INTERNET OF THINGS

IoT Communications and Networking Technologies and Protocols

Professor: Dr.Siavash Khorsandi

Lecturer: Jaber Babaki

Amirkabir University of Technology

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- Introduction
- Physical and Link Layers Protocols (IoT Access Technologies)
- Application Layer Protocols

Mostly adopted from Chapters 4, 5, and 6 of IoT Fundamentals: Networking Technologies, Protocols, and Use Cases for the Internet of Thing, Cisco press, 2017

CONTENTS

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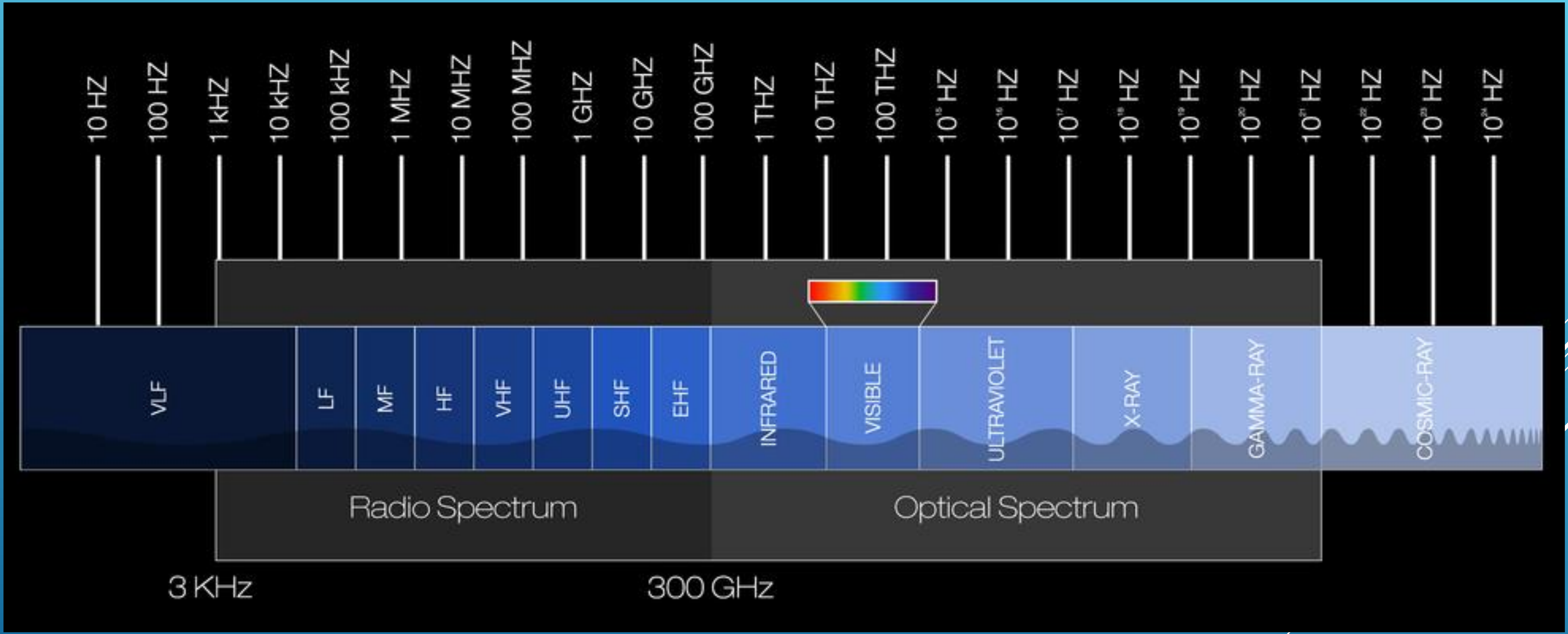
- Network Layer Protocols (IP as the IoT Network Layer)
- Transport Layer Protocols
- Application Layer Protocols

FREQUENCY RANGE

- Radio
  - Signal carried in electromagnetic spectrum
  - Propagation environment effects:
    - Reflection
    - Obstruction by objects
    - Interference

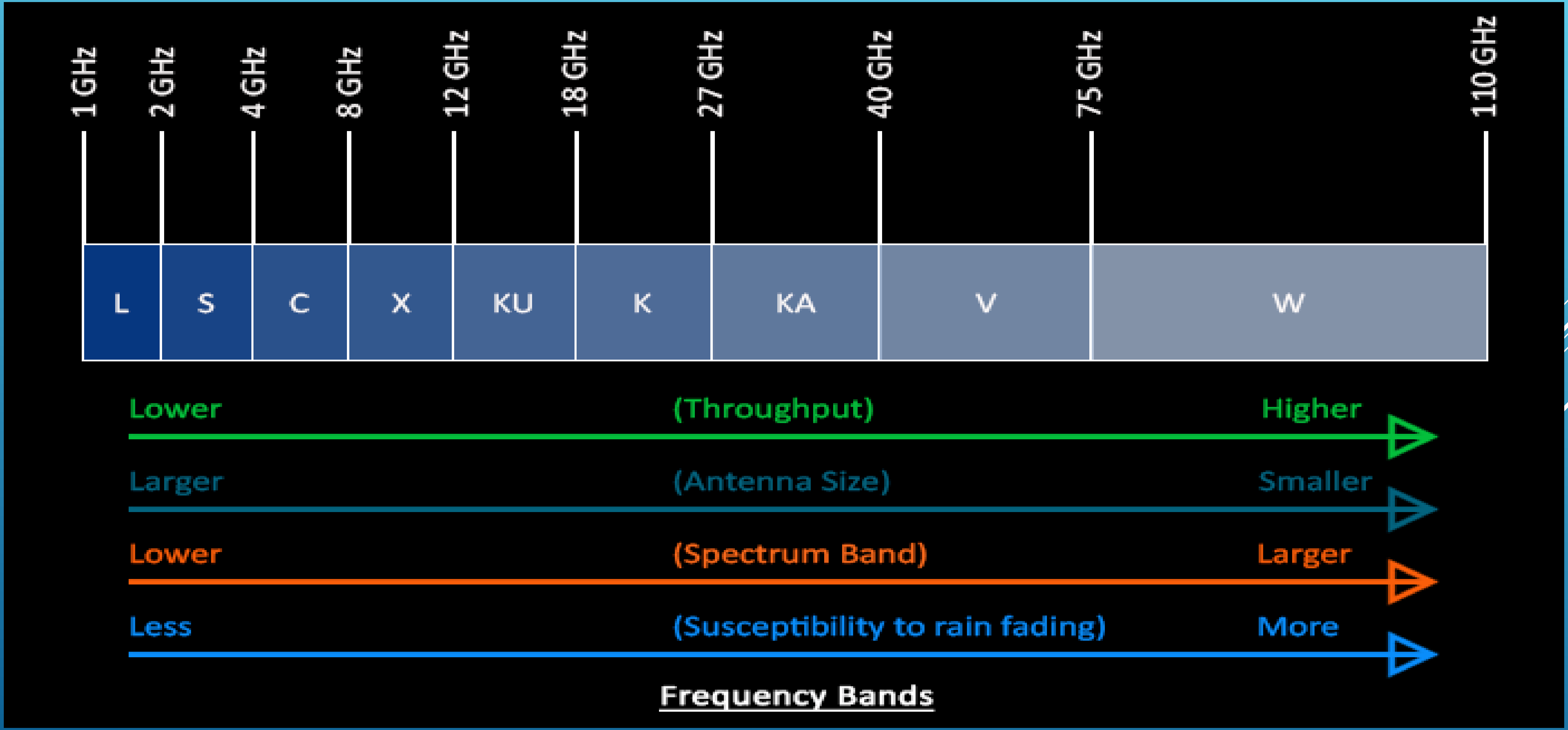
FREQUENCY RANGE



FREQUENCY RANGE

- **Radio frequency range**
  - 30 MHz to 30 GHz
  - Suitable for omnidirectional applications
  - Frequencies of 1 GHz and above are conventionally called microwave
- **Millimeter Wave**
  - Frequencies of 30 GHz and above are designated .
- **Infrared frequency range**
  - Roughly, 3x10^11 (300 GHz) to 2x10^14 (200 THz)
  - Useful in local point-to-point multipoint applications within confined areas

FREQUENCY RANGE



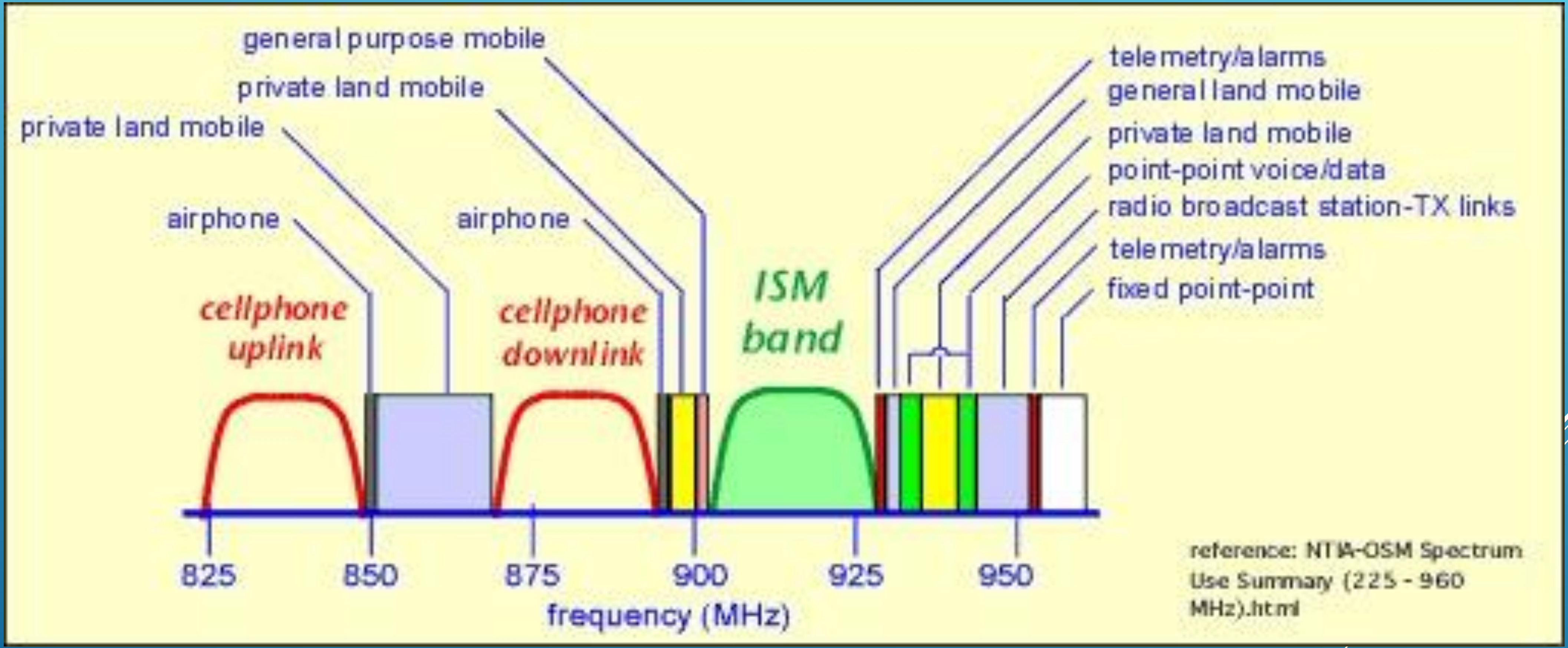
FREQUENCY RANGE

- **Most wireless applications reside in radio frequency between 30MHz to 30 GHz (VHF, UHF and SHF)**

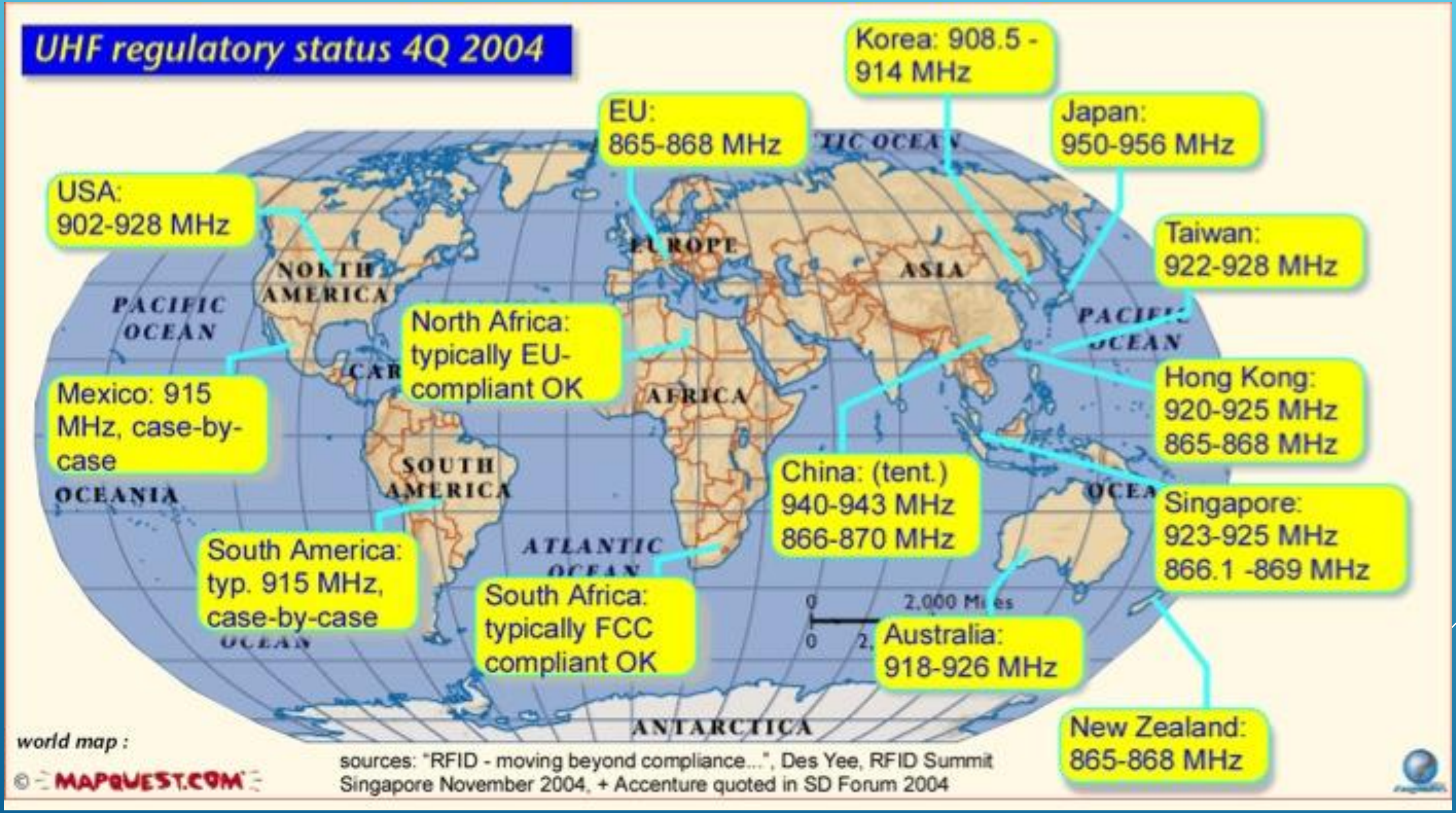
- **Why these frequencies?**
  - They are not affected by earth curvature
  - Require only moderated size antennas

*Adopted from Wireless Communication by Goldsmith (Chapter2)

EXAMPLE OF ISM FREQUENCY ALLOCATION



EXAMPLE OF ISM FREQUENCY ALLOCATION



WHAT IS THE DIFFERENCE BETWEEN CHANNEL & FREQUENCY & BAND IN RF?

- **A frequency band, or band:** is a range of frequencies with a specific least frequency and greatest frequency. Generally bands are used to describe some relevant range:
  - A radio is capable of operating within some band of frequencies; outside that band its performance will not meet specification or it will be incapable of tuning there.
  - The legal limits on transmissions are defined in terms of many bands; when people say "the 2.4 GHz band" they mean the ISM band that extends from 2.400 GHz to 2.500 GHz, which is purely a legal definition and has no technical significance other than that devices may be internally restricted to operate in those bounds.
- **Channel**
  - Usage of a band can be channelized, which means that the radios which transmit on it do not pick frequencies arbitrarily but stick to a certain step size (e.g. 10 KHz for CB radio, so frequencies like 27.105, 27.115, 27.125 MHz). This makes it easier for a receiver to match a transmitter, and allows more efficient use overall as there are no wasted narrow gaps between signals.
- **Carrier signal**
  - In telecommunications, a carrier wave, carrier signal, or just carrier, is a waveform (usually sinusoidal) that is modulated (modified) with an information-bearing signal for the purpose of conveying information

COMMUNICATION TECHNOLOGIES CRITERIA

- Currently, the number of technologies (available or under development) connecting smart objects is quite extensive,
  - but you should expect consolidation, with certain protocols eventually winning out over others in the various IoT market segments.

- Before reviewing some of these access technologies, it is important to talk about the criteria to use in evaluating them for various use cases and system solutions.

* IoT Fundamentals: Networking Technologies, Protocols, and Use Cases for the Internet of Thing, Cisco press, 2017

COMMUNICATION TECHNOLOGIES CRITERIA

- 1- Range
- 2- Frequency Bands
- 3- Power Consumption
- 4- Topology
- 5- Constrained Devices
- 6- Constrained-Node Networks

* IoT Fundamentals: Networking Technologies, Protocols, and Use Cases for the Internet of Thing, Cisco press, 2017

COMMUNICATION TECHNOLOGIES CRITERIA: 1-RANGE

- **Short range:**
  - Tens of meters of maximum distance between two device
  - Example:
    - The classical wired example is a serial cable!
    - Wireless Examples: IEEE 802.15.1, Bluetooth
- **Medium range:**
  - Tens to hundreds of meters
  - Examples:
    - IEEE 802.11 Wi-Fi and 802.15.4g WPAN.

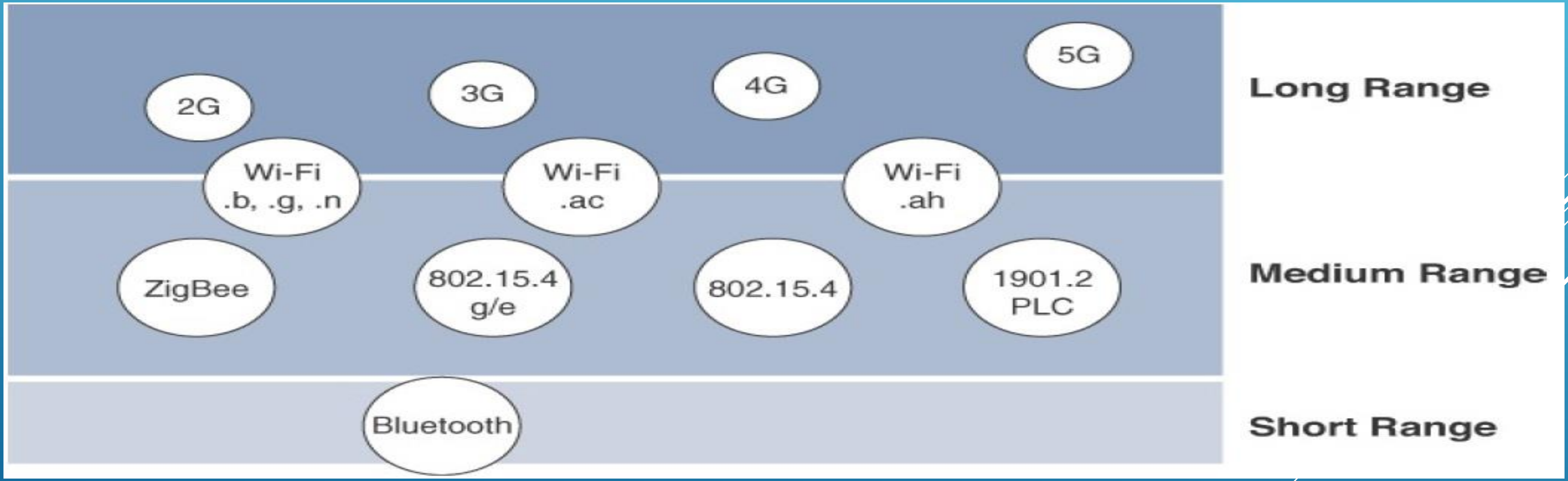
* IoT Fundamentals: Networking Technologies, Protocols, and Use Cases for the Internet of Thing, Cisco press, 2017

COMMUNICATION TECHNOLOGIES CRITERIA: 1- RANGE

- **Long range:**
  - Greater than 1 mile (1.6 km) between two devices require long-range technologies.
  - Examples: cellular (2G, 3G, 4G) and some applications of outdoor IEEE 802.11 Wi-Fi and Low-Power Wide-Area (LPWA) technologies.

* IoT Fundamentals: Networking Technologies, Protocols, and Use Cases for the Internet of Thing, Cisco press, 2017

COMMUNICATION TECHNOLOGIES CRITERIA: 1- RANGE



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COMMUNICATION TECHNOLOGIES CRITERIA: 2- FREQUENCY BANDS

- **Licensed:**
  - Generally applicable to IoT long-range access technologies and allocated to communications infrastructures deployed by services providers, public services (for example, first responders, military), broadcasters, and utilities.
  - Examples: cellular, WiMAX, and Narrowband IoT (NB-IoT) technologies.
- **Unlicensed:**
  - For the industrial, scientific, and medical (ISM) portions of the radio bands, and they are used in many communications technologies for short-range devices (SRDs).
  - Examples: 2.4 GHz band as used by IEEE 802.11b/g/n Wi-Fi, IEEE 802.15.1 Bluetooth, and IEEE 802.15.4 WPAN.

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COMMUNICATION TECHNOLOGIES CRITERIA: 3- POWER CONSUMPTION

- **Powered nodes**
  - have a direct connection to a power source
- **Battery-powered nodes:**
  - are often classified by the required lifetimes of their batteries.
  - For devices under regular maintenance, a battery life of 2 to 3 years is an option.
- Evolution of a new wireless environment known as Low-Power Wide-Area (LPWA) for battery-powered nodes

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COMMUNICATION TECHNOLOGIES CRITERIA: 4- TOPOLOGY

- Topology (star, mesh, and peer-to-peer)
  - For long range and short-range technologies, a star topology is prevalent, as seen with cellular, LPWA, and Bluetooth networks.
  - Star topologies utilize a single central base station or controller to allow communications with endpoints.
  - For medium-range technologies, a star, peer-to-peer, or mesh topology is common. Peer-to-peer topologies allow any device to communicate with any other device as long as they are in range of each other.

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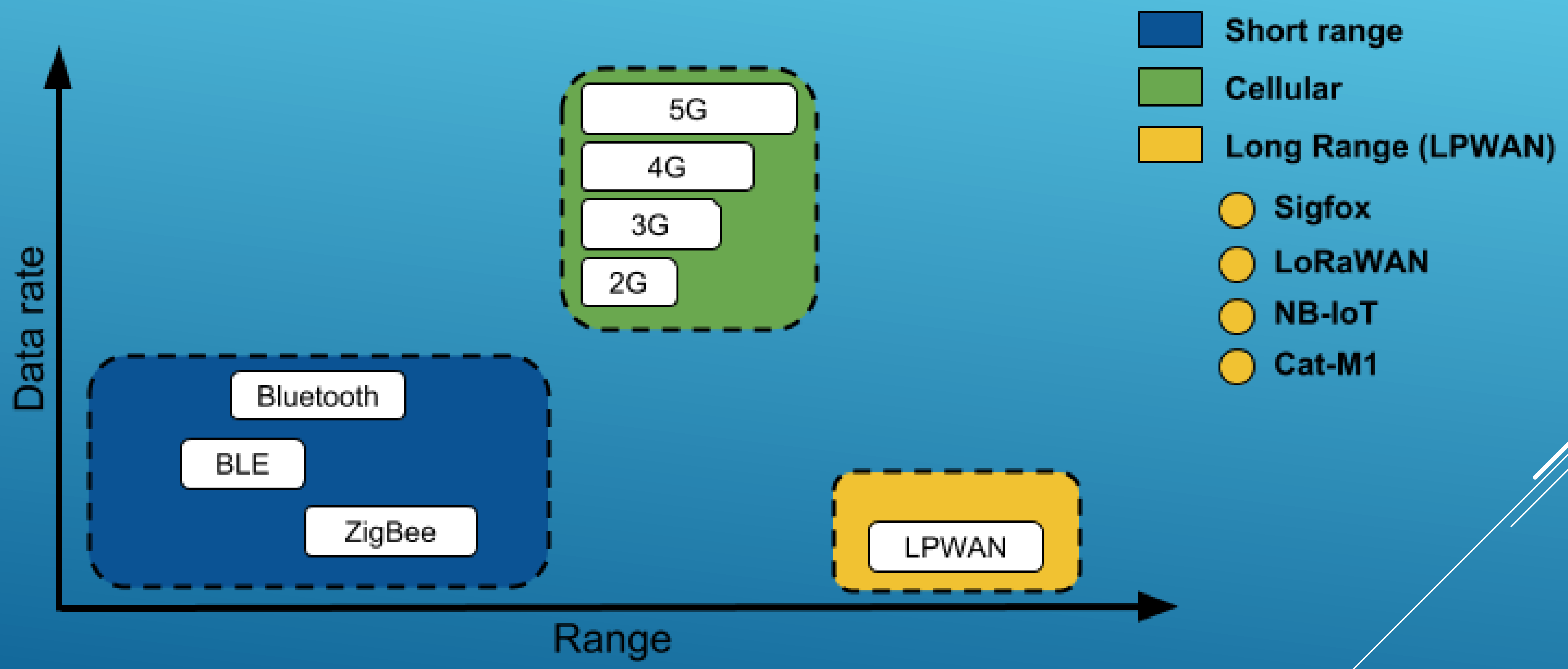
IOT PROTOCOL STACK- PHYSICAL AND LINK LAYERS PROTOCOLS



LOW POWER WIDE AREA NETWORK (LPWAN)

- Long-Range
  - Long Range Communications (WAN)
  - Low Number of Required BSs
- Low data rate
  - Less than 10 Kb/s
- Low-Power
  - Batteries last up to 10 years
- Low-Subscription Cost

LPWAN- DESIGN GOALS

- The success of LPWA technologies lies in their ability to offer low-power connectivity to massive number of devices distributed over large geographical areas at an unprecedented low-cost
- The key objective of LPWA technologies to achieve
  - a long range
  - with low power consumption and
  - low cost
  - Scalability (massive number of devices)
  - Low-rate
- This is unlike that of the other technologies for which achieving higher data rate, lower latency and higher reliability may be more important.

Techniques for Achieving Design Goals in LPWAN

- Techniques for achieving Long-ranges
  - Use of Sub-1GHz band
    - Firstly, compared to the 2.4 GHz band, the lower frequency signals experience less attenuation and multipath fading caused by obstacles and dense surfaces like concrete walls.
    - Secondly, sub-GHz is less congested than 2.4 GHz, a band used by mostpopular wireless technologies e.g., Wi-Fi, cordless phones, Bluetooth, ZigBee
  - Modulation Techniques:
    - Narrowband
    - Spread Spectrum

TECHNIQUES FOR ACHIEVING DESIGN GOALS IN LPWAN

- Low Power
  - Topology → Scalable
  - Duty Cycling
  - Lightweight Medium Access Control
  - Offloading complexity from end devices

TECHNIQUES FOR ACHIEVING DESIGN GOALS IN LPWAN

- Low Cost
  - The commercial success of LPWA networks is tied to connecting a large number of end devices, while keeping the cost of hardware below $5 and the connectivity subscription per unit as low as $1.
  - LPWA technologies adopt several ways to reduce the capital expenses (CAPEX) and operating expenses (OPEX) for both the end-users and network operators.
  - Use of star-type (instead of mesh) connectivity,
  - Simple MAC protocols,
  - Techniques to offload complexity from end devices enables manufacturers to design simple and therefore low-cost end devices.
  - Reduction in hardware complexity
  - Minimum infrastructure
  - Using license-free or owned licensed bands

LPWANS

- SigFox:
  - Developed in 2010 by the startup Sigfox (in France)
  - Operates and commercializes its own IoT solution in 31 countries
- LoRaWAN
  - First developed by the start-up Cycleo in 2009 (in France) and was purchased three years later by Semtech (USA)
  - In 2015, LoRa was standardized by LoRa-Alliance and is deployed in 42 countries
  - Investment of various mobile operators (e.g., Bouygues and Orange in France, KPN in Netherlands, and Fastnet in South Africa)
- NB-IoT
  - Based on narrow band radio technology and is standardized by the 3GPP (Release 13 on June 2016)
  - In December 2016, Vodafone and Huawei integrated NB-IoT into the Spanish Vodafone network.

SIGFOX

- SigFox
  - The Sigfox technology was developed in 2010 by the startup Sigfox (in Toulouse, France),
  - Sigfox operates and commercializes its own IoT solution in 31 countries and is still under rollout worldwide owing to the partnership with various network operators

SIGFOX: TECHNICAL SPECIFICATION

- Binary phase-shift keying (BPSK) modulation in an ultra-narrow band (100 Hz) sub- GHZ ISM band carrier

- It causes SigFox experiences
  - very low noise levels,
  - leading to very low power consumption,
  - high receiver sensitivity,
  - and low-cost antenna design
  - all, at the expense of maximum throughput of only 100 bps.

SIGFOX: TECHNICAL SPECIFICATION

- The downlink communication can only occur following an uplink communication.
- The number of messages over the uplink is limited to 140 messages per day.
- The maximum payload length for each uplink message is 12 bytes.
- However, the number of messages over the downlink is limited to 4 messages per day, which means that the acknowledgment of every uplink message is not supported.

NB-IOT AND OTHER LTE VARIATIONS

- Existing cellular technologies,
  - 2G (GPRS, Edge), 3G, and 4G/LTE,
  - are not particularly well adapted to battery-powered devices and small objects specifically developed for the Internet of Things.

- While industry players have been developing unlicensed-band LPWA technologies, 3GPP and associated vendors have been working on evolving cellular technologies to better address IoT requirements.
  - low throughput and low power consumption, and decrease the complexity and cost of the LTE devices.
  - This resulted in the definition of the LTE-M work item.

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NB-IOT AND OTHER LTE VARIATIONS

- Because the new LTE-M device category was not sufficiently close to LPWA capabilities, in 2015 3GPP approved a proposal to standardize a new narrowband radio access technology called Narrowband IoT (NB-IoT).

- NB-IoT specifically
  - the requirements of a massive number of low throughput devices,
  - low device power consumption,
  - improved indoor coverage,
  - and optimized network architecture.

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NB-IOT AND OTHER LTE VARIATIONS

- Licensed LPWAN:
  - LTE Cat 0
  - LTE-M
  - NB-IoT

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LTE CAT 0

- The first enhancements to better support IoT devices in 3GPP occurred in LTE Release 12.

- A new user equipment (UE) category, Category 0, was added, with devices running at a maximum data rate of 1 Mbps.

- Category 0 includes important characteristics to be supported by both the network and end devices.

- Meanwhile, the UE still can operate in existing LTE systems with bandwidths up to 20 MHz.

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LTE-M

- Following LTE Cat 0, the next step in making the licensed spectrum more supportive of IoT devices was the introduction of the LTE-M category for 3GPP LTE Release 13.
- LTE-M requires new chipsets and additional software development.
- Commercial deployment is expected in 2017.
- Mobile carriers expect that only new LTE-M software will be required on the base stations, which will prevent re-investment in hardware.

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NB-IOT

- Recognizing that the definition of new LTE device categories was not sufficient to support LPWA IoT requirement, 3GPP specified Narrowband IoT (NB-IoT).
- Three modes of operation are applicable to NB-IoT:
  - **Standalone**
    - A GSM carrier is used as an NB-IoT carrier, enabling reuse of 900 MHz or 1800 MHz.
  - **In-band**
    - Part of an LTE carrier frequency band is allocated for use as an NB-IoT frequency.
  - **Guard band**
    - This requires coexistence between LTE and NB-IoT bands.

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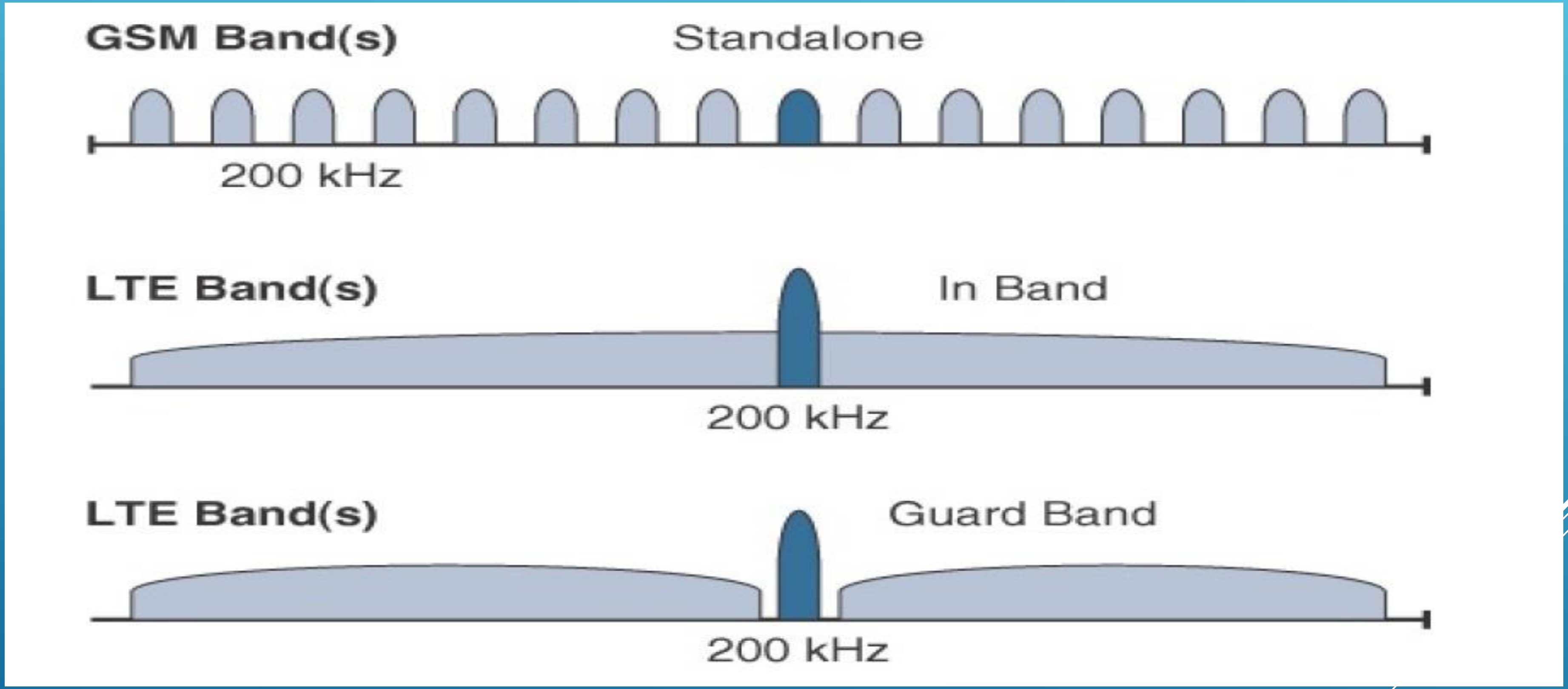
PHYSICAL AND LINK LAYERS PROTOCOLS- NB-IOT

- NB-IoT



PHYSICAL AND LINK LAYERS PROTOCOLS- LORAWAN

- LoRaWAN
  - LoRaWAN is an example of an unlicensed-band Low-Power Wide-Area (LPWA) technology.
  - LPWA particularly well adapted for long-range and battery-powered endpoints.

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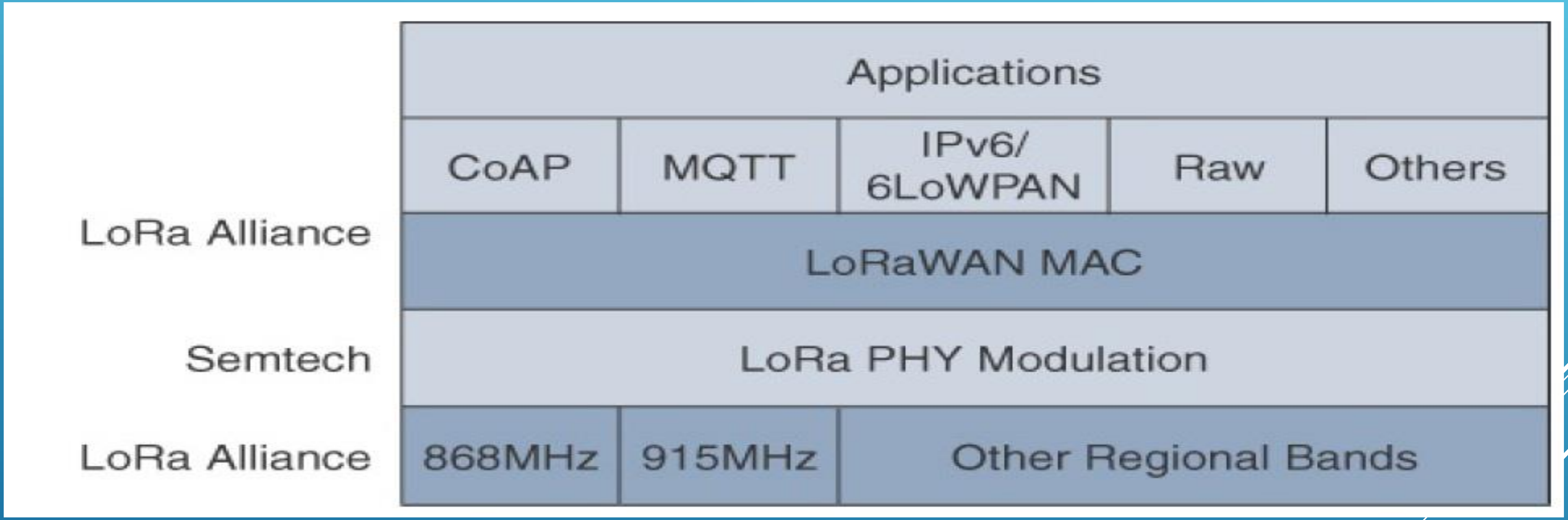
PHYSICAL AND LINK LAYERS PROTOCOLS- LORAWAN

- LoRaWAN Layers



- Semtech is responsible for the PHY layer, while the LoRa Alliance handles the MAC layer and regional frequency bands

LORA SPECIFICATION

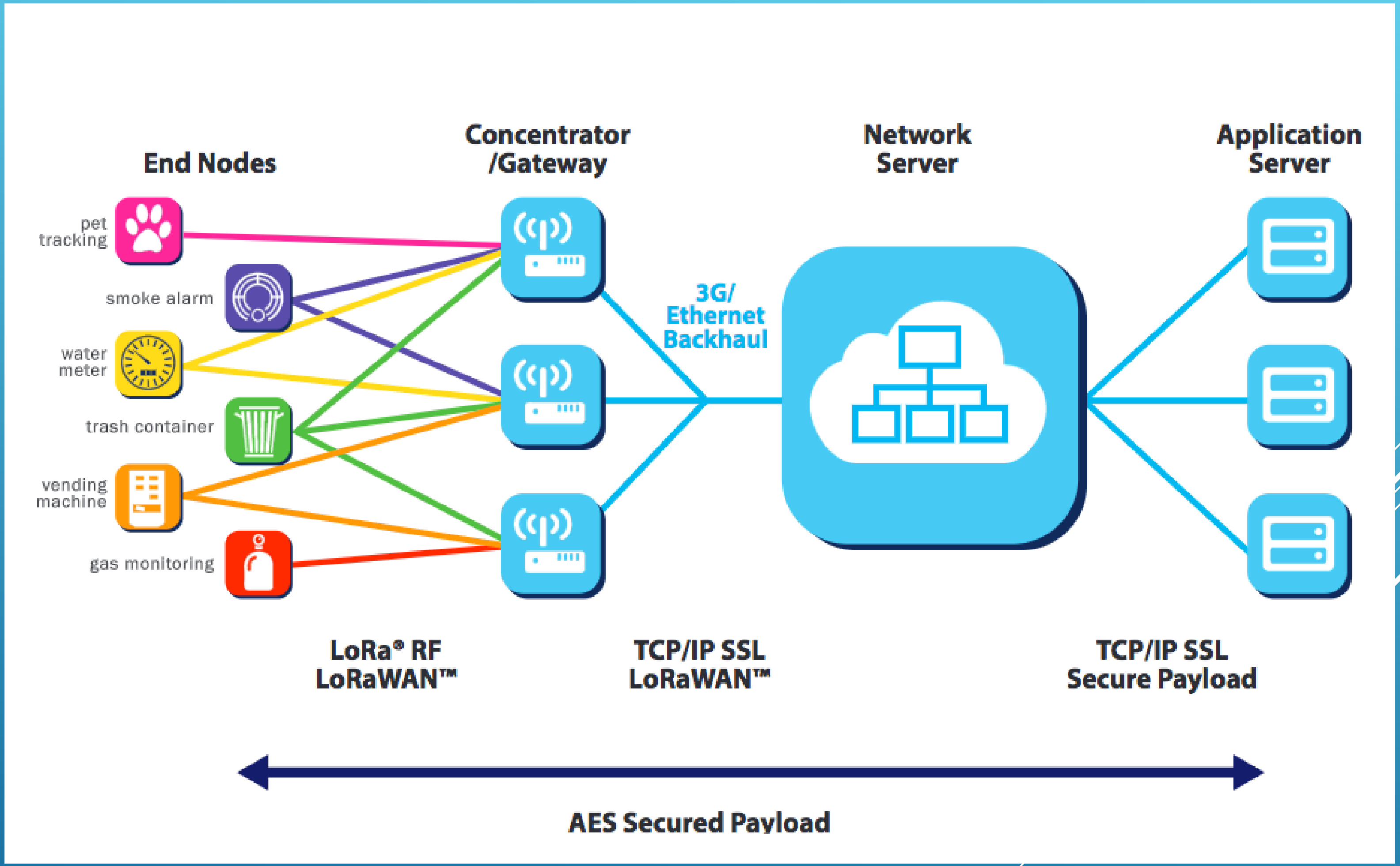
- The range between LoRa sender and receiver depends on the environment the equipment operates in. Indoor coverage largely depends on the type of building material used.

Environment	Range (km)
Urban areas (towns & cities)	2-5
Rural areas (country sides)	5-15
Direct Line of Sight	>15

- Some notable records: Andreas Spiess, ground to ground connection: 212 km (= 131.73 miles) Weather balloon to ground connection: 702.67 km (= 436.61 miles)

LORAWAN- TOPOLOGY

- LoRaWAN
  - Topology
    - Star of stars



* IoT Fundamentals: Networking Technologies, Protocols, and Use Cases for the Internet of Thing, Cisco press, 2017

LORAWAN- TOPOLOGY

- **<u>End-devices:</u>**
  - Perform the communication gateways using LoRa and LoRaWAN technologies.
- **<u>Gateways (i.e., base stations):</u>**
  - Dispatch the LoRaWAN frames from the end devices to a network server using a back-haul interface with higher throughput, usually via Ethernet, 3G/4G, satellite or Wi-Fi.
- **<u>The Network Server:</u>**
  - Decodes the packets sent by the devices, performing security checks and adaptive data rate, thus generating the control data that should be sent back to the devices.
- **<u>Each Application:</u>**
  - Receives data from the network server. It should decode the security packets and uses the information to decide the action in the application.

LORAWAN- HOW IT WORKS?

- **End Node**
  - broadcast its data to every gateway in its vicinity.
- **Gateways:**
  - Forward this packet to the network server. It is only a protocol convertor.
- **Network Server:**
  - Collects the messages from all gateways and filters out the duplicate data and determines the gateway that has the best reception.
  - Forwards the packet to the correct application server where the end user can process the sensor data.
- Optionally the application server can send a response back to the end node.
  - When a response is sent, the network server receives the response and determines which gateway to use to broadcast the response back to the end node.

LORAWAN- TOPOLOGY

- LoRa is an acronym for Long Range and it is a wireless technology where a low powered sender transmit small data packages to a receiver over a long distance.
- A gateway can handle hundreds of devices at the same time.

The Things Gateway

(gateway / concentrator)

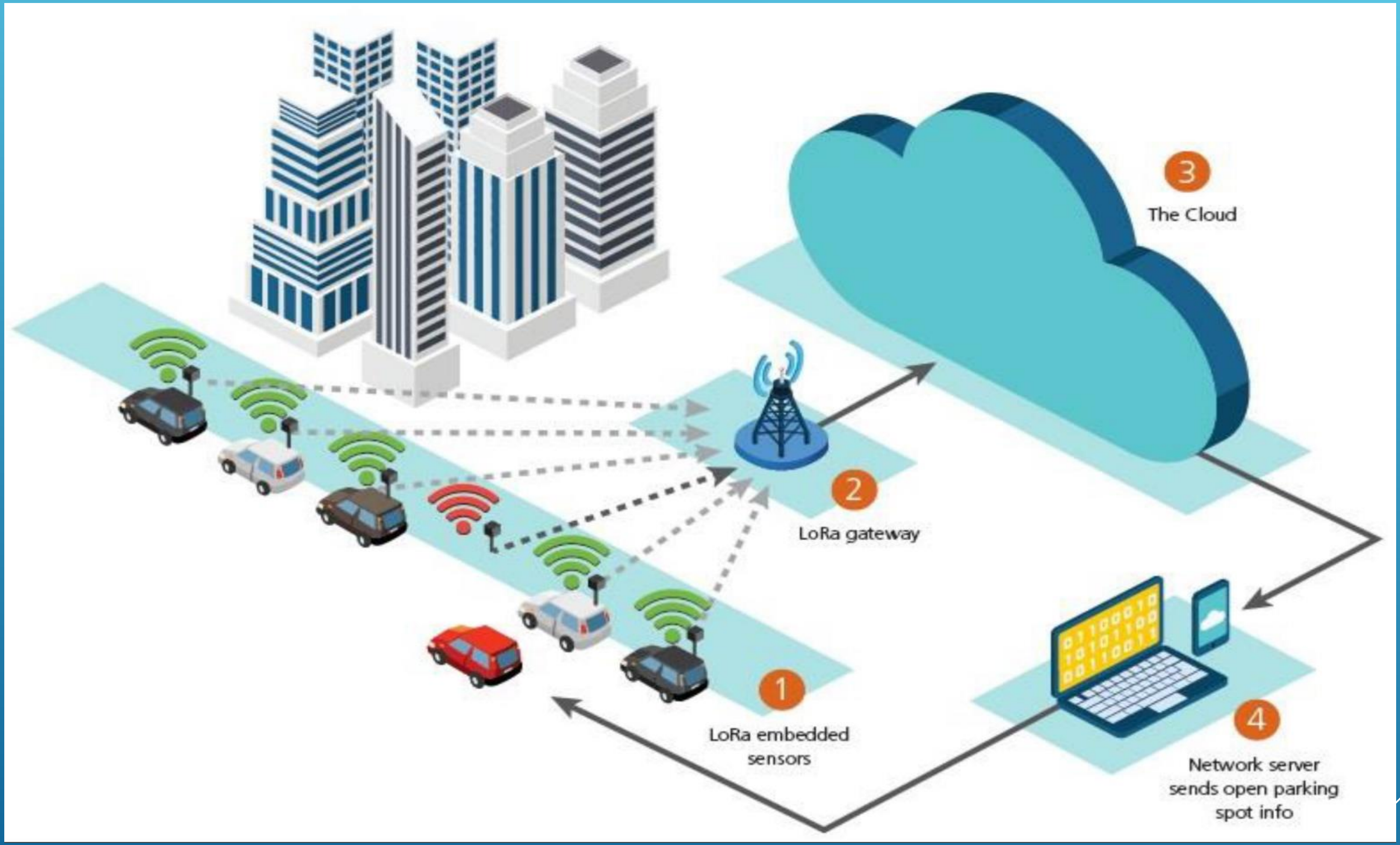
The Things Uno (end node)

LORAWAN: SPECIFICATION

- The most **critical factors** in a LPWAN are:
  - Network architecture;
  - Communication range;
  - Battery lifetime (low power);
  - Robustness to interference;
  - Network capacity (maximum number of nodes in a network);
  - Network security;
  - One-way vs two-way communication;

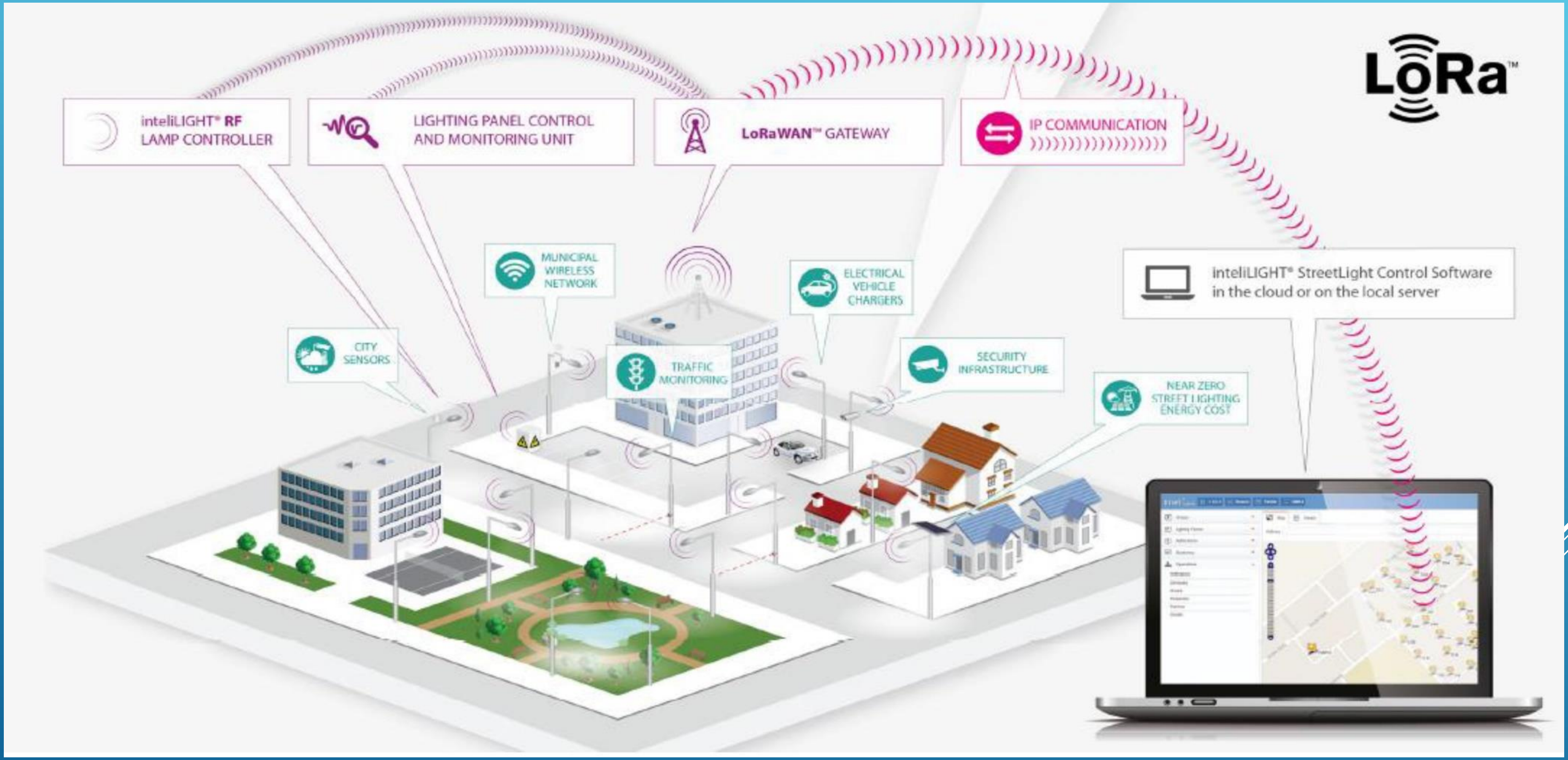
Characteristic	LoRaWAN
Topology	Star on Star
Modulation	SS Chirp
Data Rate	290bps - 50kbps
Link Budget	154 dB
Packet Size	20-256 bytes
Battery lifetime	8 $\sim$ 10 years
Power Efficiency	Very High
Security/Authentication	Yes (32 bits)
Range	2-5 km urban 15 km suburban 45 km rural
Interference Immunity	Very High
Scalability	Yes
Mobility/Localization	Yes

LORAWAN USE CASE- PARKING OCCUPANCY



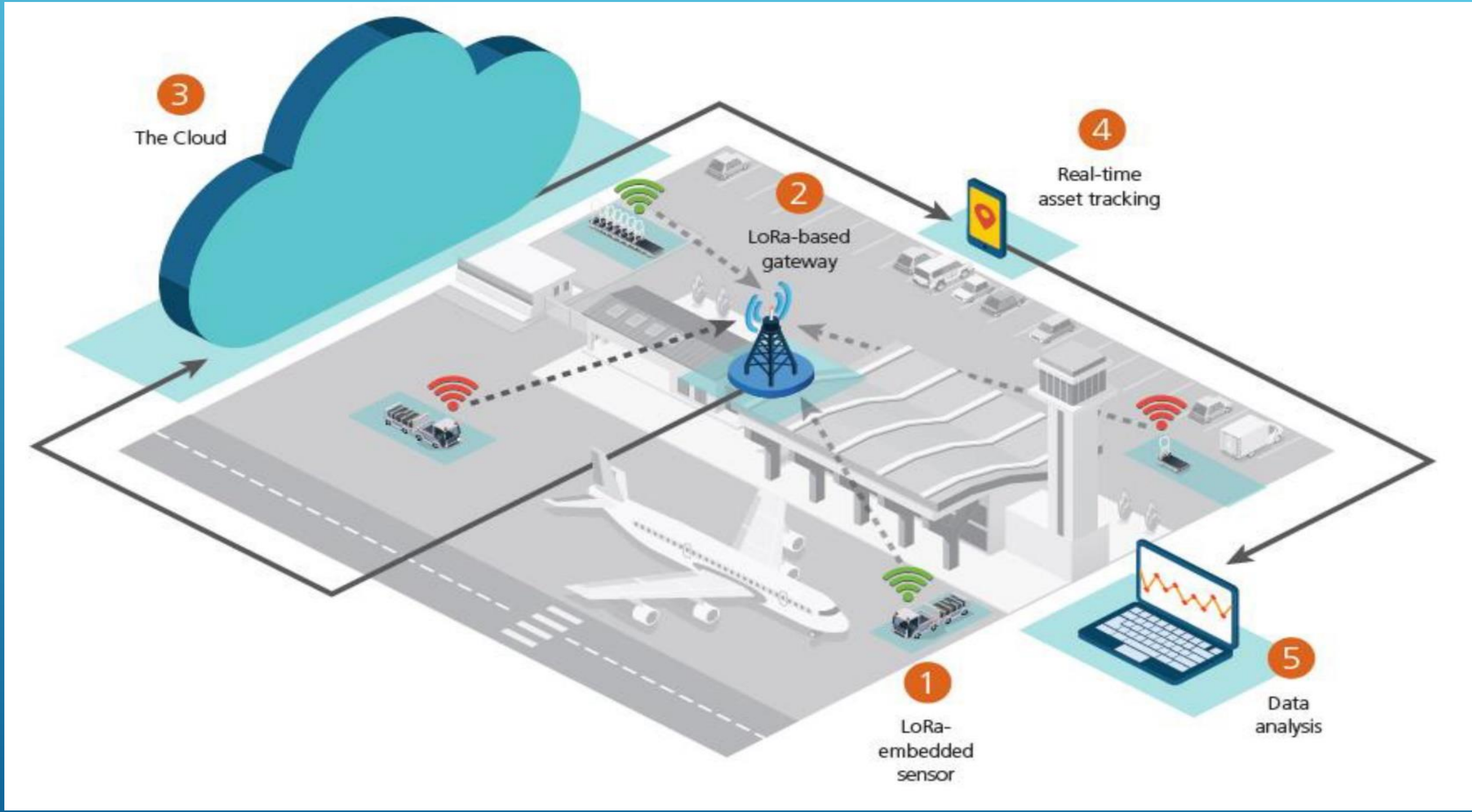
IOT and LORAWAN, Quaenet, 2018

LORAWAN USE CASE- SMART LIGHTING



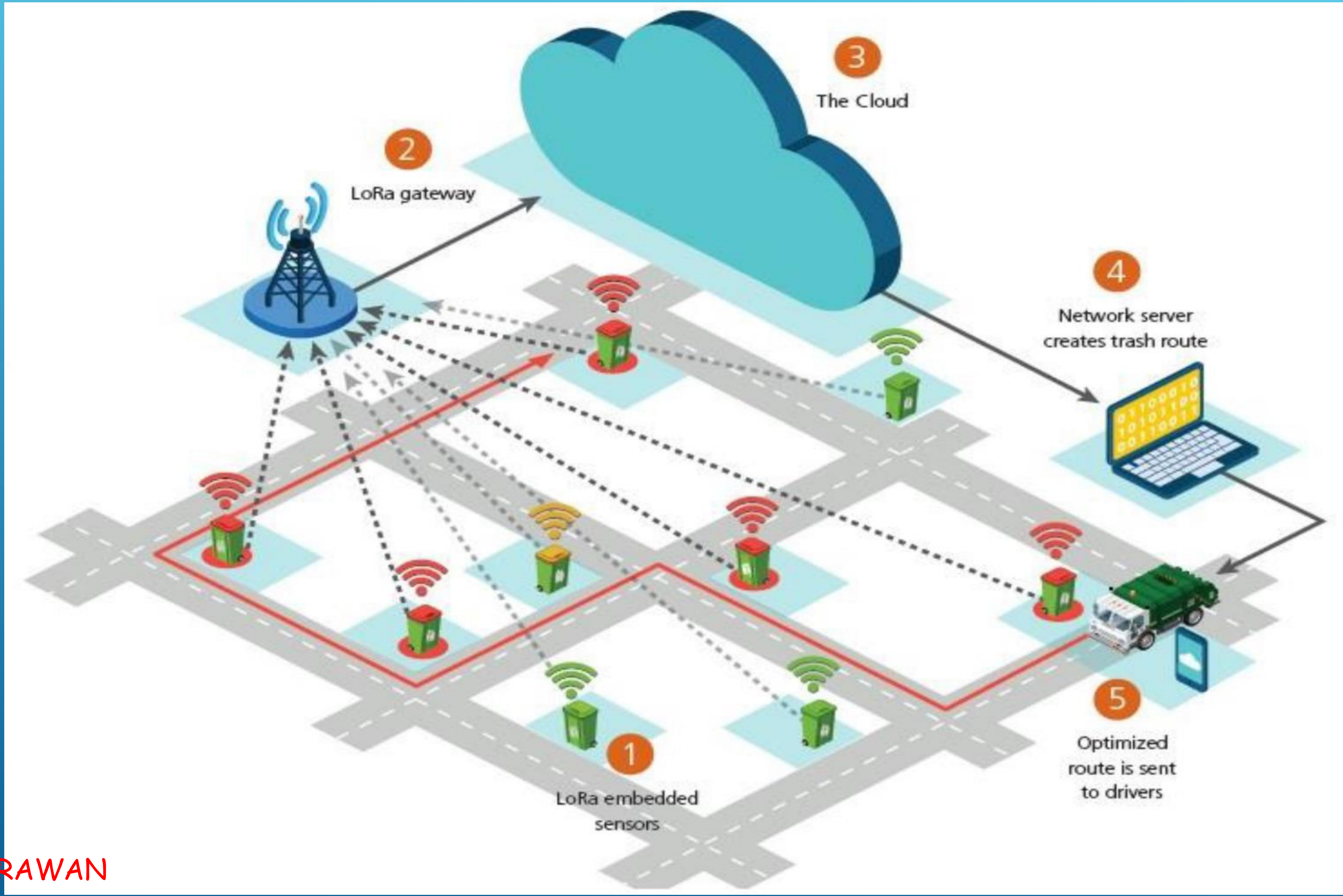
IOT and LORAWAN, Quaenet, 2018

LORAWAN USE CASE- ASSET MANAGEMENT



IOT and LORAWAN, Quaenet, 2018

LORAWAN USE CASE- SMART WASTE MANAGEMENT



LORAWAN- PHYSICAL LAYER

- LoRaWAN 1.0.2 regional specifications describe the use of the main unlicensed sub-GHz frequency bands of
  - 433 MHz,
  - 779–787 MHz,
  - 863–870 MHz,
  - and 902–928 MHz,
  - as well as regional profiles for a subset of the 902–928 MHz bandwidth
    - For example, Australia utilizes 915–928 MHz frequency bands, while South Korea uses 920–923 MHz and Japan uses 920–928 MHz.

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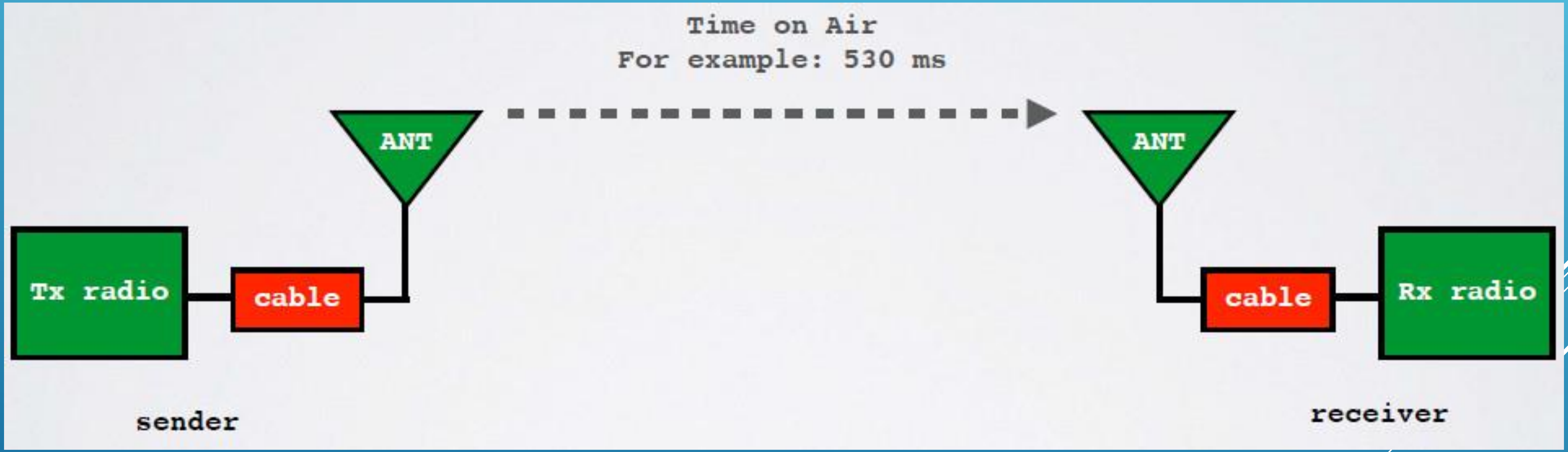
ISM BAND AND DUTY CYCLE

- In Europe when using the ISM band frequencies (863 MHz - 870 MHz) users must comply to the following rules:
  - For uplink, the maximum transmission power is limited to 25mW (14 dBm).
  - For downlink (for 869.525MHz), the maximum transmission power is limited to 0.5W (27 dBm)
  - There is an 0.1% and 1.0% duty cycle per day depending on the channel.

- Besides these ISM band rules, the network service provider (for example The Things Network) can also add additional restrictions.

TIME ON AIR (TOA)

- Duty cycle is the proportion of time during which a component, device, or system is operated. The duty cycle can be expressed as a ratio or as a percentage.



- As mentioned previously in Europe there is a 0.1% and 1.0% duty cycle per day depending on the channel.

DUTY CYCLE

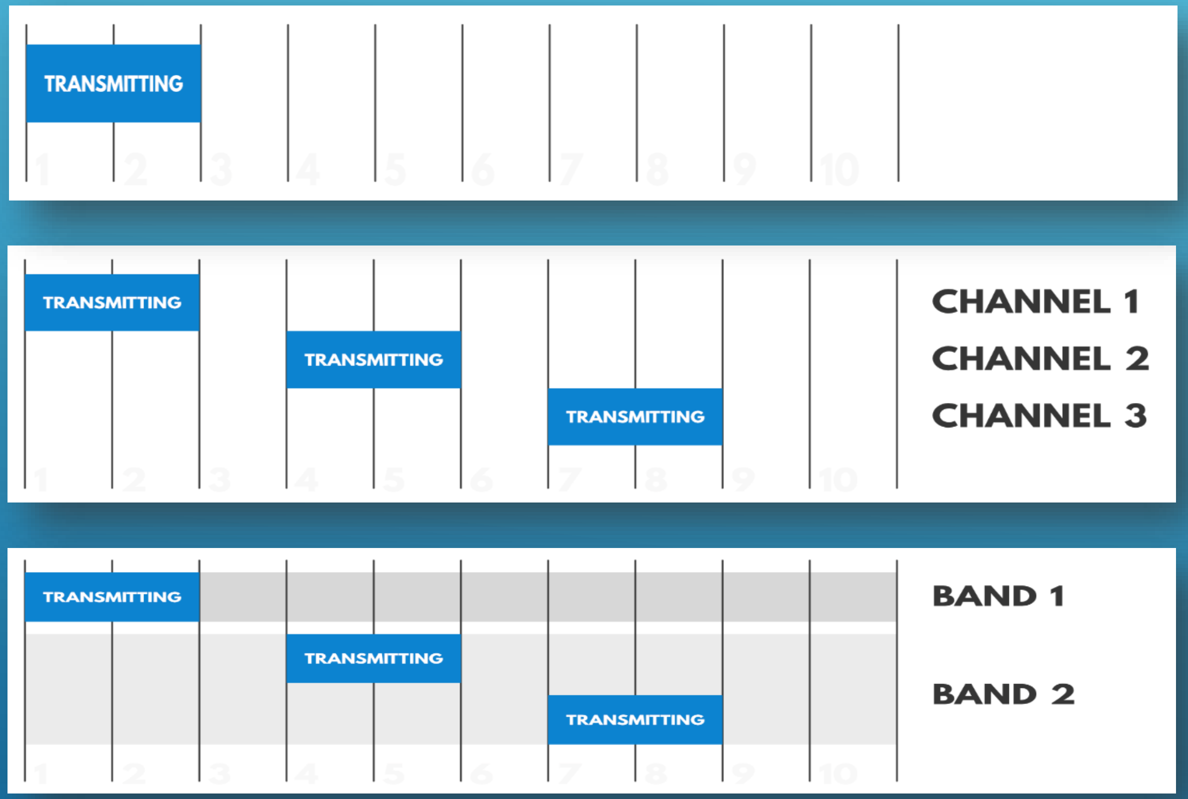
Duty-cycle regulations in the ISM bands: The maximum time each device may occupy the channel

duty cycle = 20%

duty cycle = 60%

duty cycle = 20%

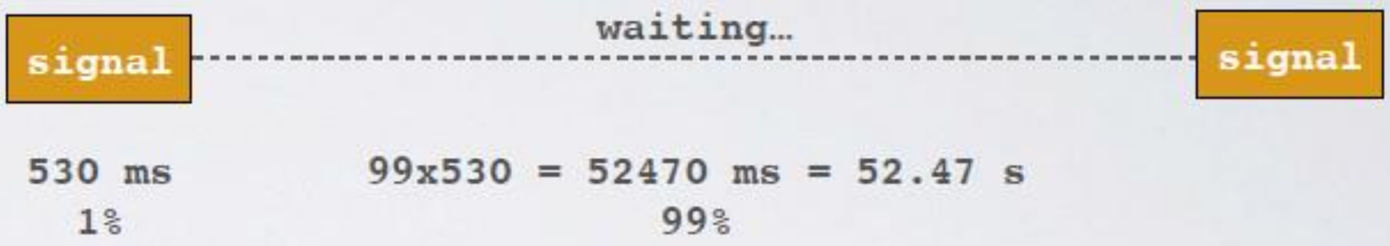
duty cycle = 40%



” Duty Cycle for LoRaWAN Devices”, https://www.thethingsnetwork.org/docs/lorawan/duty-cycle.html

DUTY CYCLE

For example:
Time on Air = 530 ms
Duty cycle = 1%



For example:
Time on Air = 400 ms
Duty cycle = 0.1%

LORAWAN- PHYSICAL LAYER

- Semtech LoRa modulation is based on chirp spread spectrum modulation, which trades a lower data rate for receiver sensitivity to significantly increase the communication distance.
- It allows demodulation below the noise floor, offers robustness to noise and interference, and manages a single channel occupation by different spreading factors.
- An important feature of LoRa is its ability to handle various data rates via the spreading factor.

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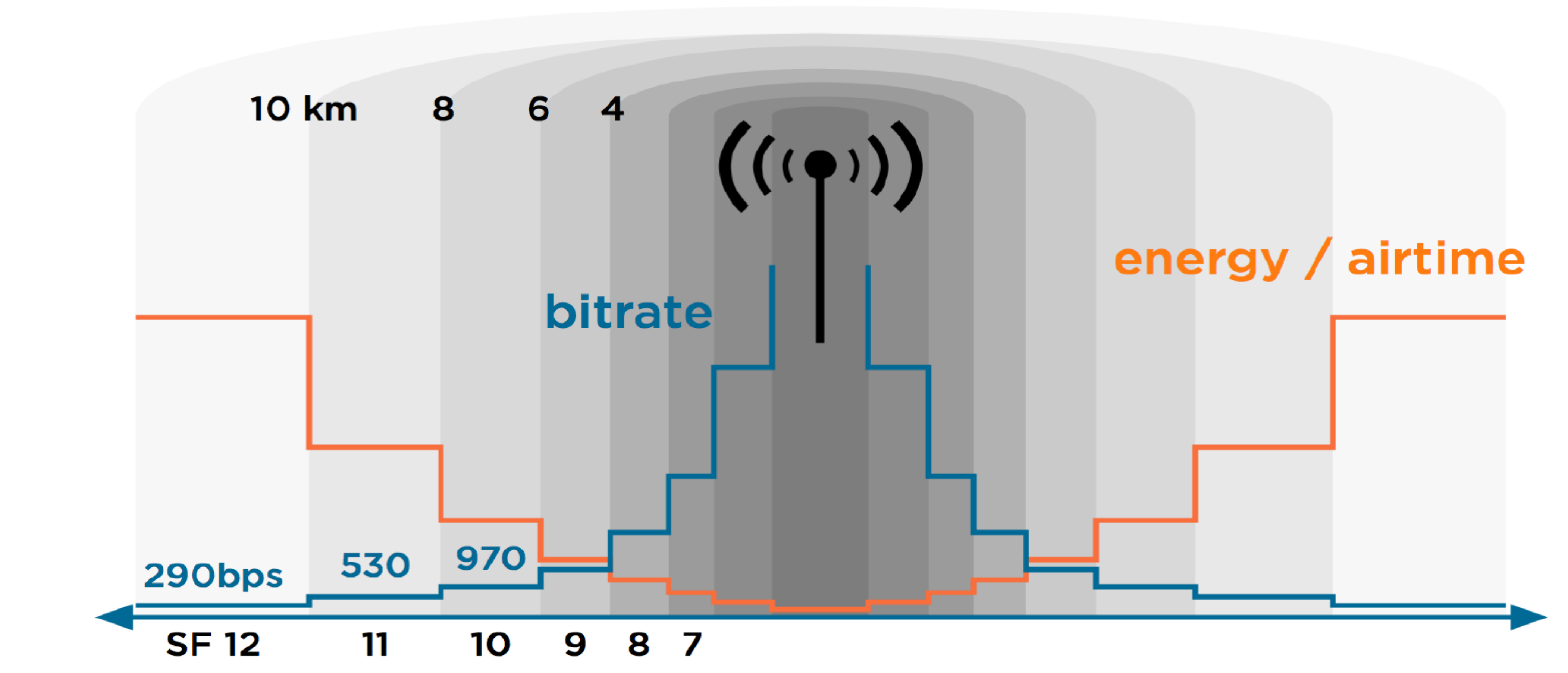
LORAWAN- PHYSICAL LAYER

- The Data Rate Story: There are three physical factors:
  - **transmission power**,
  - **bandwidth**
  - **spreading factor**
- If you lower the tx power, you'll save battery, but the range of the signal will obviously be shorter.
- The other two factors (spreading factor and bandwidth) combined form the data rate. This determines how fast bytes are transmitted.

LORAWAN- PHYSICAL LAYER



http://www.linuxembedded.fr/2017/12/introduction-a-lora/

LORAWAN- ADAPTIVE DATA RATE

- Adaptive Data Rate (ADR) is a mechanism for optimizing data rates, airtime and energy consumption in the network.

- End devices decide if ADR should be used or not, not the application or the network.

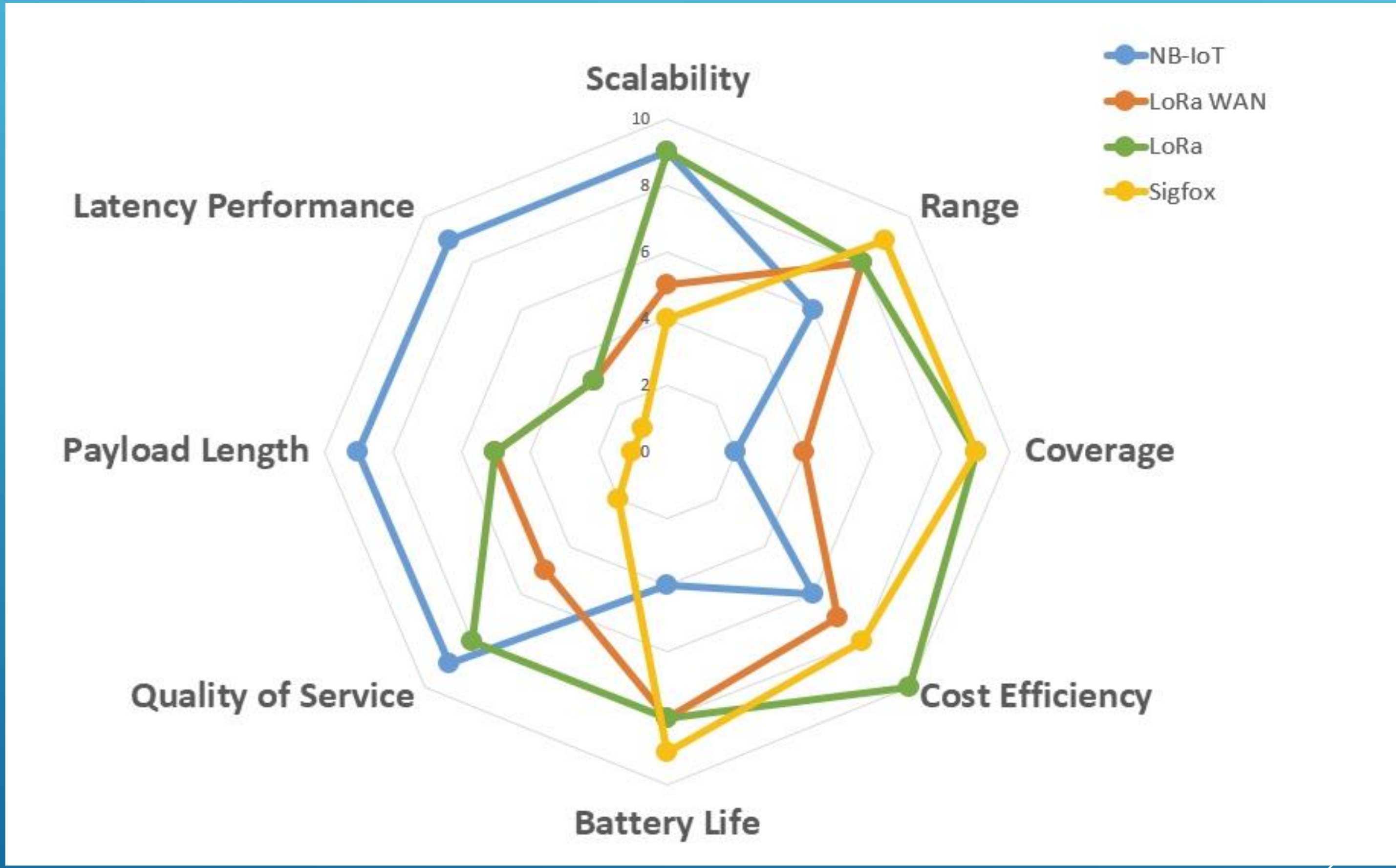
LORAWAN DEVICE CLASES

- The LoRaWAN specification defines three device classes:

Class	Description
A(ll)	Battery powered devices. Each device uplink to the gateway and is followed by two short downlink receive windows.
B(eacon)	Same as class A but these devices also opens extra receive windows at scheduled times.
C(ontinuos)	Same as A but these devices are continuously listening. Hence these devices uses more power and are often mains powered.

COMMUNICATION TECHNOLOGIES COMPARISON

- Comparison of SigFox, LoRa, LoRaWAN, and NB-IoT in terms of different criteria



* https://www.betasolutions.co.nz/Blog/25/20-Things-to-Consider-When-Planning-an-IoT-Solution-_-Part-2

PHYSICAL AND LINK LAYERS PROTOCOLS- USE CASES

Key IoT Verticals	LPWAN (Star)	Cellular (Star)	Zigbee (Mostly Mesh)	BLE (Star & Mesh)	Wi-Fi (Star & Mesh)	RFID (Point-to-point)
Industrial IoT	●	○	○			
Smart Meter	●					
Smart City	●					
Smart Building	●		○	○		
Smart Home			●	●	●	
Wearables	○			●		
Connected Car					○	
Connected Health		●		●		
Smart Retail		○		●	○	●
Logistics & Asset Tracking	○	●				●
Smart Agriculture	●					

● Highly applicable ○ Moderately applicable

* https://behrtech.com/blog/6-leading-types-of-iot-wireless-tech-and-their-best-use-cases/