Superframe

- The structure of superframes is controlled by two parameters: *beacon order (BO)* and *superframe order (SO)*
  - BO decides the length of a superframe
  - SO decides the length of the active portion in a superframe

- For channels 11 to 26, the length of a superframe can range from 15.36 *msec* to 215.7 *sec*.
  - which means very low duty cycle
- Remember: Duty Cycle
  - **Duty Cycle indicates the fraction of time a resource is busy.**
  - When a single device transmits on a channel for 2 *time units* every 10 *time units*, this device has a duty cycle of 20%.

Superframe

- Each device will be active for $2^{-(BO-SO)}$ portion of the time, and sleep for $1-2^{-(BO-SO)}$ portion of the time
- In IEEE 802.15.4, devices' duty cycle follow the specification

BO-SO	0	1	2	3	4	5	6	7	8	9	≧10
Duty cycle (%)	100	50	25	12	6.25	3.125	1.56	0.78	0.39	0.195	< 0.1

BO – Beacon Order
SO – Superframe Order

GTS concepts

- A guaranteed time slot (GTS) allows a device to operate on the channel within a portion of the superframe
- A GTS shall only be allocated by the PAN coordinator
- The PAN coordinator can allocate up to seven GTSs at the same time
- The PAN coordinator decides whether to allocate GTS based on:
  - Requirements of the GTS request
  - The current available capacity in the superframe

GTS concepts

- A GTS can be **deallocated**
  - At any time at the discretion of the PAN coordinator or
  - By the device that originally requested the GTS
- A data frame transmitted in an allocated GTS shall use only short addressing
- The PAN coordinator shall be able to store the info of devices that are necessary for GTS, including starting slot, length, direction and associated device address

GTS concepts

- Before GTS starts, the GTS direction shall be specified as either transmit or receive
- Each device may request one **transmit** GTS and/or one **receive** GTS
- A device shall only attempt to allocate and use a GTS if it is currently tracking the beacon
- If a device loses synchronization with the PAN coordinator, all its GTS allocations shall be lost
- The use of GTSs be an RFD is optional

Channel access mechanism

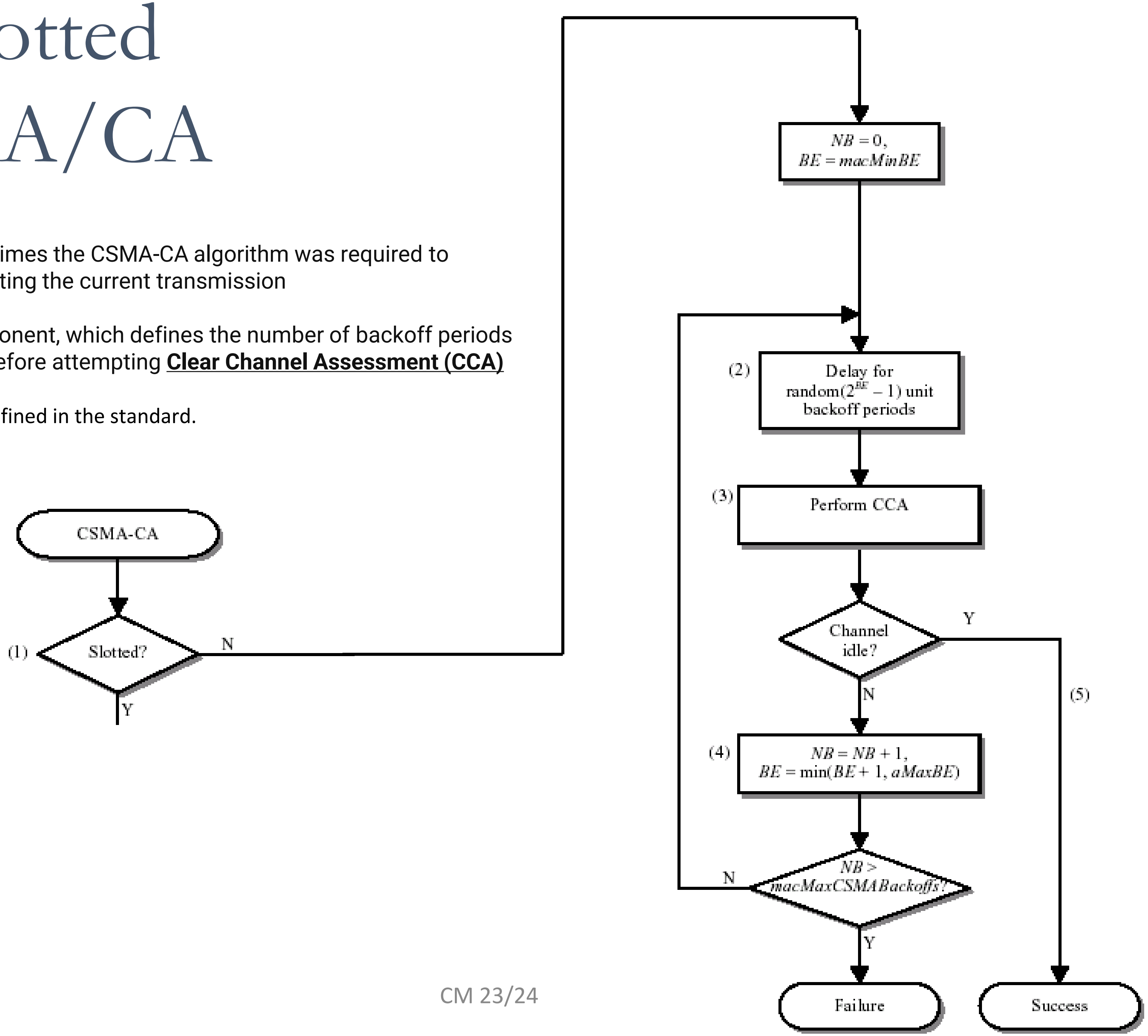
- Two type channel access mechanism:
  - In non-beacon-enabled networks → unslotted CSMA/CA channel access mechanism
  - In beacon-enabled networks → slotted CSMA/CA channel access mechanism

Unslotted CSMA/CA

NB is the number of times the CSMA-CA algorithm was required to backoff while attempting the current transmission

BE is the backoff exponent, which defines the number of backoff periods a node should wait before attempting **Clear Channel Assessment (CCA)**

MacMinBE constant defined in the standard.



CSMA/CA algorithm

- 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 first backoff period of each device is aligned with the start of the beacon transmission
  - The MAC sublayer shall ensure that the PHY layer commences **all of its transmissions on the boundary of a backoff period**

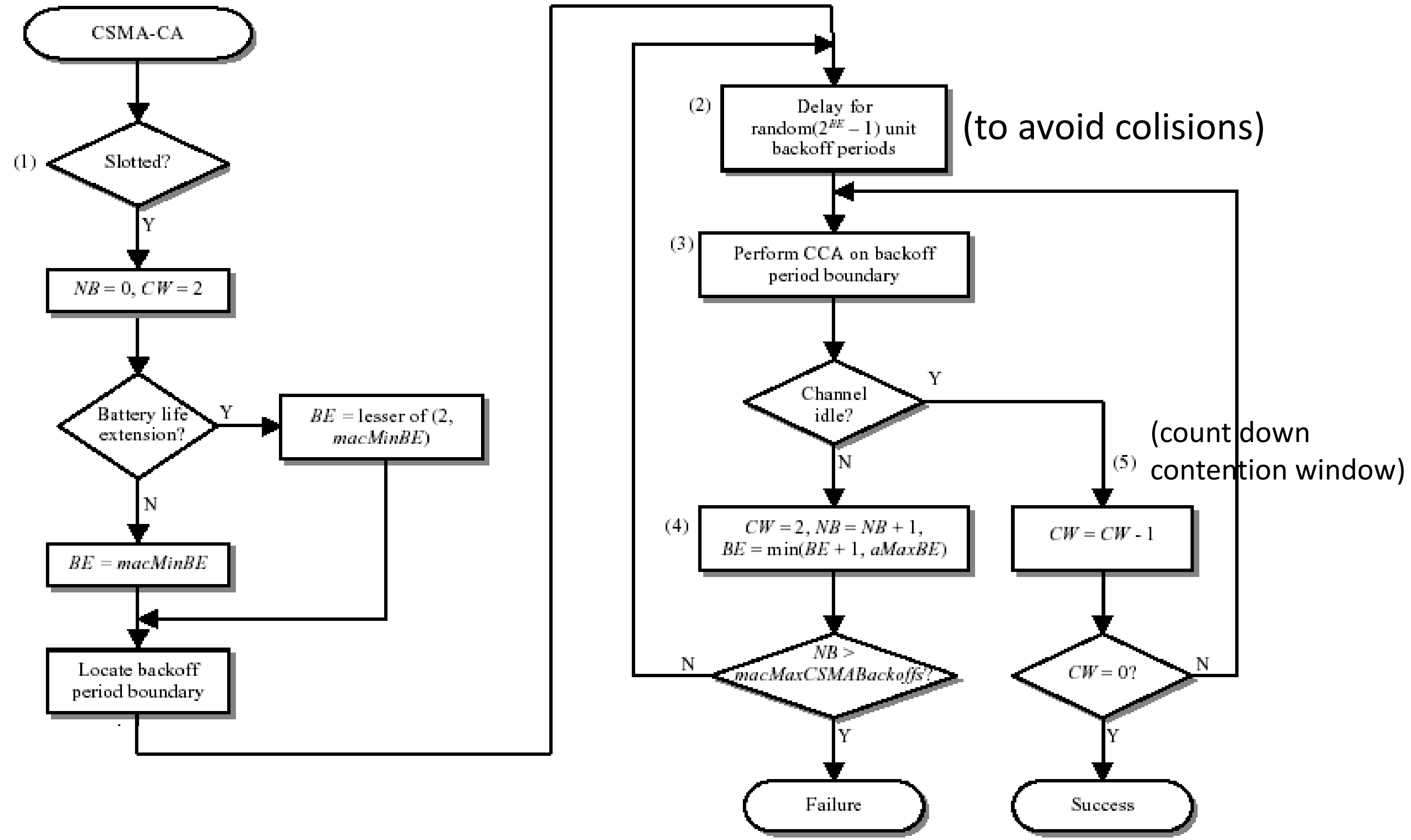
CSMA/CA algorithm

- Each device shall maintain three variables for each transmission attempt
  - NB: number of time the CSMA/CA algorithm was required to backoff while attempting the current transmission
  - CW: contention window length, the number of backoff periods that needs to be clear of channel activity before transmission can commence (initial to 2 and reset to 2 if sensed channel to be busy)
  - BE: the backoff exponent which is related to how many backoff periods a device shall wait before attempting to assess a channel

Slotted CSMA/CA

NB is the number of times the CSMA-CA algorithm was required to backoff while attempting the current transmission

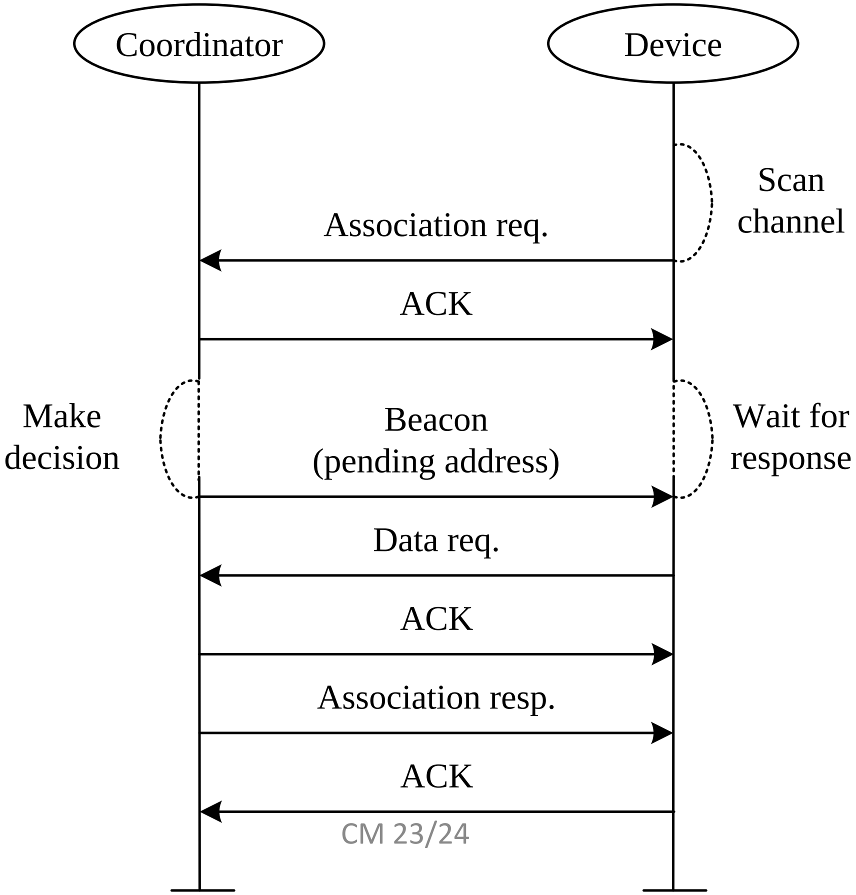
BE is the backoff exponent, which defines the number of backoff periods a node should wait before attempting **Clear Channel Assessment (CCA)**



This ensures performing two CCA operations to prevent potential collisions of acknowledgement frames.
If the channel is again sensed as idle (CW = 0), the node attempts to transmit.

Association procedures

- A device becomes a member of a PAN by associating with its coordinator
- Procedures



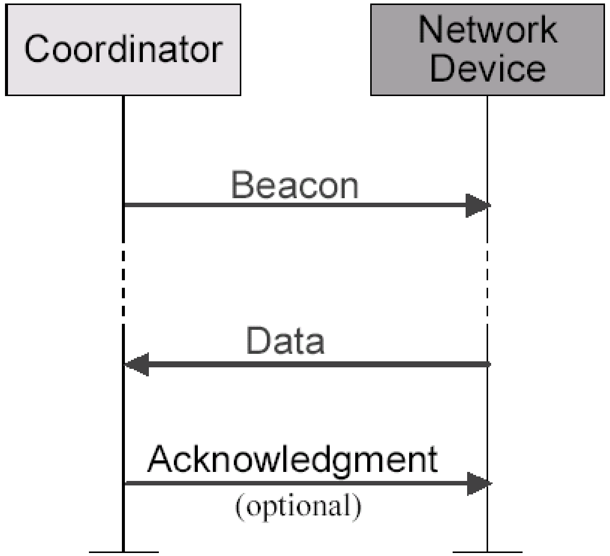
Association procedures

- In IEEE 802.15.4, **association results** are announced in an indirect fashion
- A coordinator responds to association requests by appending devices' long addresses (64 bit) in beacon frames
- Devices need to send a data request to the coordinator to acquire the association result

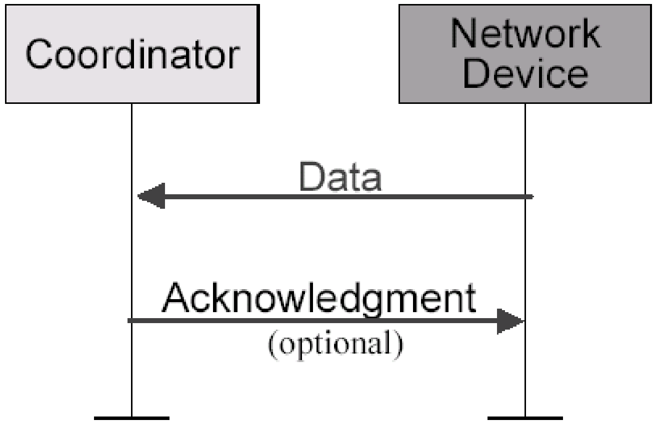
- After associating to a coordinator, a device will be assigned a 16-bit *short address*.

Data transfer model (device to coordinator)

- Data transferred from device to coordinator
  - In a beacon-enable network, the device finds the beacon to synchronize to the superframe structure. Then uses slotted CSMA/CA to transmit its data.
  - In a non beacon-enable network, device simply transmits its data using unslotted CSMA/CA



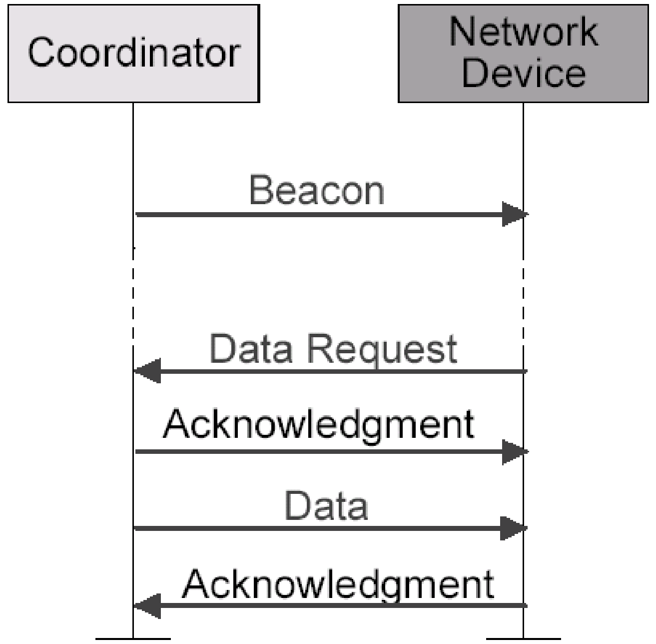
Communication to a coordinator
In a beacon-enabled network



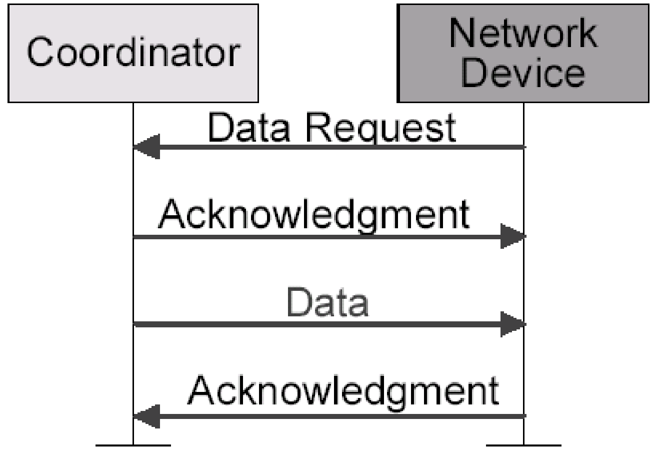
Communication to a coordinator
In a non beacon-enabled network

Data transfer model (coordinator to device)

- Data transferred from coordinator to device
  - In a beacon-enable network, the coordinator indicates in the beacon that the data is pending. Device periodically listens to the beacon and transmits a MAC command request using slotted CSMA/CA if necessary.
  - In a non-beacon-enable network, a device transmits a MAC command request using unslotted CSMA/CA. If the coordinator has its pending data, the coordinator transmits data frame using unslotted CSMA/CA. Otherwise, coordinator transmits a data frame with zero length payload.

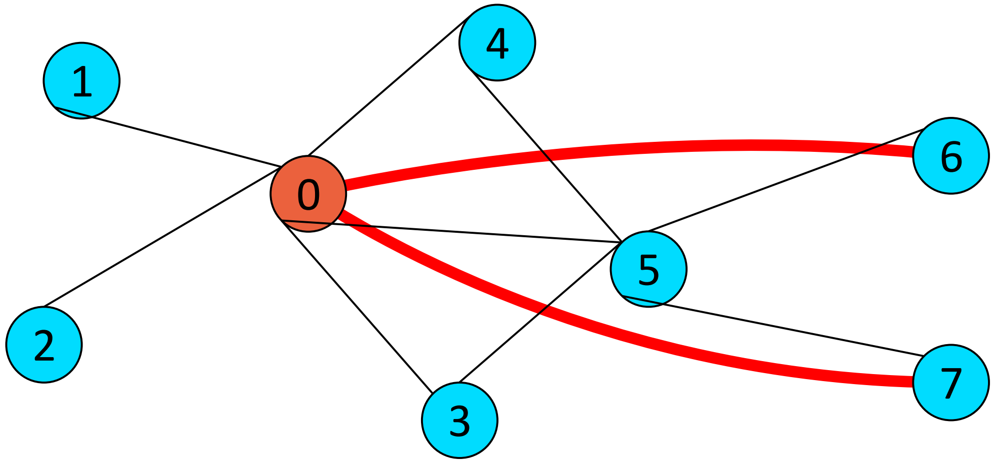


Communication from a coordinator
In a beacon-enabled network



Communication from a coordinator
in a non beacon-enabled network

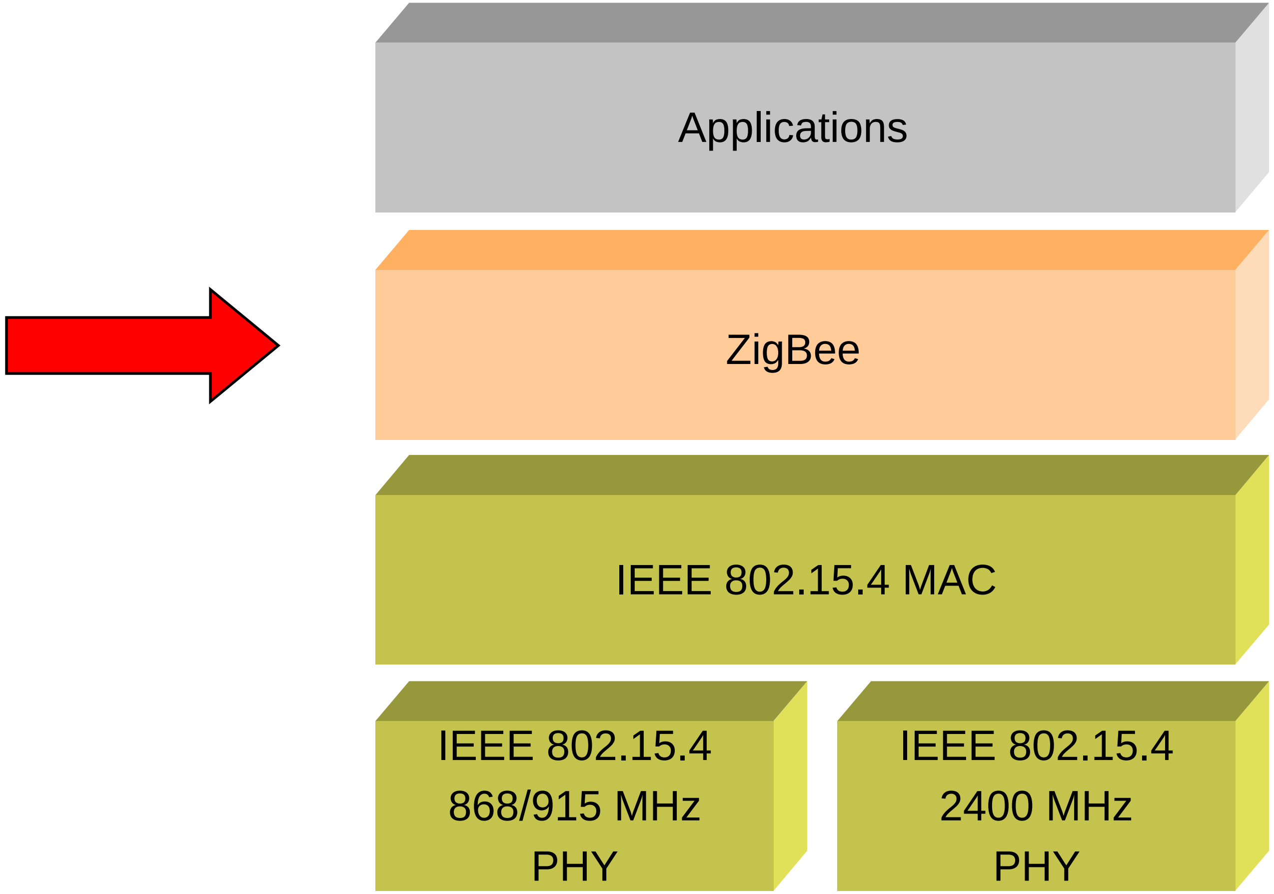
MAC layer



How 6 and 7 connect to coordinator 0?

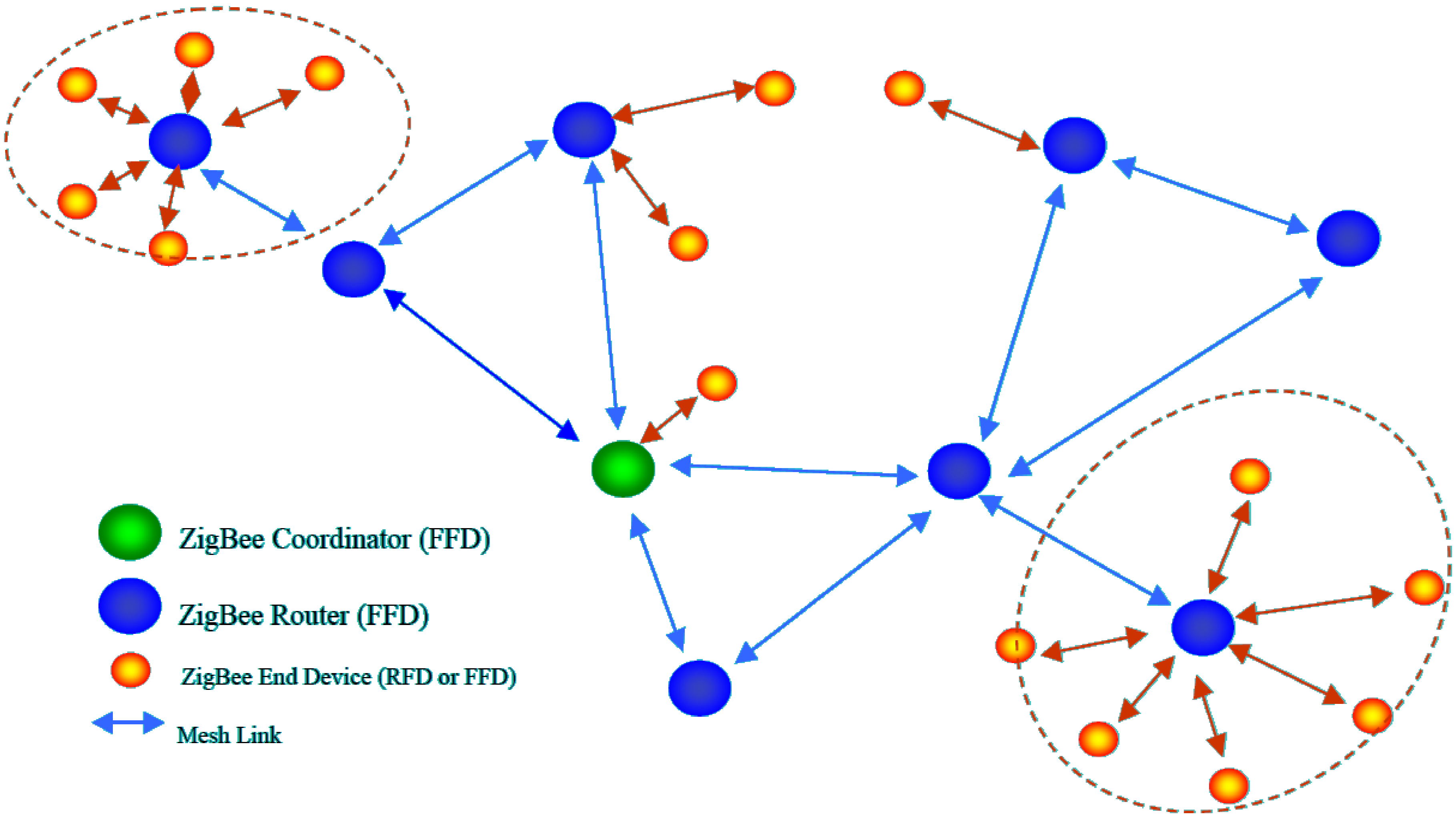
Routing (NWK Layer)

802.15.4 Architecture



- Network Routing
- Address translation
- Packet Segmentation
- Profiles

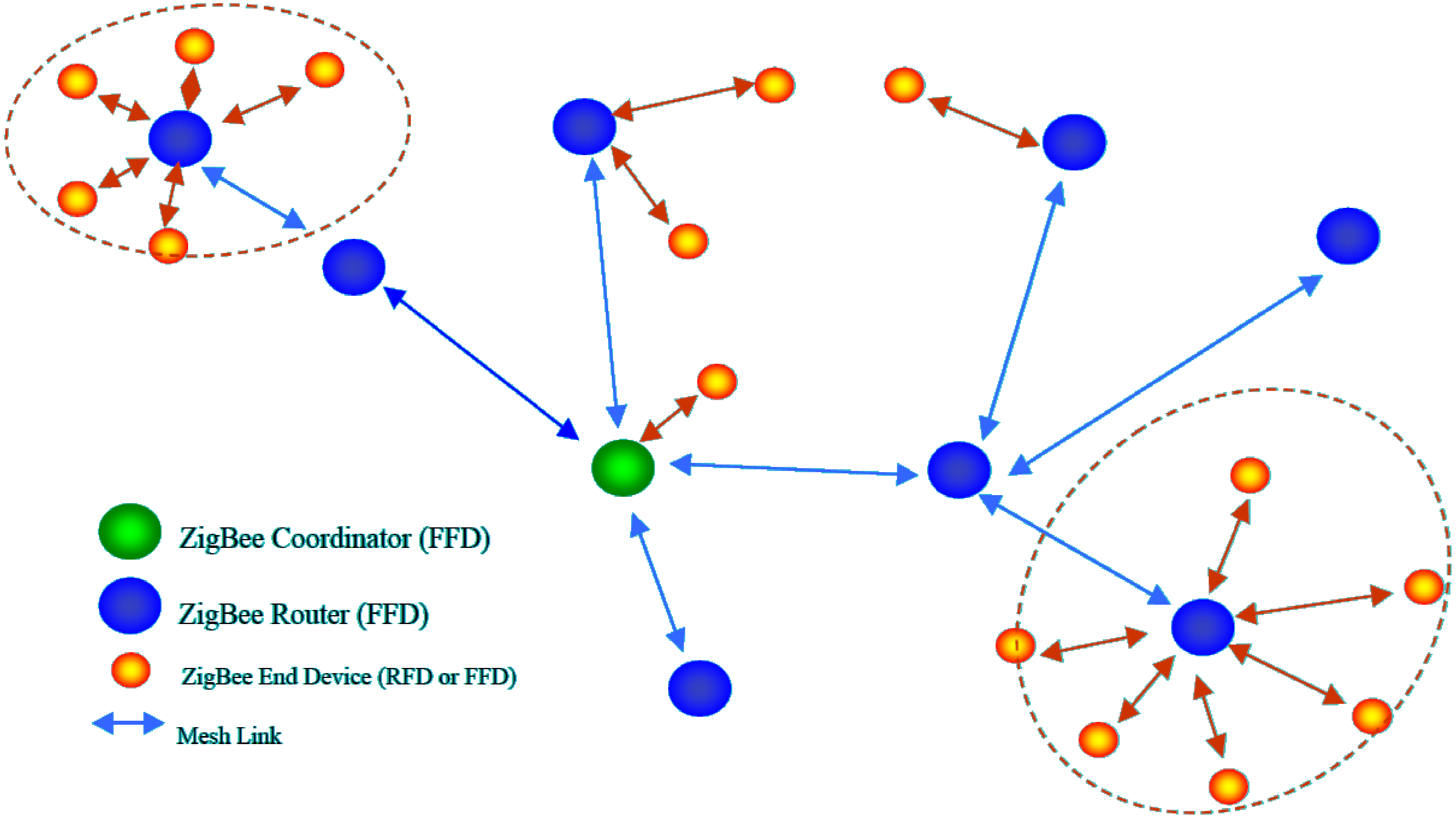
Combined topologies: Mesh Topologies



In a mesh network, regular beacons are not allowed.

- Devices in a mesh network can only communicate with each other by peer-to-peer transmissions

Combined Topologies: Tree



In a tree network, the coordinator and routers can announce beacons.

Device addressing

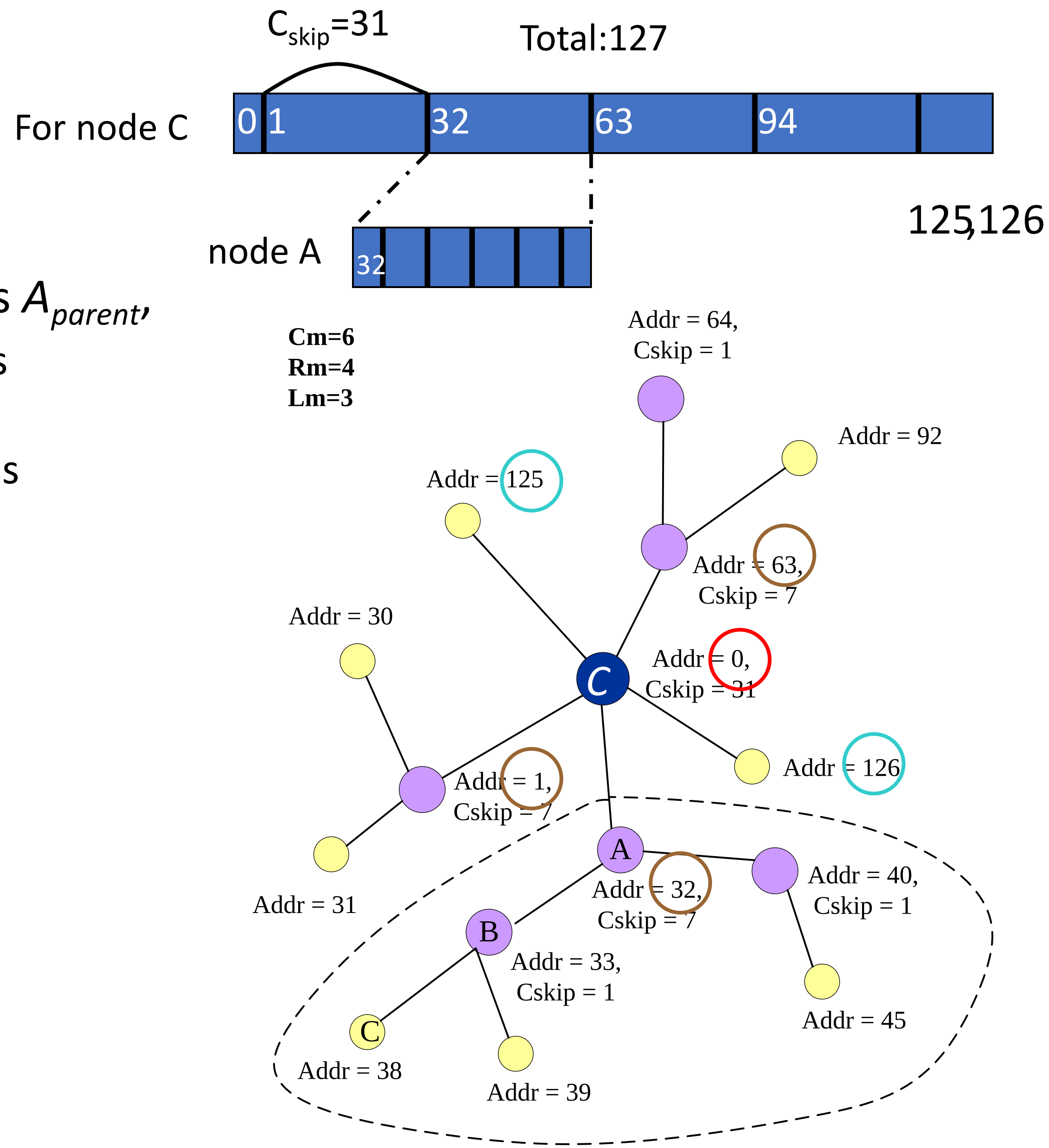
- Two or more devices communicating on the same physical channel constitute a WPAN which includes <u>at least one FFD (PAN coordinator)</u>
- Each independent PAN will select a unique PAN identifier
- All devices operating on a network shall have unique 64-bit extended address (IEEE 802.15.4). This address can be used for direct communication in the PAN
- The network address can use a 16-bit short address, which is allocated to the child routers by the PAN coordinator when the device associates
- 256 sub addresses may be allocated for subunits

Address assignment in a ZigBee network

- In ZigBee, network addresses are assigned to devices by a **distributed address assignment scheme**
- The ZigBee coordinator determines three network parameters to set the allocations
  - the maximum number of children (C_m) of a ZigBee router
  - the maximum number of child routers (R_m) of a parent node
  - the depth of the network (L_m)
- A parent device utilizes C_m, R_m, and L_m to compute a parameter called C_{skip}
  - which is used to compute the size of its children's address pools

$$Cskip(d) = \begin{cases} 1 + Cm \cdot (Lm - d - 1), & \text{if } Rm = 1 \quad \cdots\cdots\cdots\cdots (\text{a}) \\ \dfrac{1 + Cm - Rm - Cm \cdot Rm^{Lm-d-1}}{1 - Rm}, & \text{Otherwise} \quad \cdots\cdots\cdots\cdots (\text{b}) \end{cases}$$

- If a parent node at depth d has an address A_{parent},
  - the nth child router is assigned to address $A_{parent}+(n\text{-}1)\times C_{skip}(d)+1$
  - nth child end device is assigned to address $A_{parent}+R_m\times C_{skip}(d)+n$



ZigBee routing protocols

- In a tree network
  - Utilize the address assignment to obtain the routing paths
- In a mesh network
  - Two options
    - Reactive routing: if having routing capacity
    - Use tree routing: if do not have routing capacity

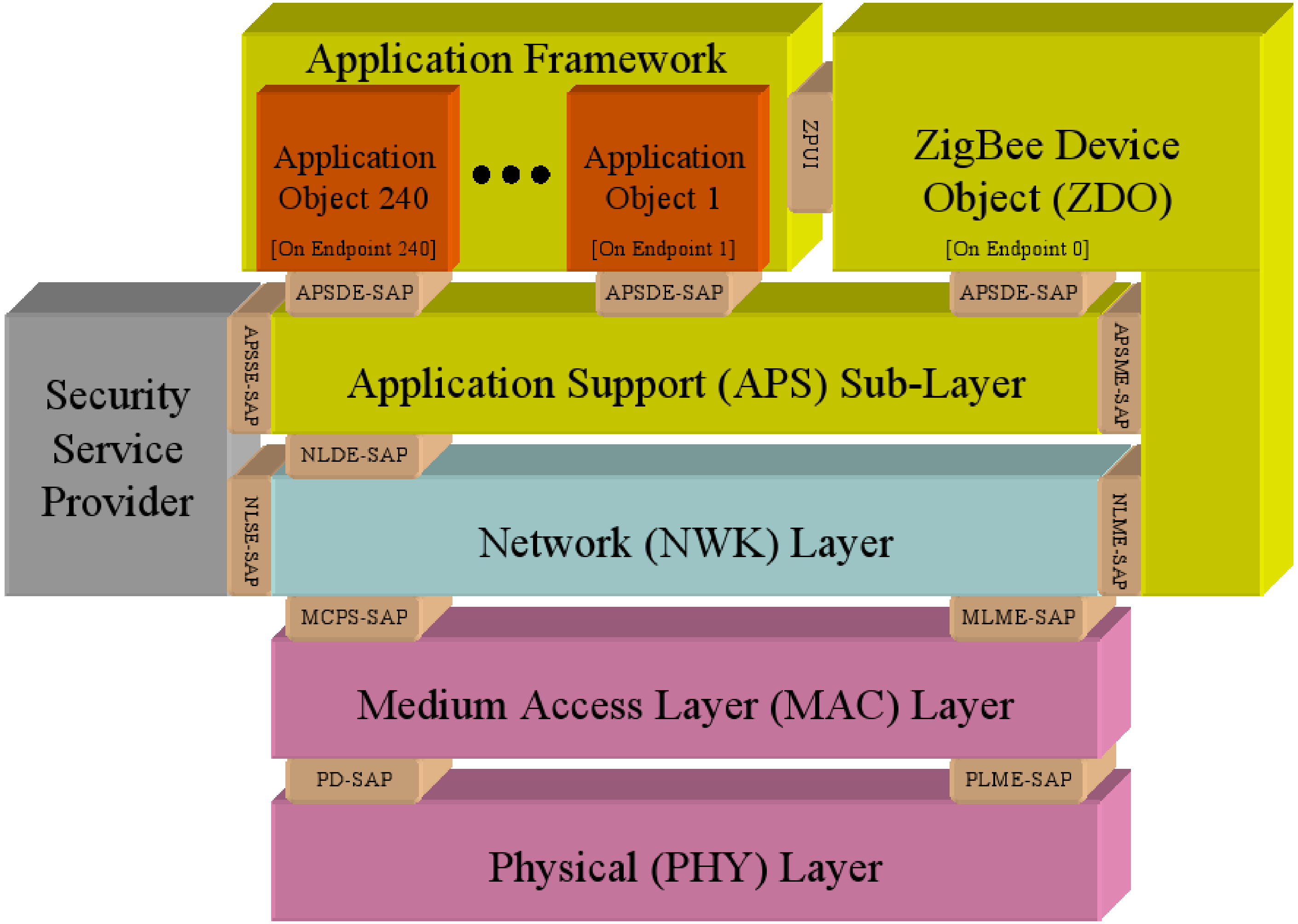
- Note:
  - ZigBee coordinators and routers are said to have *routing capacity* if they have routing table capacities and route discovery table capacities

Summary of ZigBee network layer

- Pros and cons of different kinds of ZigBee network topologies

	Pros	Cons
Star	1. Easy to synchronize 2. Support low power operation 3. Low latency	1. Small scale
Tree	1. Low routing cost 2. Can form superframes to support sleep mode 3. Allow multihop communication	1. Route reconstruction is costly 2. Latency may be quite long
Mesh	1. Robust multihop communication 2. Network is more flexible 3. Lower latency	1. Cannot form superframes (and thus cannot support sleep mode) 2. Route discovery is costly 3. Needs storage for routing table

Application Level



ZigBee defined Objects (ZDO):

- provides common function for applications
- Initializes APS, NWK-Layer and Security Service Specification
- offers services like device-/service-descovery, binding and security management
- assembles information about the network
- for ZBC/ZBR -> e.g. binding table

Command	Addressing	
	Request	Response
End device bind	Unicast to ZC	Unicast
Bind	Unicast to ZC or Src	Unicast
Unbind	Unicast to ZC or Src	Unicast

Profiles:

Definition of ZigBee-Profiles

- describes a common language for exchanging data
- defines the offered services
- device interoperatbility across different manufacturers
- Standard profiles available from the ZigBee Alliance
- **profiles contain device descriptions**
- unique identifier (licensed by the ZigBee Alliance)

ZigBee and BLE

- Business comparison:
  - ZigBee is older. It has gone through some iterations
  - ZigBee has market mindshare, but not a lot of shipments yet.
  - Market barriers: connectivity – ZigBee is not in PCs or mobile phones yet.
- Technical comparison:
  - Zigbee is low power; Bluetooth LE is even lower. Detailed analysis depends on specific applications and design detail, no to mention chip geometry.
  - ZigBee stack is light; the Bluetooth LE/GATT stack is even simpler
    - Remember: GATT – Generic ATTribute profile
- Going forward:
  - ZigBee has a lead on developing applications and presence
  - Bluetooth low energy has improved technology, and a commanding presence in several existing markets: mobile phones, automobiles, consumer electronics, PC industry
  - Replacing “classic Bluetooth ” with “dual mode” devices will bootstrap this market quickly

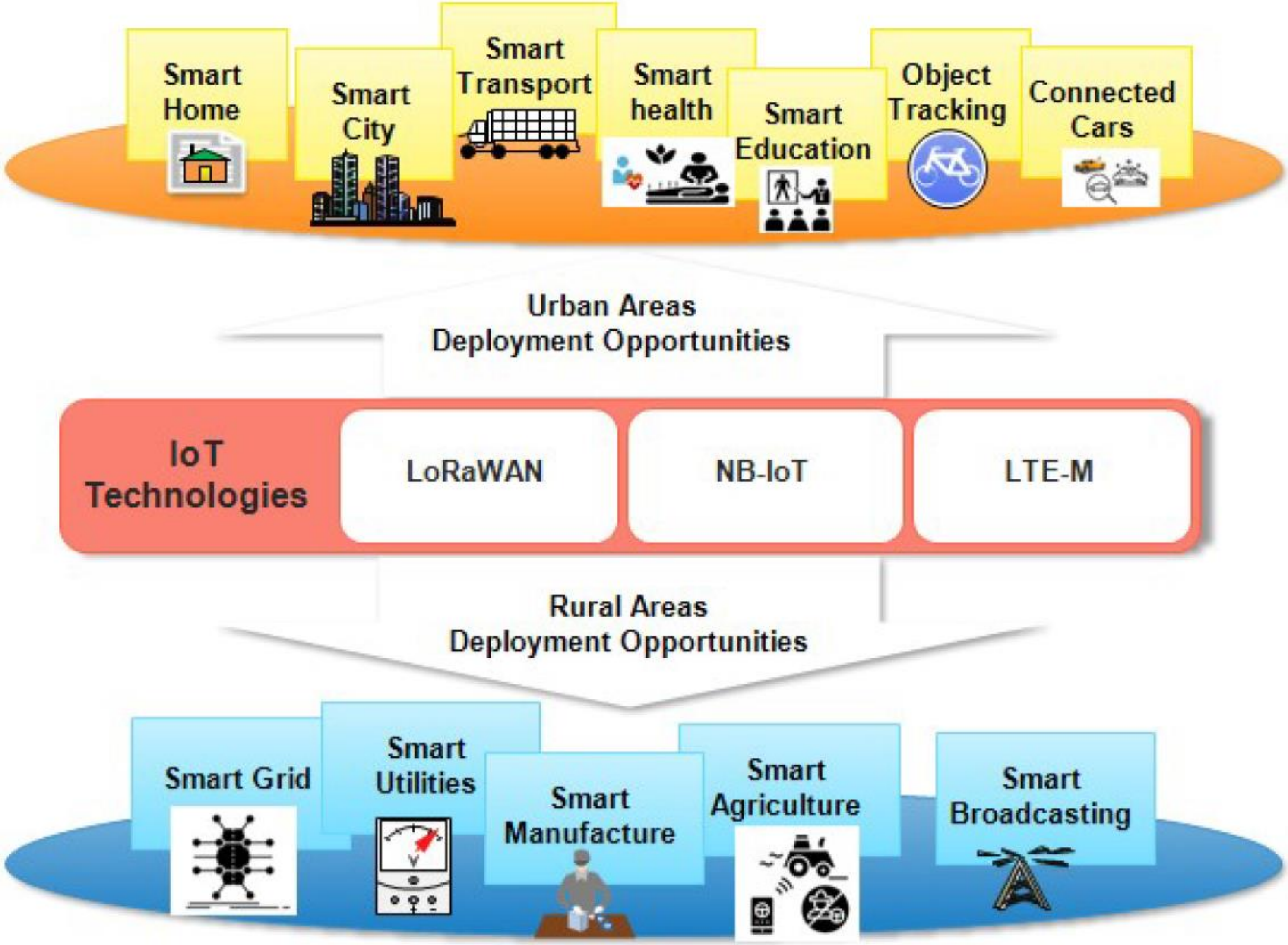
Wide Area Wireless Sensor Networks

WWSN

What is this?

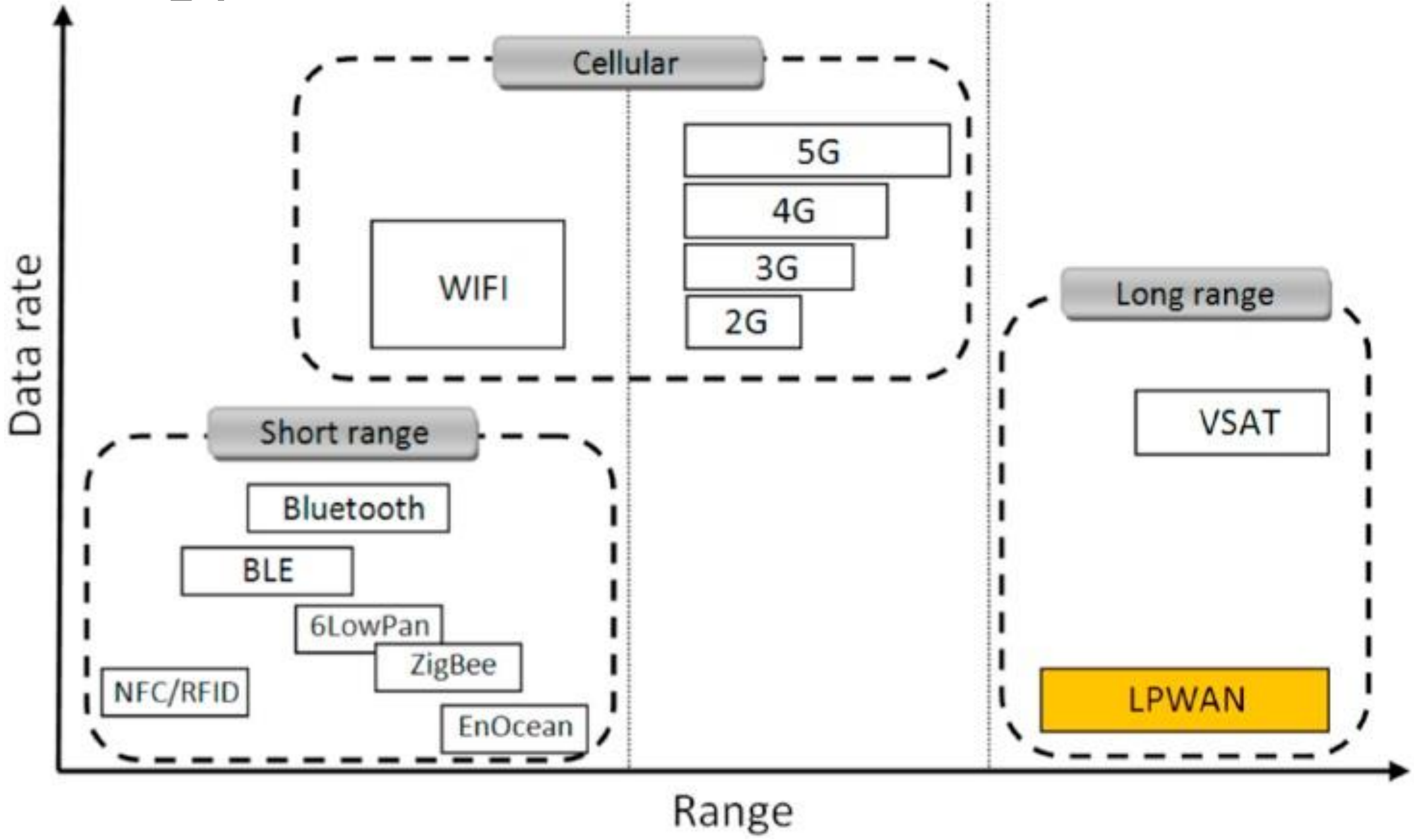
- WWSN – wide area wireless sensor networks
- LPWSN – low power wireless sensor networks
- Technologies for sensor networks in wide areas
  - either for low power, or for geography
  - Typically: Sigfox, LoRa, cellular (LTE-M, NB-IoT)

LPWSN

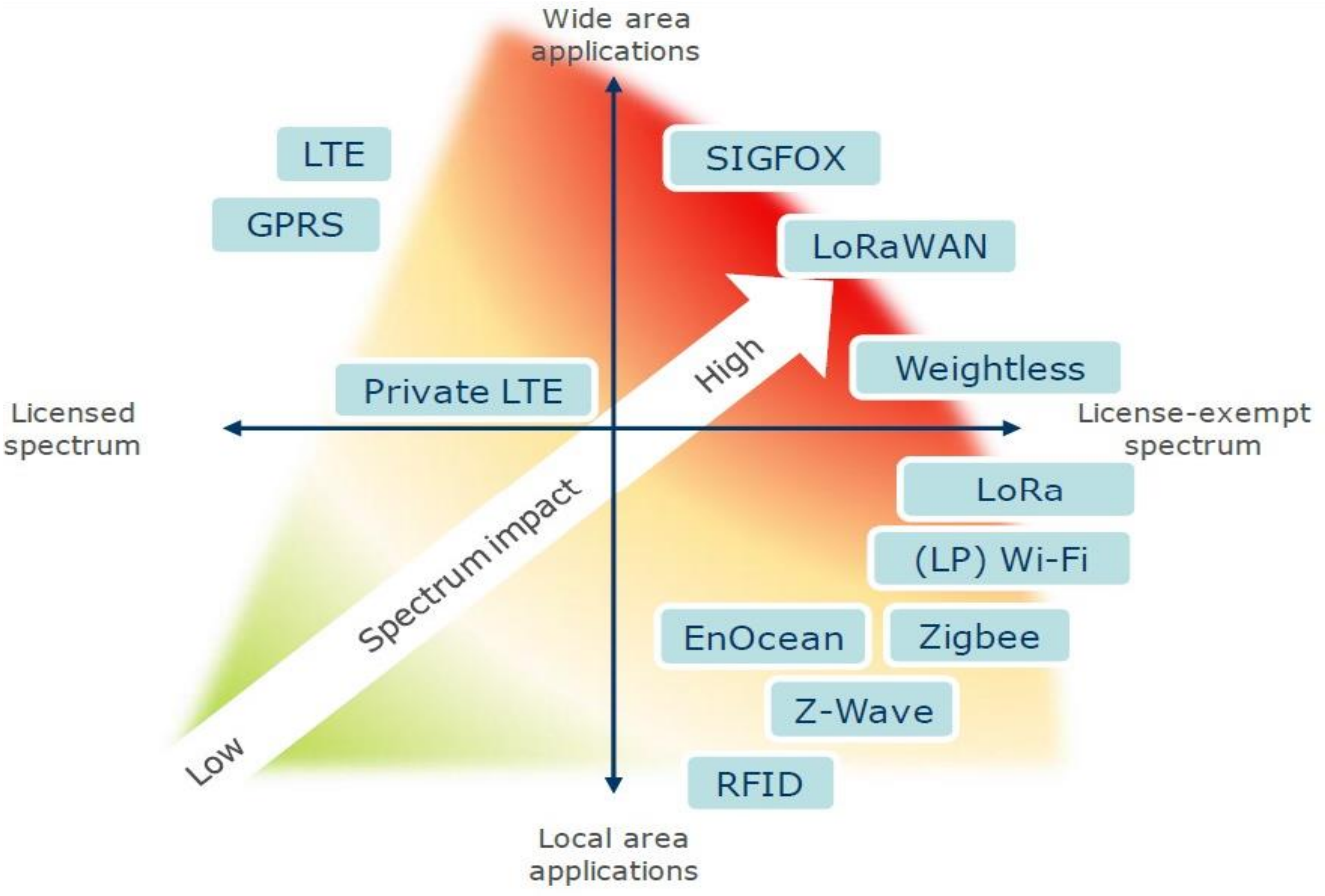


Smart Home
Smart City
Smart Transport
Smart health
Smart Education
Object Tracking
Connected Cars
Urban Areas
Deployment Opportunities
IoT Technologies
LoRaWAN
NB-IoT
LTE-M
Rural Areas
Deployment Opportunities
Smart Grid
Smart Utilities
Smart Manufacture
Smart Agriculture
Smart Broadcasting

Technology review



Licensed vs licensed-exempt



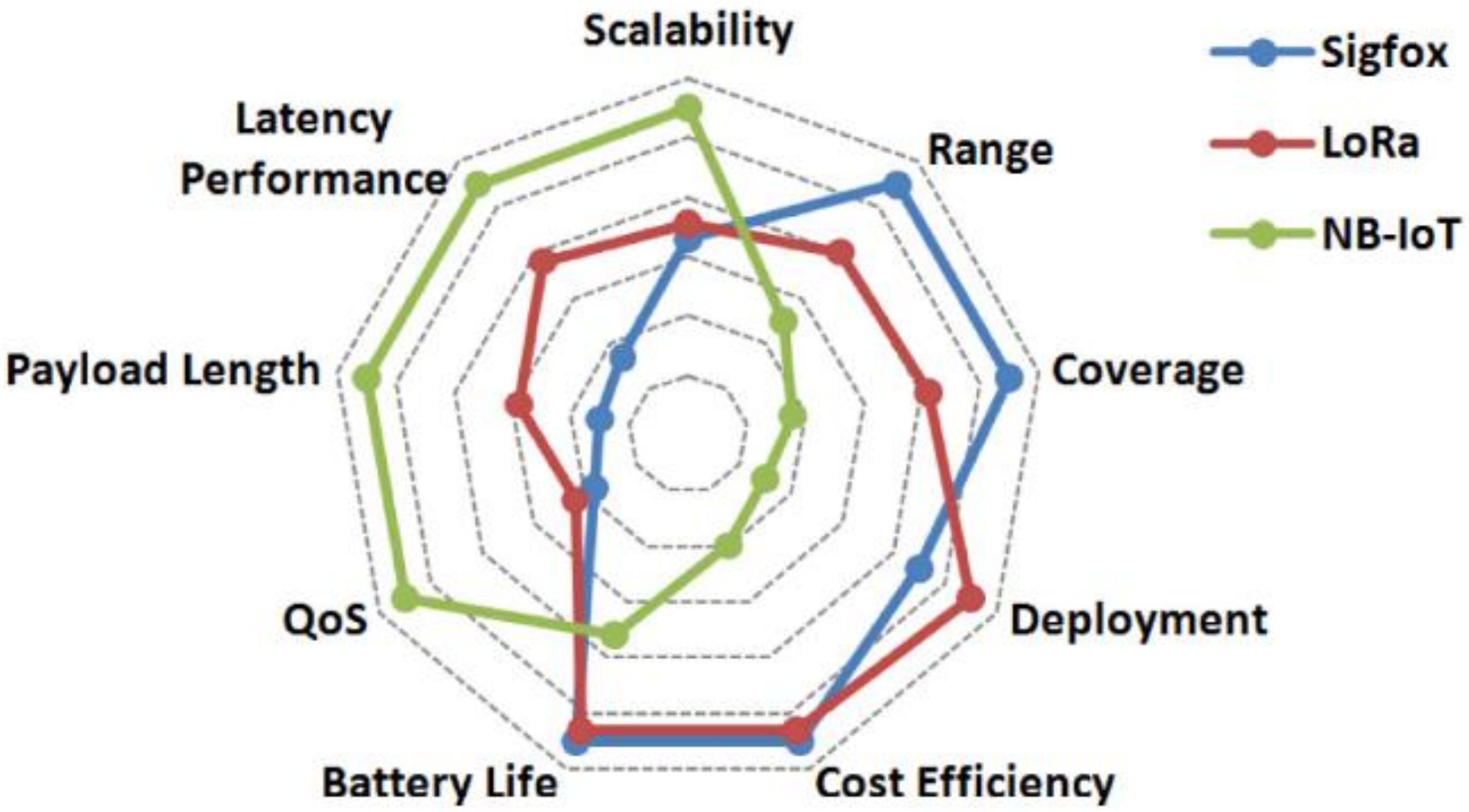
Overview of LPWAN

Overview of LPWAN technologies: Sigfox, LoRa, and NB-IoT.

	Sigfox	LoRaWAN	NB-IoT
Modulation	BPSK	CSS	QPSK
Frequency	Unlicensed ISM bands (868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia)	Unlicensed ISM bands (868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia)	Licensed LTE frequency bands
Bandwidth	100 Hz	250 kHz and 125 kHz	200 kHz
Maximum data rate	100 bps	50 kbps	200 kbps
Bidirectional	Limited / Half-duplex	Yes / Half-duplex	Yes / Half-duplex
Maximum messages/day	140 (UL), 4 (DL)	Unlimited	Unlimited
Maximum payload length	12 bytes (UL), 8 bytes (DL)	243 bytes	1600 bytes
Range	10 km (urban), 40 km (rural)	5 km (urban), 20 km (rural)	1 km (urban), 10 km (rural)
Interference immunity	Very high	Very high	Low
Authentication & encryption	Not supported	Yes (AES 128b)	Yes (LTE encryption)
Adaptive data rate	No	Yes	No
Handover	End-devices do not join a single base station	End-devices do not join a single base station	End-devices join a single base station
Localization	Yes (RSSI)	Yes (TDOA)	No (under specification)
Allow private network	No	Yes	No
Standardization	Sigfox company is collaborating with ETSI on the standardization of Sigfox-based network	LoRa-Alliance	3GPP

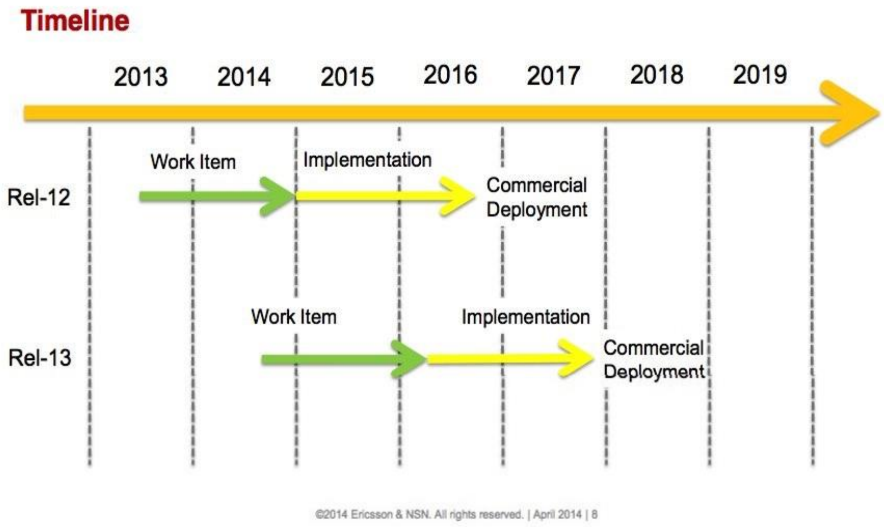
	Spectrum cost	Deployment cost	End-device cost
Sigfox	Free	>4000€/base station	<2€
LoRa	Free	>100€/gateway >1000€/base station	3–5€
NB-IoT	>500 M€ /MHz	>15 000€/base station	>20€

Comparison Radar



LTE-M - Overview

- Evolution of LTE optimized for IoT
- Low power consumption and autonomous
- Easy Deployment
- Interoperability with existing LTE networks
- Coverage up to 11 Km
- Max Throughput ≤ 1 Mbps



- ✓ First released in Rel.12 in 2 Q4 2014
- ✓ Optimization in Rel.13
- ✓ Specifications completed in Q1 2016
- ✓ Available since 2017

Evolution from LTE to LTE-M

3GPP Releases	8 (Cat.4)	8 (Cat. 1)	12 (Cat.0) LTE-M	13 (Cat. 1,4 MHz) LTE-M
Downlink peak rate (Mbps)	150	10	1	1
Uplink peak rate (Mbps)	50	5	1	1
Number of antennas (MIMO)	2	2	1	1
Duplex Mode	Full	Full	Half	Half
UE receive bandwidth (MHz)	20	20	20	1.4
UE Transmit power (dBm)	23	23	23	20

Release 12

- New category of UE ("Cat-0"): lower complexity and low cost devices
- Half duplex FDD operation allowed
- Single receiver
- Lower data rate requirement (Max: 1 Mbps)

Release 13

- Reduced receive bandwidth to 1.4 MHz
- Lower device power class of 20 dBm
- 15dB additional link budget: better coverage
- More energy efficient because of its extended discontinuous repetition cycle (eDRX)