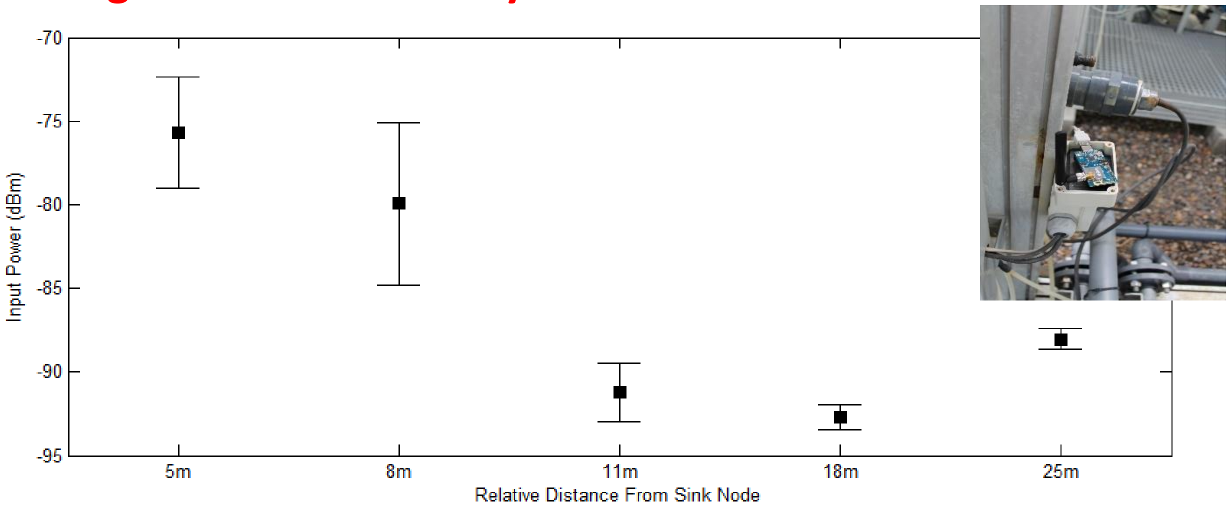




@ Industrial environment: Transmission range can be reduced by half!

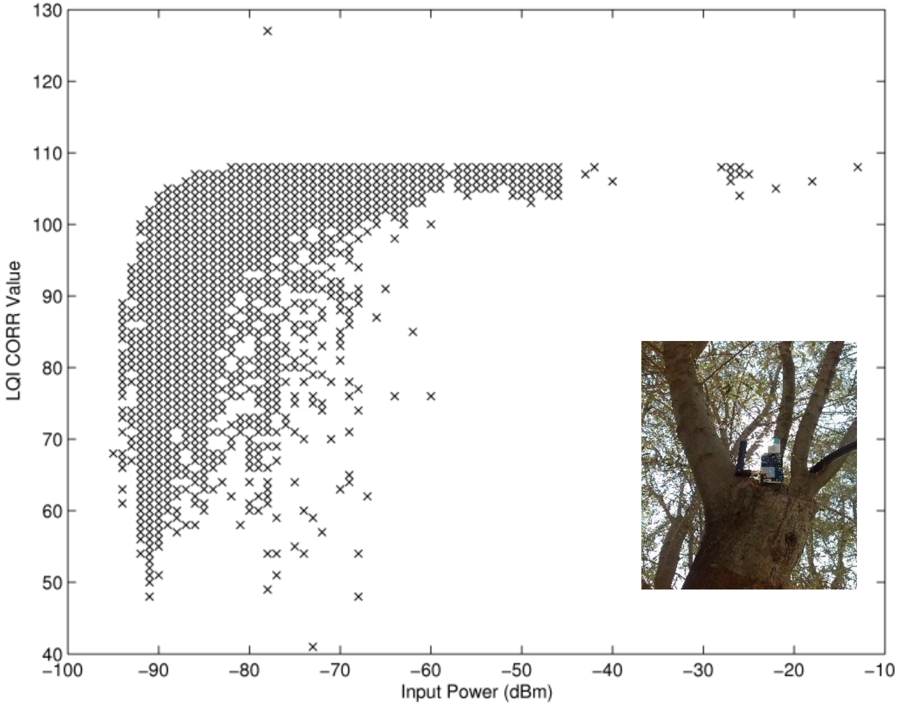
Industrial



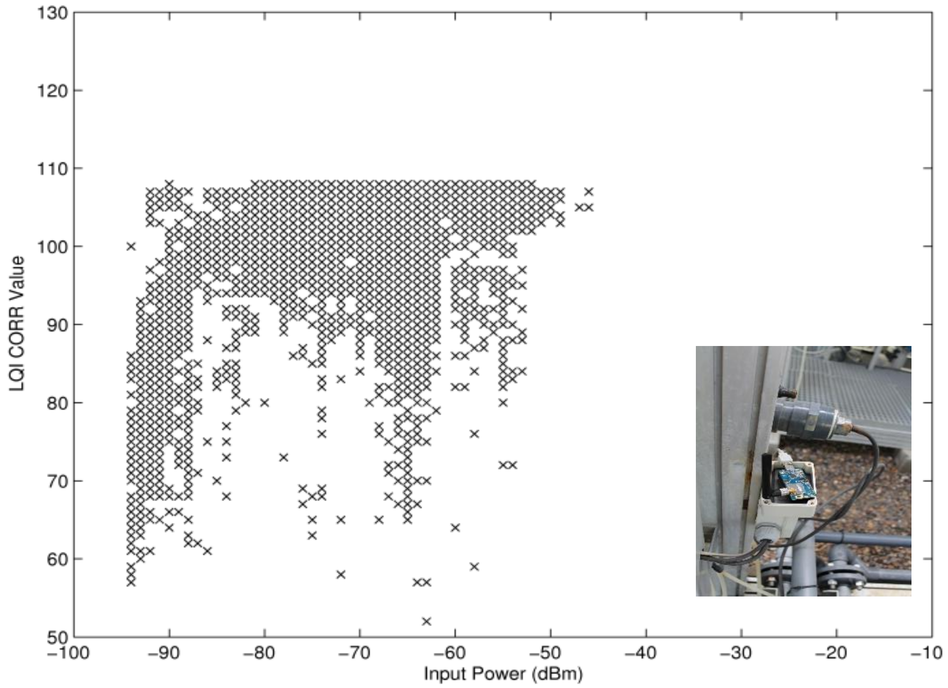


PHY metrics…

Rural



Industrial



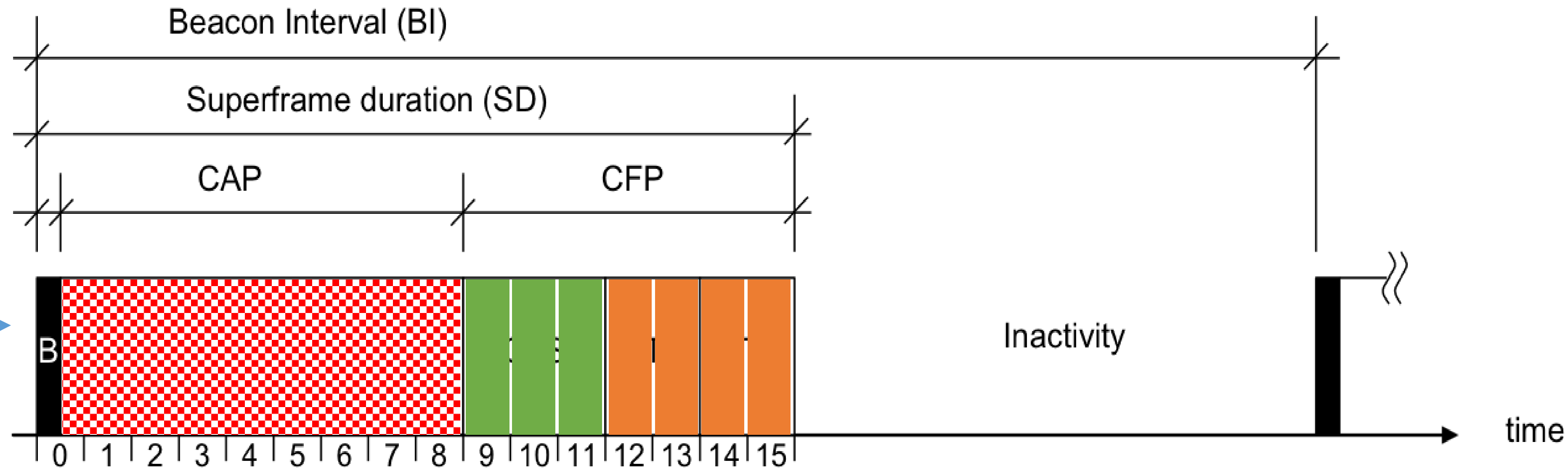
- RSSI Vs LQI: cuttoff threshold of RSSI that affects the LQI (=> chip error rate)
- However: different environment has also different RSSI – LQI relationship
- @ industrial environment: higher LQI variation Vs @ home / working environments, where LQI presents lower variations…[17,18]

IEEE 802.15.4

The MAC [15]

- Non-beacon enabled mode: CSMA-CA, peer-to-peer topologies
- Beacon Enabled mode: slotted CSMA-CA & up to 7 slots of guaranteed access (GTS), star and peer-to-peer topologies

PAN Coordinator



CAP: Contention Access Period->Nodes compete for accessing the wireless medium

CFP: Contention Free Period -> Nodes transmit on their pre-allocation slots

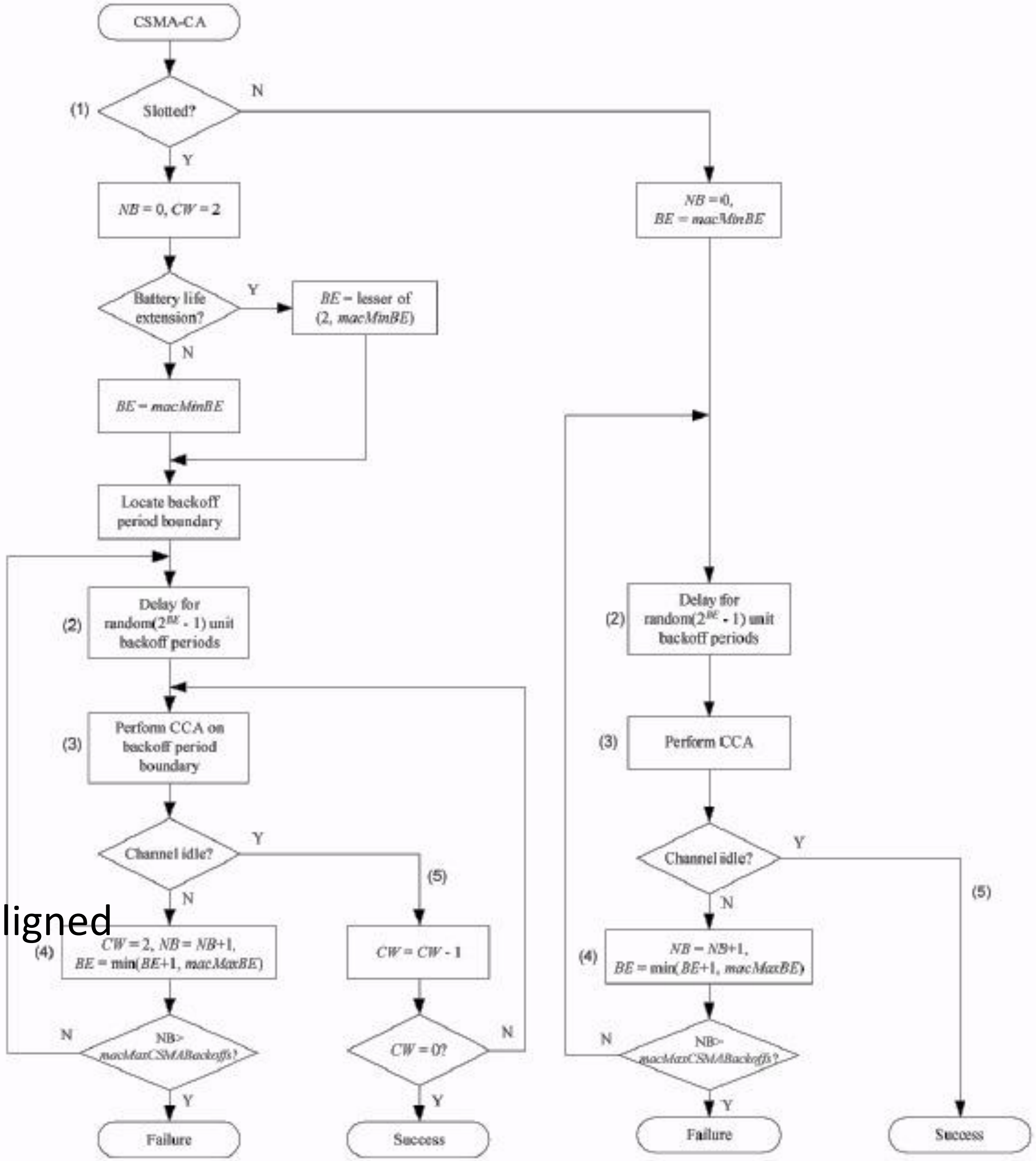
IEEE 802.15.4

The MAC [15]

Two modes for accessing the channel

- Unslotted CSMA-CA
  - Delay for backoff exponent;
  - Perform Clear Channel Assessment;
  - If channel is idle => transmission
  - Else => increase backoff exponent and try again

- Slotted CSMA-CA
  - Basic steps of 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



A comparison….[14]

	Bluetooth LE	IEEE 802.15.4		
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)
Data rate	1 Mbps	250 Kbps / 1 Mbps	Varying w.r.t to chirp rate (110 Kbps – 27400 Kbps)	250 Kbps
Range	10-30 m	~10-30 m	few meters-30 m (depending on PHY and data rate)	~10-30 m
Network topology	Star	Star, peer-to-peer, cluster-tree		
Network size	Unlimited	65,535		
Network join time	~6 ms	<<1 s		
Real-time support	No	Guaranteed time slots		
Protocol complexity	Simple	Simple		
Security	Authentication, encryption			
Peak current consumption	15-20 mA	15-25 mA		
FEC support	No	Yes		

On top of 802.15.4

- Routing mechanisms

- Routing Vs Forwarding..
  - Routing: Build routing tables with information on how a given destination can be reached
  - Forwarding: Consult a routing table to forward a packet to its next hop.

- Whilst considering…
  - Topologies are dynamic (even if nodes are static, topologies change as new sensor join the network, or old ones leave the network, e.g. due to battery depletion)
  - Optimization metrics vary w.r.t. to application demands:
    - Increase lifetime (energy-efficient paths)
    - Minimize interference
    - Exploit geographic characteristics

Routing for wireless sensor networks

- Basic categories for routing [19]
  - **Data-driven.** Data are flooded towards from the source nodes towards the sink. OR Paths are build based on gossiping mechanism OR The sink sends queries to certain regions and waits for data from the sensors located in the selected regions.

  Examples. Directed-diffusion, SPIN

  - **Hierarchical.** Nodes are organized in clusters or in trees, and they perform data aggregation towards a cluster head or a sink. Cluster formation is typically based on the energy reserve of sensors and sensor's proximity to the cluster head.

  Examples. Collection-tree protocol, LEACH, Routing Low-power & Lossy Networks (RPL)

Routing for wireless sensor networks

- Basic categories for routing (cont')

  - **Location-based.** When the region to be sensed is known, using the location of sensors, the query can be diffused only to that particular region which will eliminate the number of transmission significantly. OR Determine next hop based on position (absolute or relative) OR Flooding to any node within an area (**geocasting**)

  Examples. Geographic and Energy-aware routing (GEAR)

  - **Network flow & QoS-aware.** Route setup is modeled and solved as a network flow problem. QoS-aware protocols consider end-to-end delay requirements while setting up the paths in the sensor network.

  Examples. Ad-hoc On-demand Distance Vector (AODV)

Routing for wireless sensor networks

An example: Collection-tree protocol [20]

- Some number of nodes in a network advertise themselves as tree roots.
- Nodes form a set of routing trees to these roots.
- CTP is **address-free** in that a node does not send a packet to a particular root; instead, it implicitly chooses a root by choosing a next hop.
- Nodes generate routes to roots using a routing gradient
  - Routing gradient: expected transmissions (ETX)
  - ETX is the number of expected transmissions of a packet necessary for it to be received without error at its destination

Forward Engine
(handling transmission queue. It decides when and if to send them – forwarding and on-node generated packets)

Routing Engine
(based on Link Estimator, deciding the next hop/parent)

Link Estimator
(ETX)

ZigBee

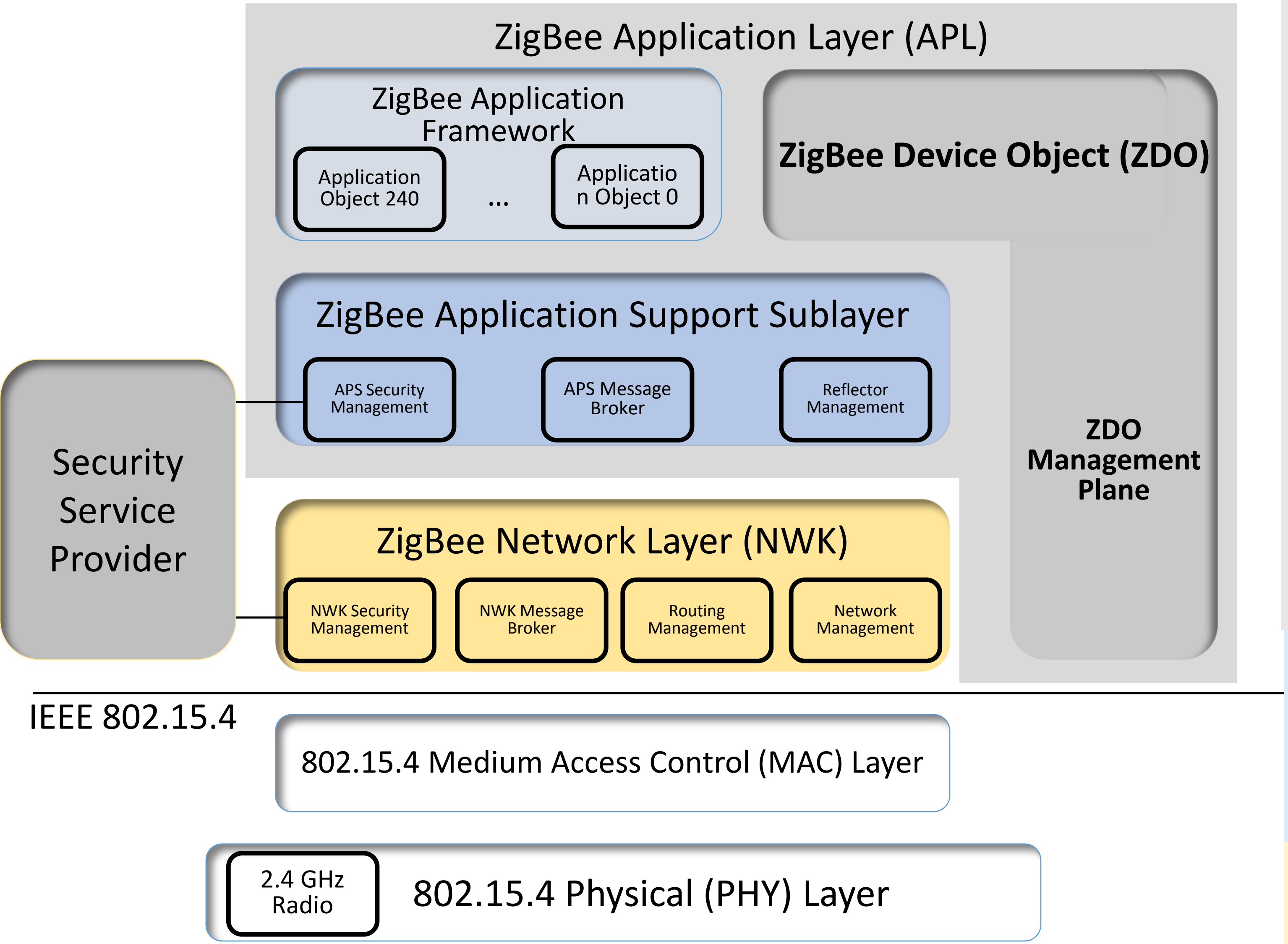
- A specification for higher-level protocols that rely on 802.15.4 for implementing WSN in different application scenarios.

- An alliance between WSN vendors and policy makers, e.g.

and many many more

- Define the device architecture and the ***application profiles*** with respect to application framework

ZigBee – the device architecture..



ZDO. defines the role of the device within the network (for instance the ZigBee coordinator or end device)
Manages the node configuration
initiates and/or responds to binding requests (secure relationships between network devices).
Network discovery (which other devices are operating in the network).
Creates the necessary level of abstraction that allows the application developer not to worry about the low-level details. A baseline upon which user applications are Implemented (user no need to know underlying details)

APS. maintains tables for binding (i.e. the logical connection of devices based on their services and needs)
Forwards messages between bound devices

NWK. Routing and Multi-hopping functions for logical network topologies

ZigBee

- Zigbee ***Application Profiles ->*** Agreement on types of messages, message format and processing action

secure and reliable monitoring and control of commercial building systems.

monitor, control, inform and automate the delivery and use of energy and water.

create smarter homes that enhance the comfort, convenience, security and energy management for the consumer

secure and reliable monitoring and management of non-critical, low-acuity healthcare services targeted at chronic disease, aging independence and general health, wellness and fitness.

Conclusions

- Introduction to WSN
- Core aspects
- The IEEE 802.15 standards family – IEEE 802.15.4
  - Topologies
  - PHY metrics & real-life aspects
  - MAC aspects
- Routing: one size does not fit them all!
  - Rule of thumb – use the one that better fits your application needs and if necessary modify…
- ZigBee: specifications for people for don’t care about the WSN needy greedy implementation details….

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Reading material & References

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