Internet of Things – which connectivity technology ?

Eugen Borcoci
University POLITEHNICA of Bucharest - UPB
Bucharest, Romania
Email: eugen.borcoci@elcom.pub.ro

1. INTRODUCTION

- **Acknowledgement**

➢ This presentation **is a short overview, compiled and structured based on several public documents** such as: conference proceedings, studies (overviews, tutorials, research papers), standards, projects, etc. (see specific references in the text and in the Reference list).

➢ **The topic selection, text organization and explanations belong to this author.**

➢ **Notes:**

- Given the extension of the topics, this **presentation is limited to a high level overview only**, mainly on conceptual, architectural and a few specific design aspects.
- Some examples taken from the literature, projects, etc., are selected to illustrate architecture and implementations to support IoT connectivity.

Contents

1. Introduction
2. IoT connectivity
3. Short range technologies
4. Mid-long range technologies
5. Cellular technologies for IoT
6. 5G connectivity solutions for IoT
7. Selection of IoT communication technology
8. Conclusions

Contents

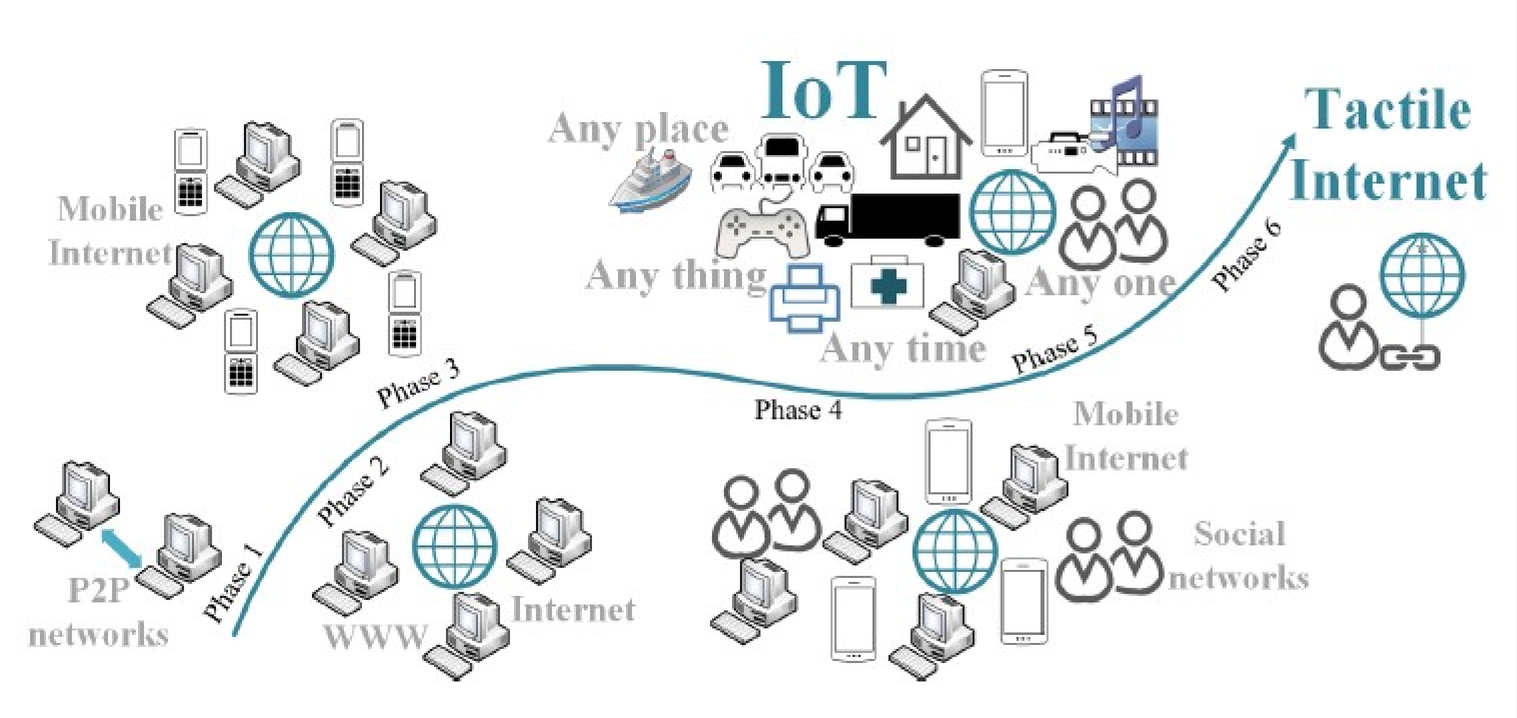
1. Introduction
2. IoT connectivity
3. Short range technologies
4. Mid-long range technologies
5. Cellular technologies for IoT
6. 5G connectivity solutions for IoT
7. Selection of IoT communication technology
8. Conclusions

1. INTRODUCTION

- **Internet of Things (IoT)**
  - Traditional basic Internet communication : human-to-human (H2H) and human to machine (H2M)
  - **IoT:**
    - Internet evolution that mainly adds **machine-to-machine (M2M)** communications
    - provides connectivity for ***everyone*** and ***everything***
    - embeds intelligence in Internet **connected objects**, allowing them to communicate, exchange information, take decisions, invoke actions aiming to provide a large range of services
    - allows autonomous and secure connection and exchange of data between real world devices and applications
  - **Traditional Internet terminal devices** : personal computers, laptops, tablets, smart phones, PDAs and other hand-held embedded devices
  - **IoT objects:** sensor devices, communication infrastructure, computational and processing unit (may be placed in clouds), decision making and action invoking system
    - The objects have certain unique features; they are uniquely identifiable and accessible via the Internet
    - IoT characteristic : huge set of terminals/objects accepted (many “things”!)

1. INTRODUCTION

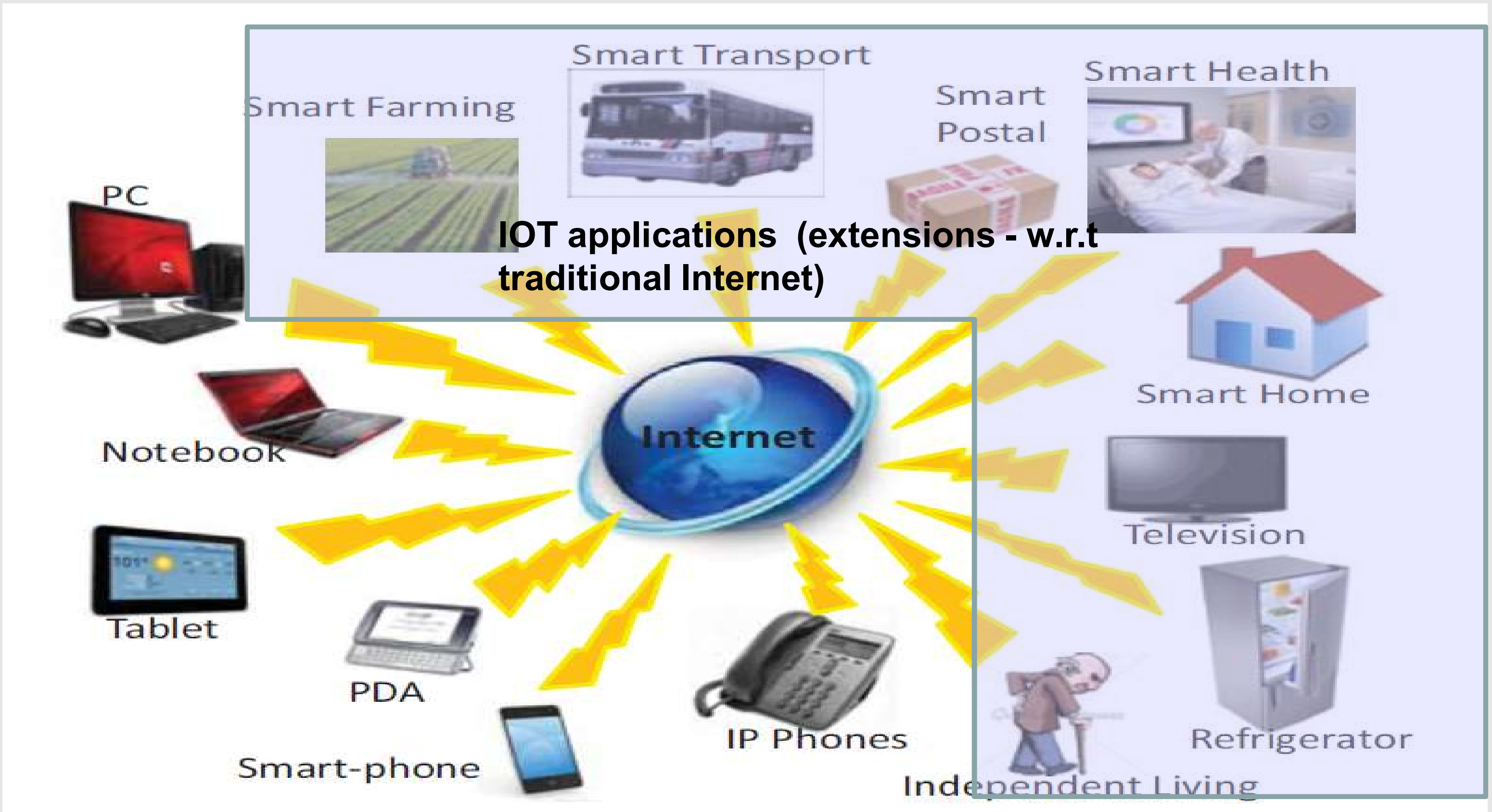
- **Internet evolution**
  - Several phases: P2P, WWW, Mobile Internet, Social networks, **IoT**, Tactile Internet, ….
  - Today: strong trend to develop and deploy IoT in many domains



Source: P.Porambage,et.al., "Survey on Multi-Access Edge Computing for IoT Realization", arXiv:1805.06695v1 [cs.NI] May 2018

1. INTRODUCTION

- **Internet of Things (IoT) – applications-** examples

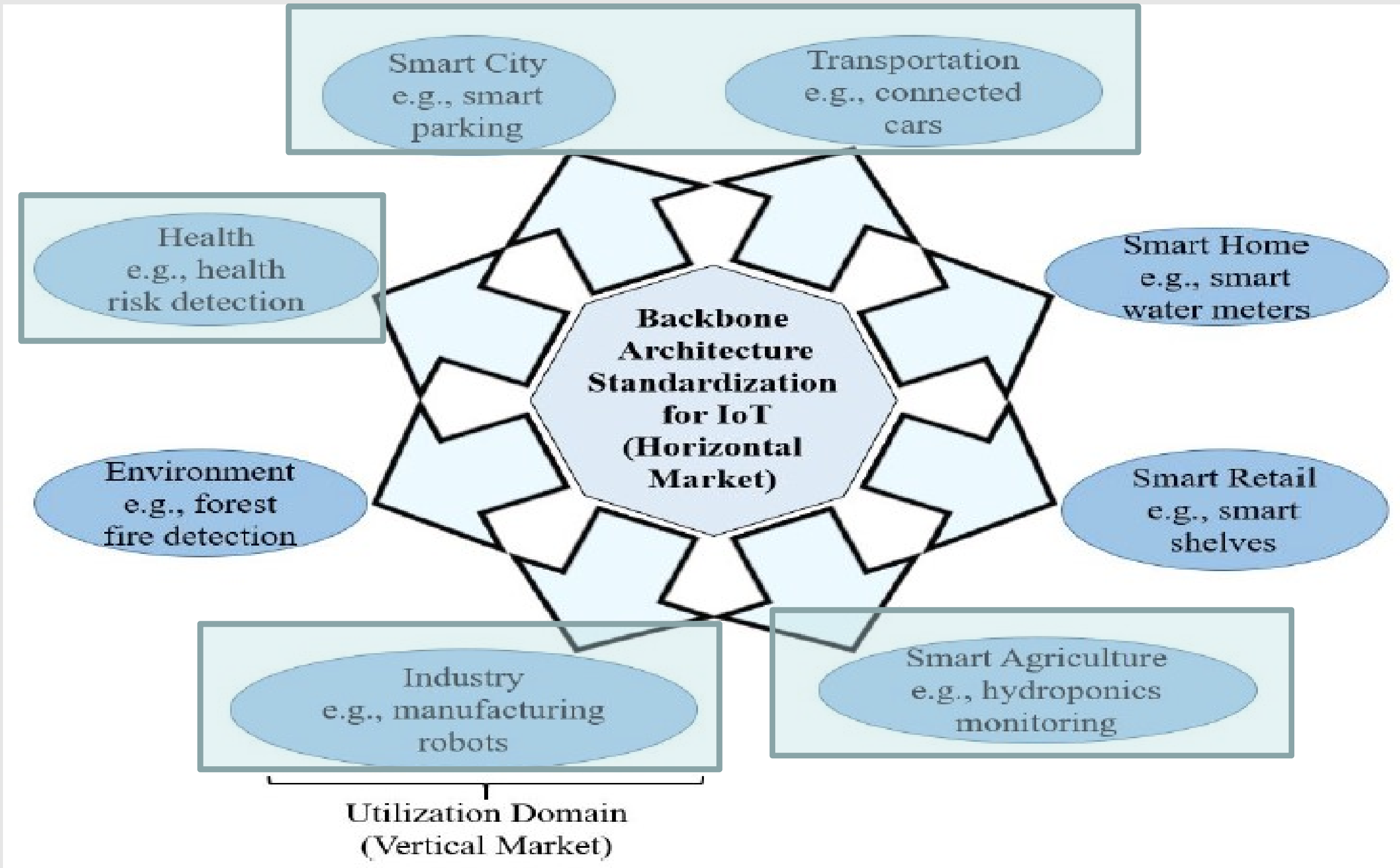


Source: R,Khan et al., "Future Internet: The Internet of Things Architecture, Possible Applications and Key Challenges", Dec. 2012, https://www.researchgate.net/publication/261311447

1. INTRODUCTION

- **IoT applications and utilization domains: -** many "verticals"

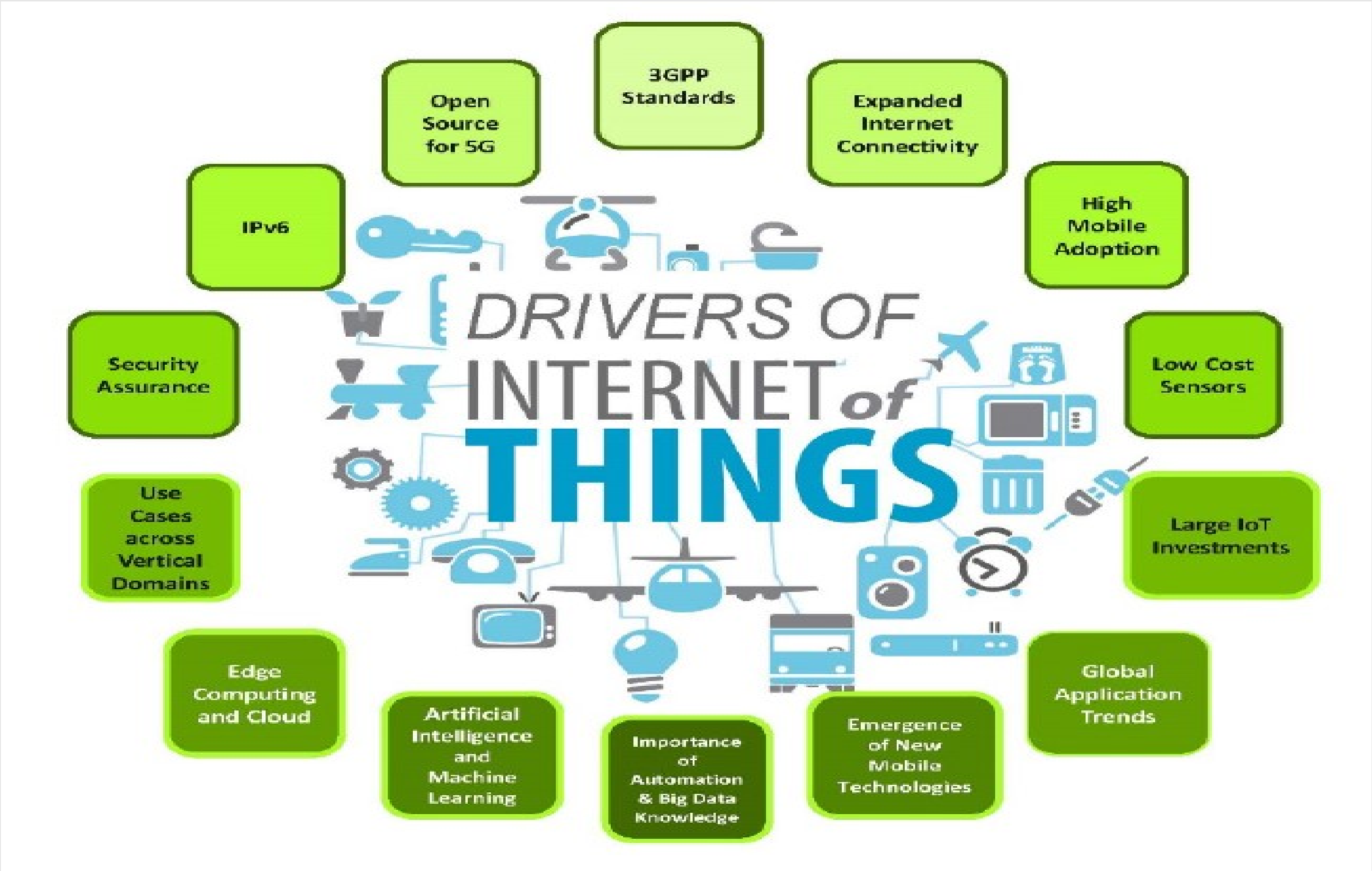
Mobility is involved



Adapted from source: J.Ding, M.Nemati, C.Ranaweera, and J.Choi, "IoT Connectivity Technologies and Applications:A Survey" arXiv:2002.12646v1 [eess.SP] 28 Feb 2020.

1. INTRODUCTION

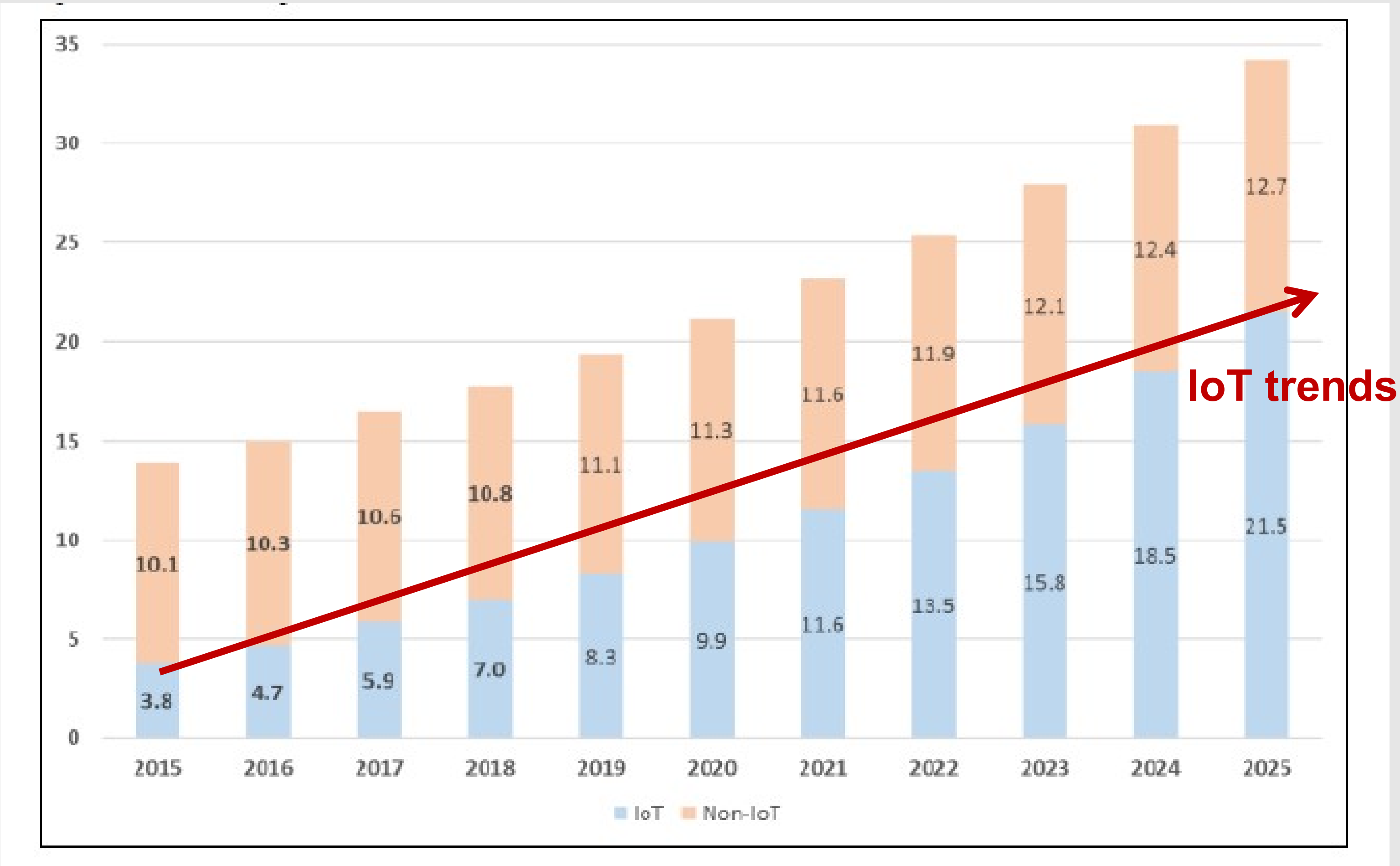
- **IoT Market Drivers and Trends-** *5G Americas vision*



Source: 5G Americas white Paper, "5G A future of IoT", July 2019,
https://www.5gamericas.org/5g-the-future-of-iot/

1. INTRODUCTION

- **Global Number of Connected Devices ($ Billions)**



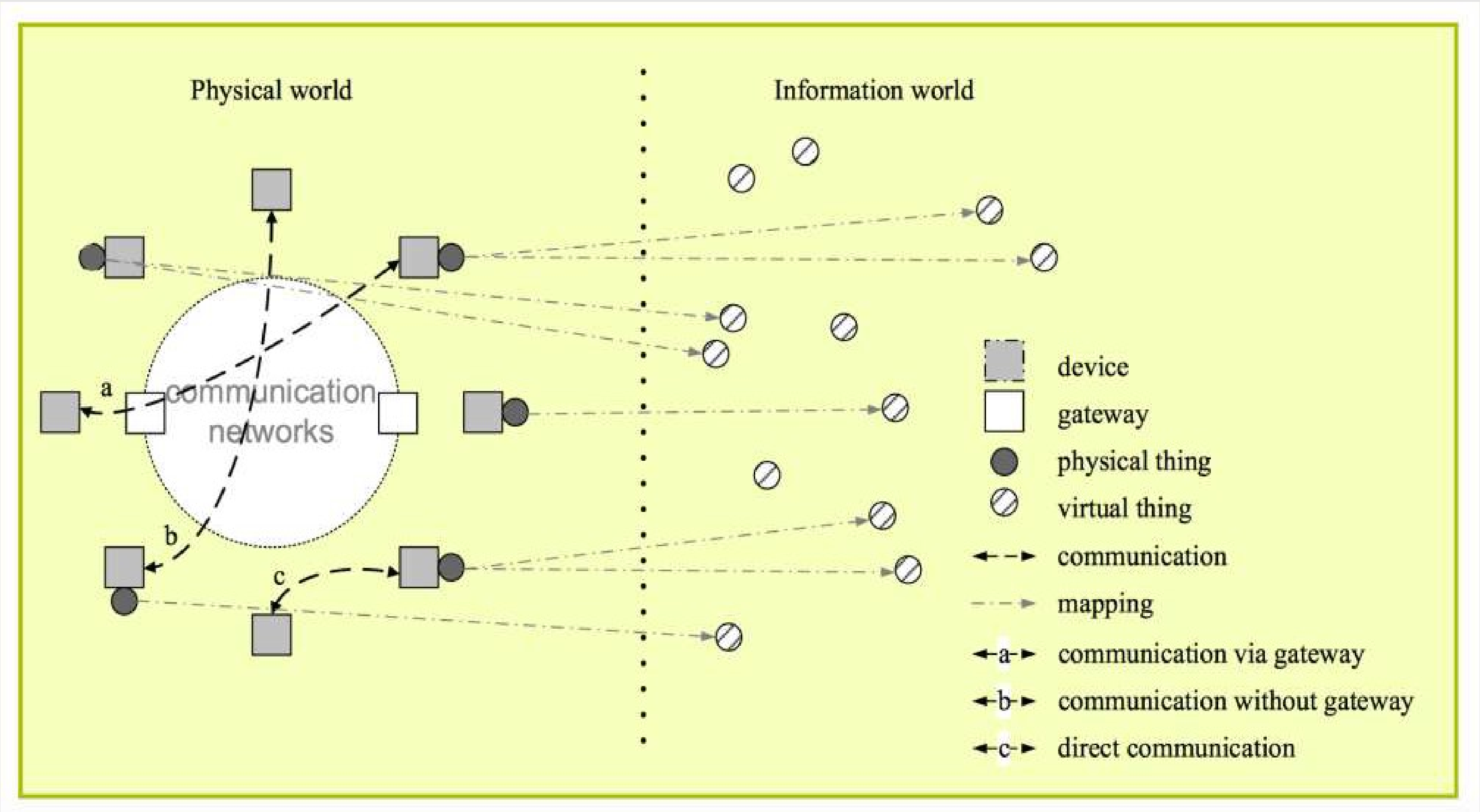
Adapted from source: Internet Analytics, August 8, 2018, https://iot-analytics.com/state-of-the-iot-update-q1-q2-2018-number-of-iot-devices-now-7b/.

1. INTRODUCTION

- **Internet of Things (IoT)- ITU Definition**
  - **IoT** : a global infrastructure for the information society, enabling advanced services by **interconnecting (Phy/V) things** based on existing and evolving interoperable ICT
    - *Source: Recommendation ITU-T Y.2060*
  - **Things:** objects of the physical (physical things) or the information world (virtual) which are capable of being identified and integrated into regional or global communication networks
    - They have associated information, which can be static and dynamic
    - Things/Objects systems differentiate according to:
      - The network coverage **range** (short, medium, long)
      - The **type of interaction** with the system (i.e., service type):
        - » Alarms (transmission initiated by the end-device only, according to the events, bursty traffic)
        - » Measurements (triggered either by the end-device or by the system)
        - » Control (transmissions initiated by the system)
        - » Combination of these

1. INTRODUCTION

- **Internet of Things (IoT)- ITU vision**
  - *Physical* and *virtual* things and communication types



- ***Source: Recommendation ITU-T Y.2060***

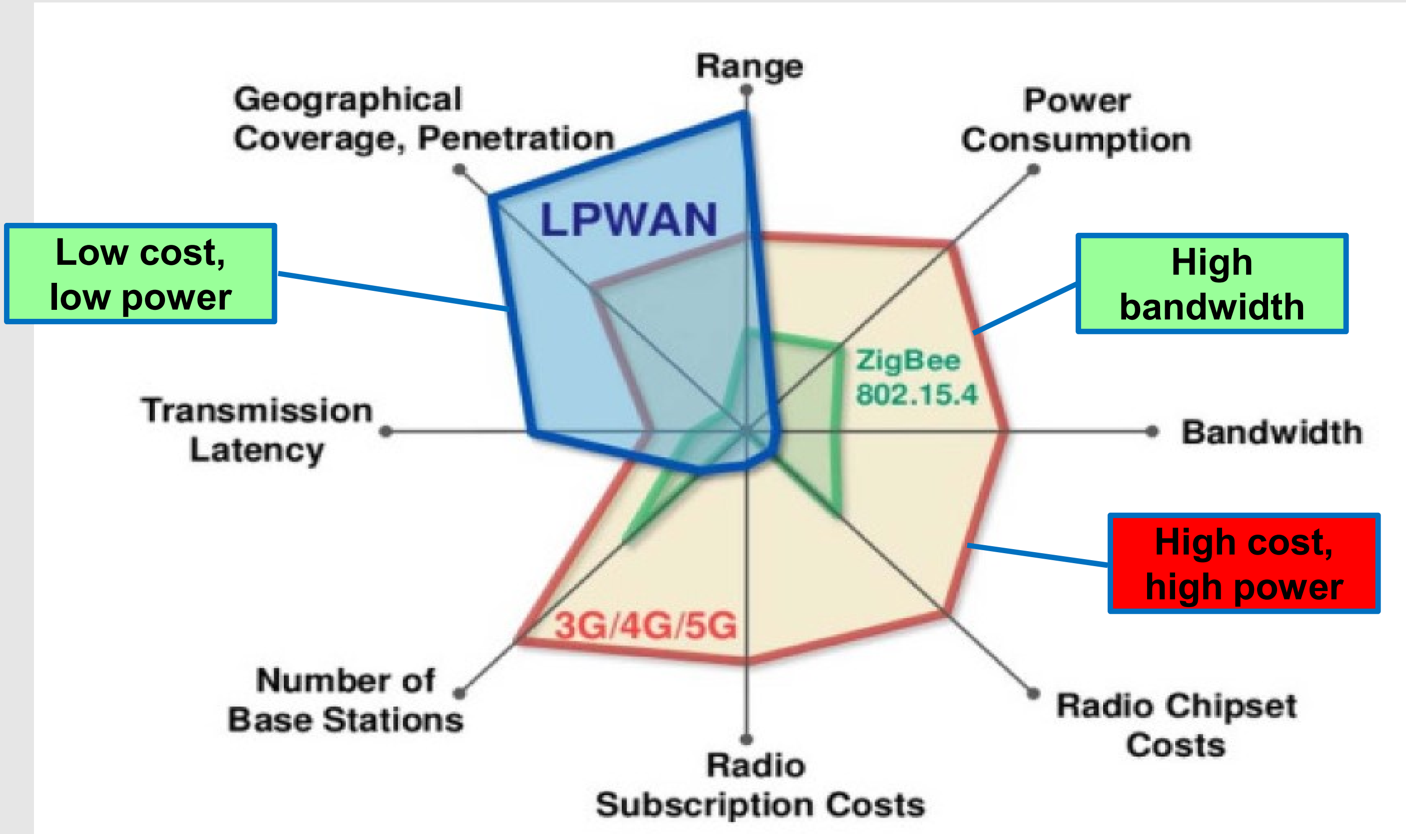
1. INTRODUCTION

- **IoT General Characteristics**
  - Low power, low or medium bit rate, low cost (network and end devices)
    - High bit rate are needed in special applications only
  - Geographical range
    - *Short* (first type of technologies) or
    - *Long* (second type of technologies)
  - Long battery duration (years)
  - Location: in any area (deep indoor, urban areas (home, health, administration, city facilities, transportation) industrial environment, rural/ forests/ agricultural areas, desert, vehicular domain, …

- **IoT communications specifics – versus - cellular**
  - Low**:** cost, power, processing/storage capacity, bitrate
  - Long: battery duration, range
  - Higher number of connections in IoT
  - Smaller size devices
  - Larger range of latencies required
  - Simple network architecture and protocols

1. INTRODUCTION

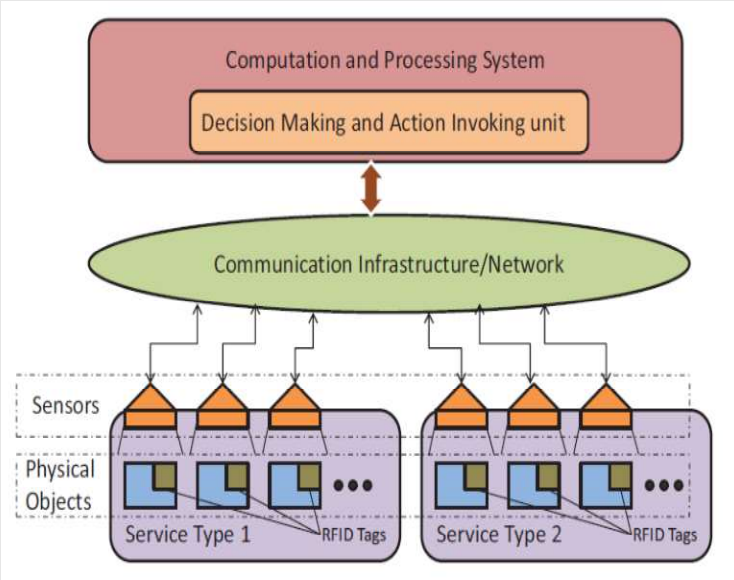
- **Examples of communication technologies and IoT characteristics**
  - LPWAN- Low Power Wide Area Network



Adapted from source: ITU-T S.Tabanne, "IoT systems overview", 30 Sept.-03 Oct. 2019, Bangkok, Thailand, *https://www.itu.int/en/ITU-D/Regional-Presence/AsiaPacific/SiteAssets/Pages/Events/2019/ITU-ASP-CoE-Training-on-/IoT%20systems%20overview.pdf*

1. INTRODUCTION

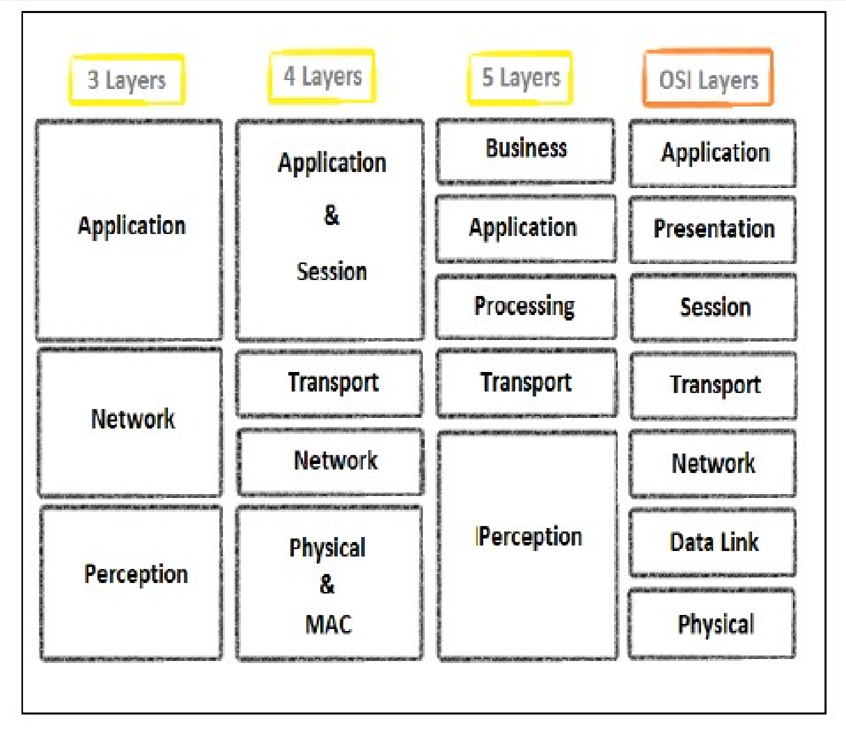
- **The basic IoT workflow**
  - **Object sensing, identification and communication of object specific information**
    - Information : sensed data about temperature, orientation, motion, vibration, acceleration, humidity, chemical changes in the air etc., depending on the type of sensors
    - A combination of different sensors can be used for the design of smart services
  - **Trigger an action**
    - the received object information is processed by a smart device/system
    - that can determine an automated action to be invoked
  - **The smart device/system**
    - provides rich services
    - includes a mechanism to provide feedback to an administrator about the current system status and the results of actions invoked



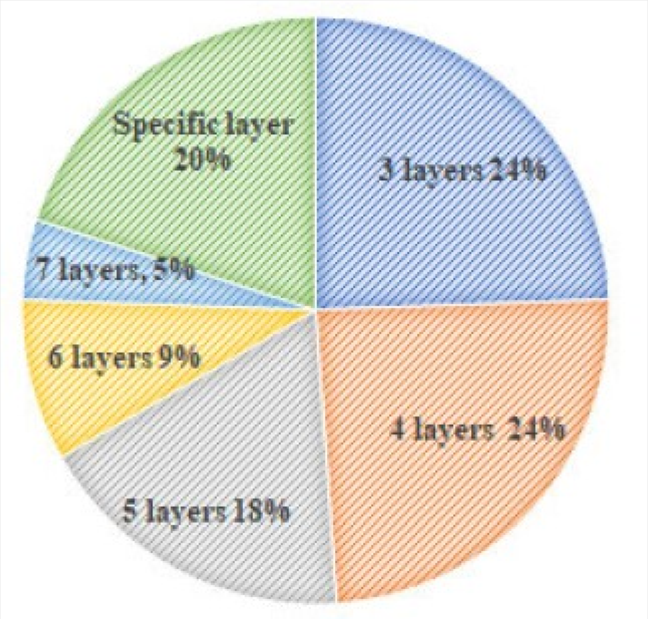
Example of a basic IoT system

1. INTRODUCTION

- **IoT functional layered architecture**
  - Several variants proposed
  - 3,4,5, .. Layers stack



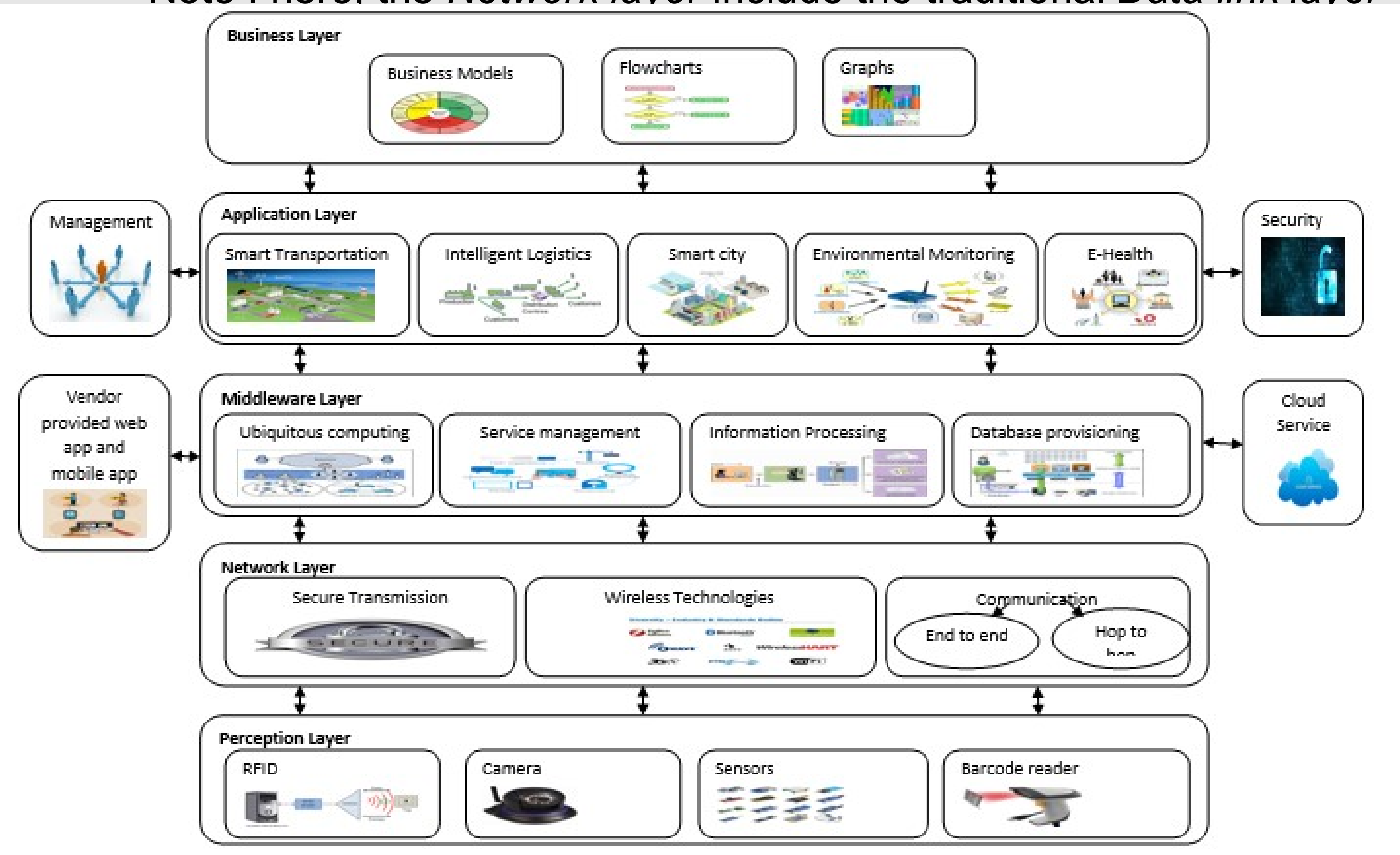
Trend of IoT architecture layers.



Source: A. Hakifaz Mohd Aman et al., "A Survey on Trend and Classification of IoT Reviews", IEEE Acces, 2020, DOI 10.1109/ACCESS.2020.3002932

1. INTRODUCTION

- **IoT functional layered architecture**
  - **A variant of 5 -layer model**
    - Note : here, the *Network layer* include the traditional *Data link layer*



Source: Srinivasa A H, Dr.Siddaraju, "A Comprehensive Study Of Architecture, Protocols And Enabling Applications In Internet Of Things (Iot)", ,INTERNATIONAL JOURNAL OF SCIENTIFIC & TECHNOLOGY RESEARCH VOLUME 8, ISSUE 11, NOVEMBER 2019 ISSN 2277-8616, 1767, IJSTR©2019, www.ijstr.org

1. INTRODUCTION

- **IoT layered functional architecture** (cont'd)
  - **Perception Layer (PL)** (a.k.a *Device Layer*)
    - includes physical objects (e.g., sensor devices)
      - the sensors could be (but not limited) RFID, 2D-barcode, or Infrared sensor depending upon objects identification method
    - identifies and collects objects specific information from sensor devices (location, temperature, orientation, motion, vibration, acceleration, humidity, chemical changes in the air, etc.)
    - passes the information to the upper *Network layer* for its transmission to the information processing system
  - **Network Layer (NL) (**a.k.a *Transmission Layer*)
    - securely transfers the information received from sensor devices to the *Middleware layer* for processing system
    - Large set of technologies and protocols available : wired/ wireless – IEEE 802.11, IEEE 802.15 (Bluetooth), Infrared, ZigBee, 3G/4G/5G, LPWAN, etc.

1. INTRODUCTION

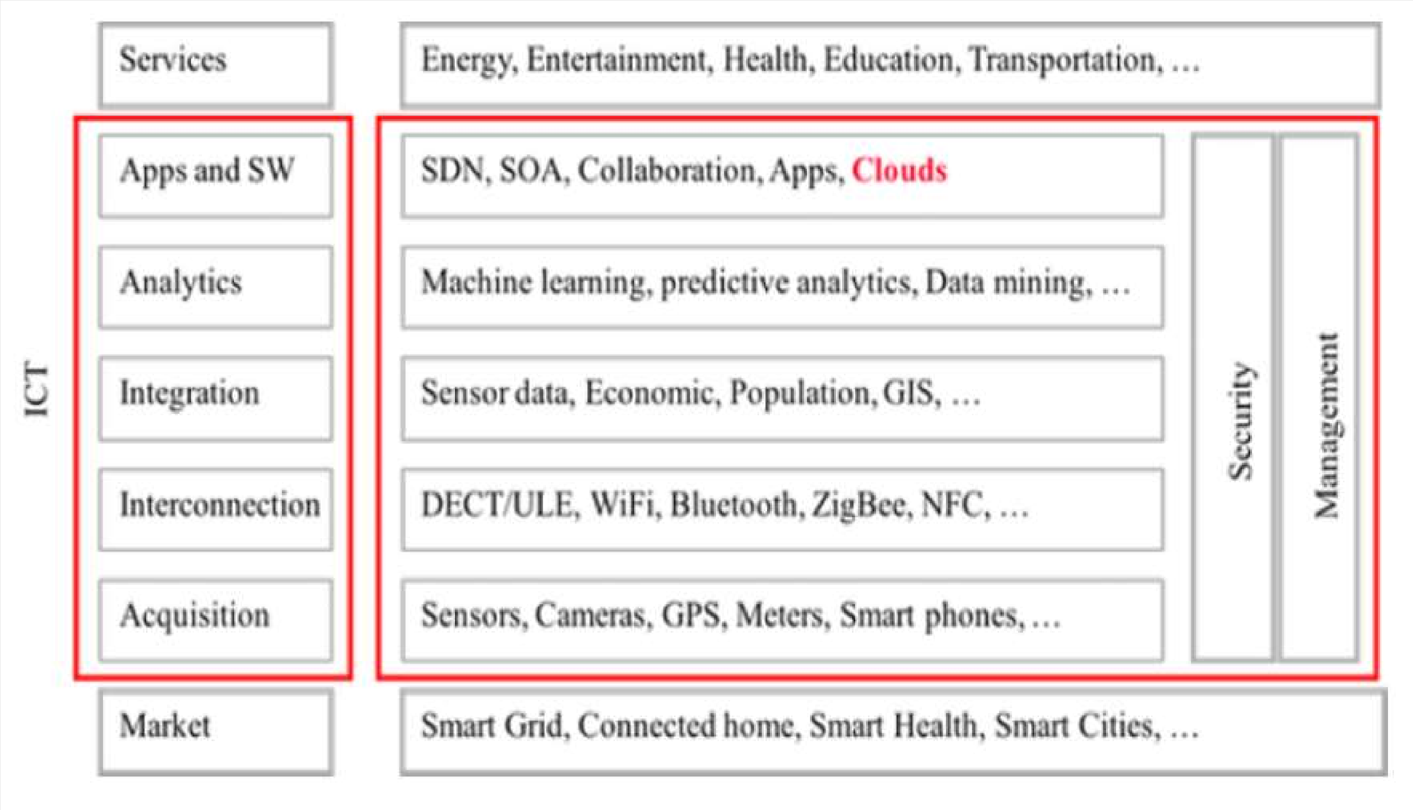
- **IoT layered functional architecture** (cont'd)
  - **Middleware Layer (ML)**
    - The IoT devices implement different type of services
      - Each device usually connects and communicates with only other devices which implement the same service type
    - ML is responsible for the *service management* and has a link to a *database*
      - It receives the information from NL and store it in the database
    - ML performs info processing and ubiquitous computation and takes automatic decision based on the results
  - **Application Layer (AL)**
    - provides global management of the application based on the objects info processed in the ML layer
    - The applications can be smart health, smart farming, smart home, smart city, industrial, intelligent transportation, etc.

1. INTRODUCTION

- **IoT layered functional architecture** (cont'd)
  - **Business Layer (BL)**
    - responsible for the management of overall IoT system including the applications and services
    - It builds **business models**, (like graphs, flowcharts, etc.) based on the data received from AL
    - **The real success of the IoT technology depends not only on technical solutions but also on some good business models**
      - able to meet the requirements of specific applications and also to accommodate various actors to cooperate
    - Based on the analysis of results, BL can determine the future actions and business strategies

1. INTRODUCTION

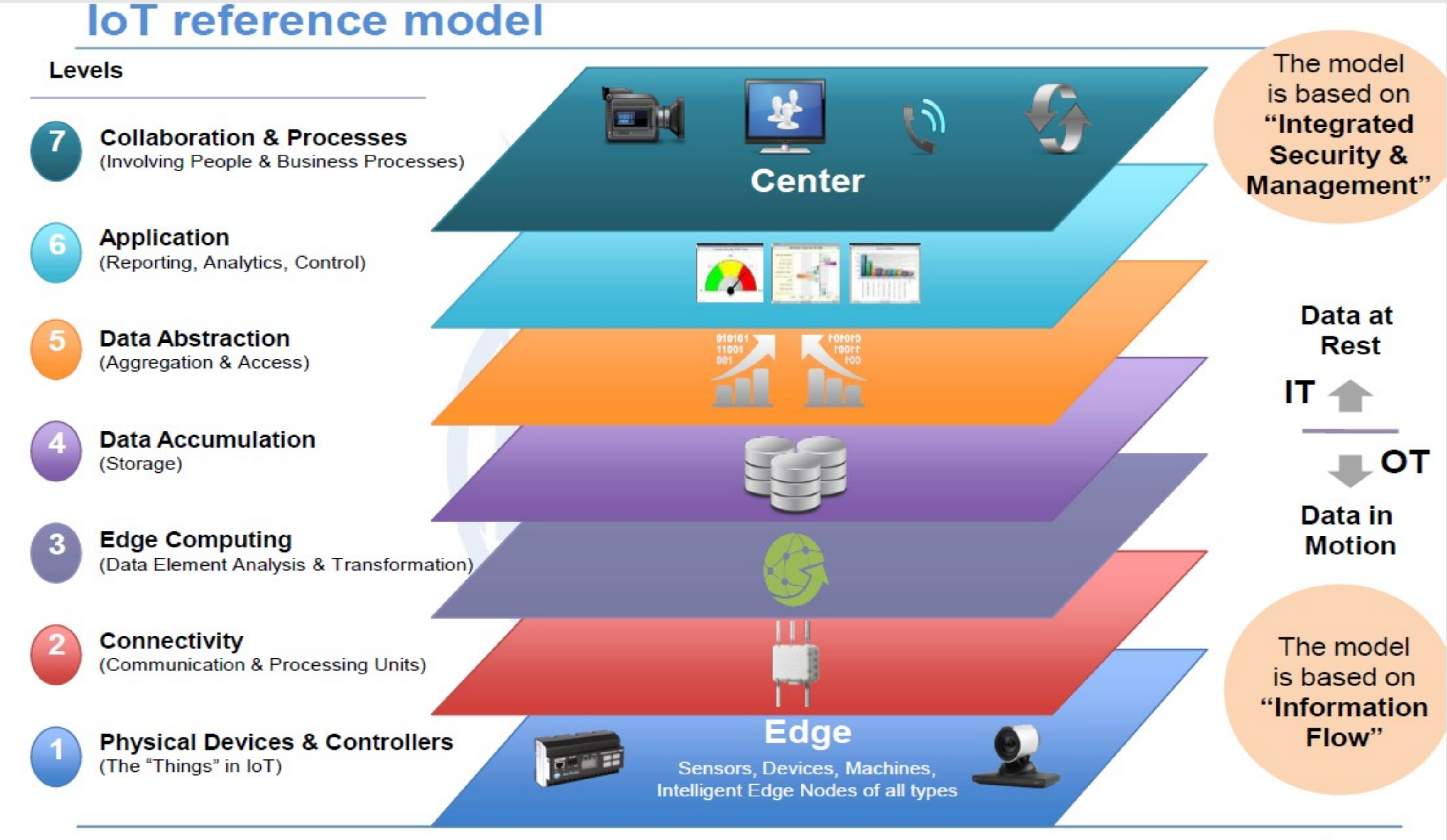
- **IoT ecosystem model - example**
  - Layered model also, but oriented more to the business vision



Source: T. Salman, R.Jain, "A Survey of Protocols and Standards for Internet of Things", https://arxiv.org/ftp/arxiv/papers/1903/1903.11549.pdf

1. INTRODUCTION

- **Detailed IoT architectural reference model (ITU)**



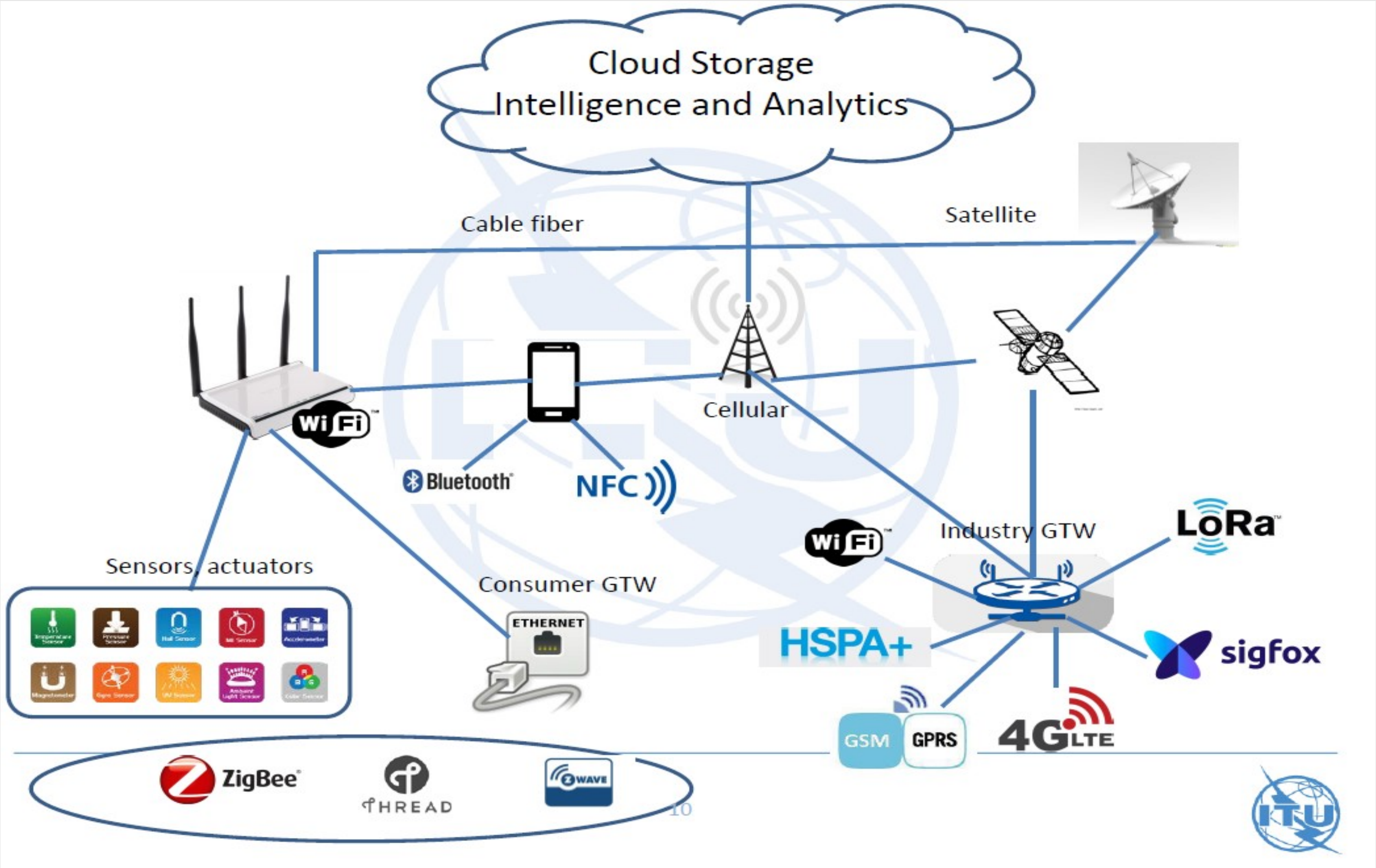
Source: ITU- S.Tabanne, "IoT Standards, Part I: IoT Technology and Architecture", September 2018, Bandung – Indonesia, https://www.itu.int/en/ITU-D/Regional-Presence/AsiaPacific/Documents/Events/2018/IoT-BDG/IoT%20Standards%20Part%20I%20Sami.pdf

Contents

1. Introduction
2. IoT connectivity
3. Short range technologies
4. Mid-long range technologies
5. Cellular technologies for IoT
6. 5G connectivity solutions for IoT
7. Selection of IoT communication technology
8. Conclusions

2. IoT Connectivity

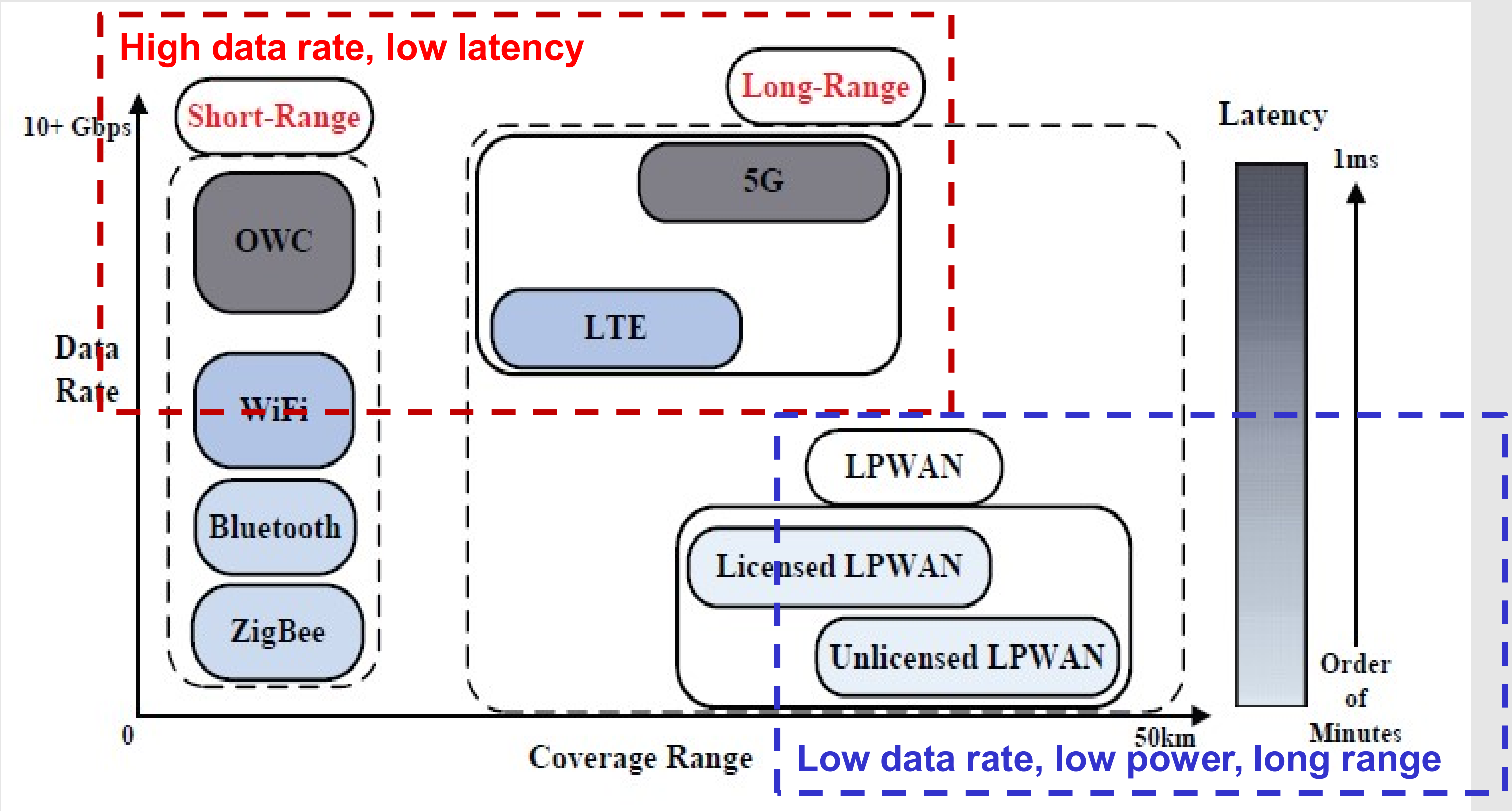
- **IoT Connectivity:** mainly deals with network layer functions
- **IoT general architecture (ITU- vision)**



Source: ITU, S.Tabanne, "Internet of Things: A technical overview of the ecosystem", "Developing the ICT ecosystem to harness Internet-of-Things (IoT)", 28-30 June 2017, Mauritius

2. IoT Connectivity

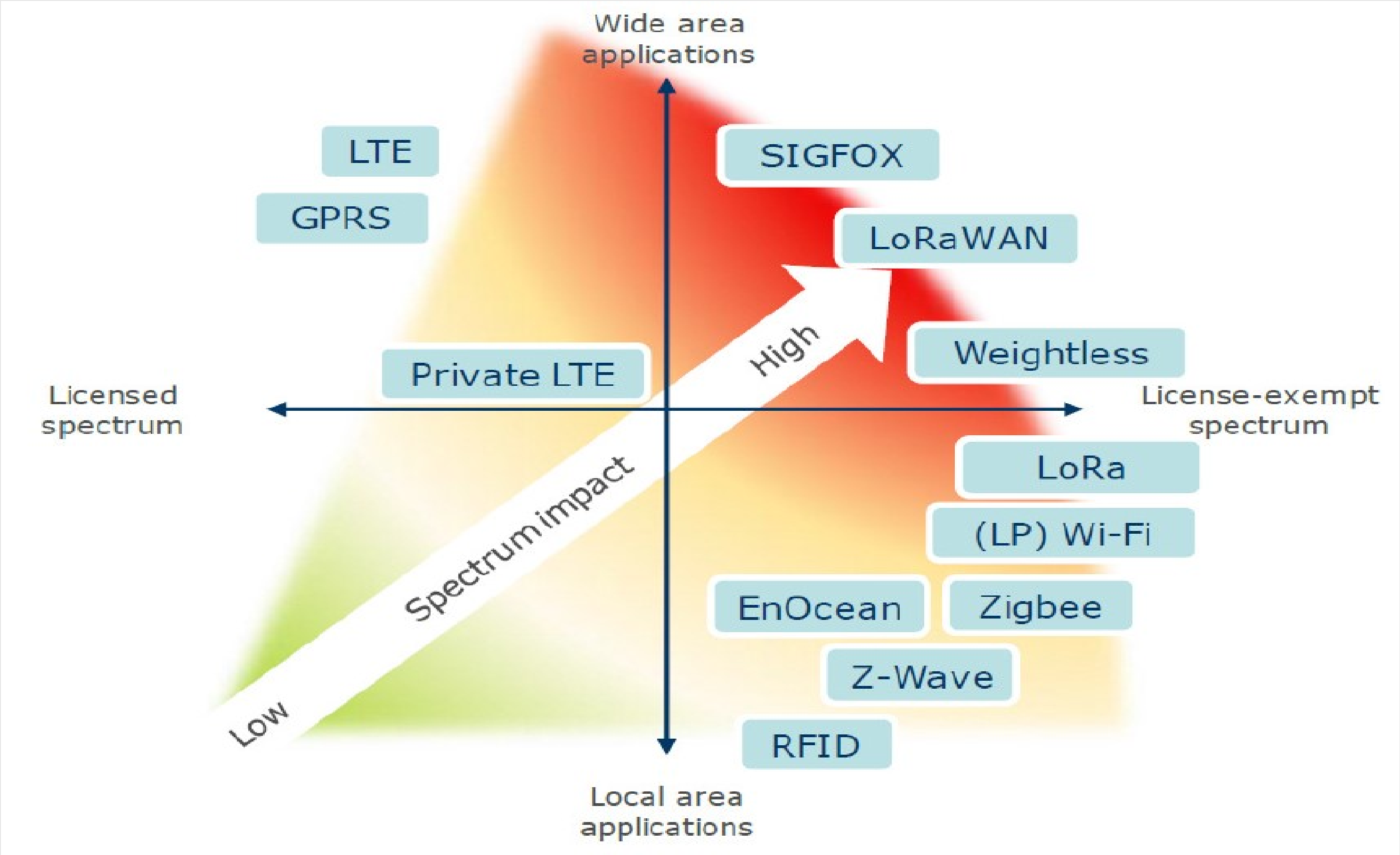
- **IoT connectivity- related technologies and protocols**
  - They belong to the first two lower architectural layers (perception, network)
  - Figure: IoT connectivity technologies in terms of : *data rate*, *coverage*, *latency*



Adapted from source: J.Ding, M.Nemati, C.Ranaweera, and J.Choi, "IoT Connectivity Technologies and Applications:A Survey" arXiv:2002.12646v1 [eess.SP] 28 Feb 2020.

2. IoT Connectivity

- **IoT wireless communication technologies**



Source: ITU-T S.Tabanne, "IoT systems overview", 30 Sept.-03 Oct. 2019, Bangkok, Thailand, https://www.itu.int/en/ITU-D/Regional-Presence/AsiaPacific/SiteAssets/Pages/Events/2019/ITU-ASP-CoE-Training-on-/IoT%20systems%20overview.pdf

2. IoT Connectivity

- **IoT connectivity- related protocols**
- **Focus: on the interconnection layer**
  - **Basic architectural layers: Data link**, **Network**, and **Transport/session** layers
    - *See the figure on next slide*
  - **Data and Control architectural planes**
    - **Data link layer**
      - connects two IoT elements (e.g., two sensors or a sensor and GW device that connects a set of sensors to the Internet)
      - multiple sensors could exist, to communicate and aggregate information before getting to the Internet
    - **Network layer**
      - Encapsulation protocols
      - Routing protocols
    - **Session layer**
      - enable messaging among various elements of the IoT communication subsystem
  - **Security and management architectural planes**
    - Depicted as vertical entities – meaning that they can interact with, and control all other layers

2. IoT Connectivity

- **IoT connectivity- related protocols** (cont'd)
  - **Protocol mapping on architectural layers**

Session	MQTT, SMQTT, CoRE, DDS, AMQP , XMPP, CoAP, IEC,…
Network	Encapsulation 6LowPAN, 6TiSCH, 6Lo, Thread… Routing RPL, CORPL, CARP
Datalink	WiFi, Bluetooth Low Energy, Z-Wave, ZigBee Smart, DECT/ULE, 3G/LTE, NFC, Weightless, HomePlug GP, 802.11ah, 802.15.4e, G.9959, WirelessHART, DASH7, ANT+, LTE-A, LoRaWAN, ISA100.11a, DigiMesh, WiMAX, …

Security: IEEE 1888.3, TCG, OAuth 2.0, SMACK, SASL, EDSA, ace, DTLS, Dice, …

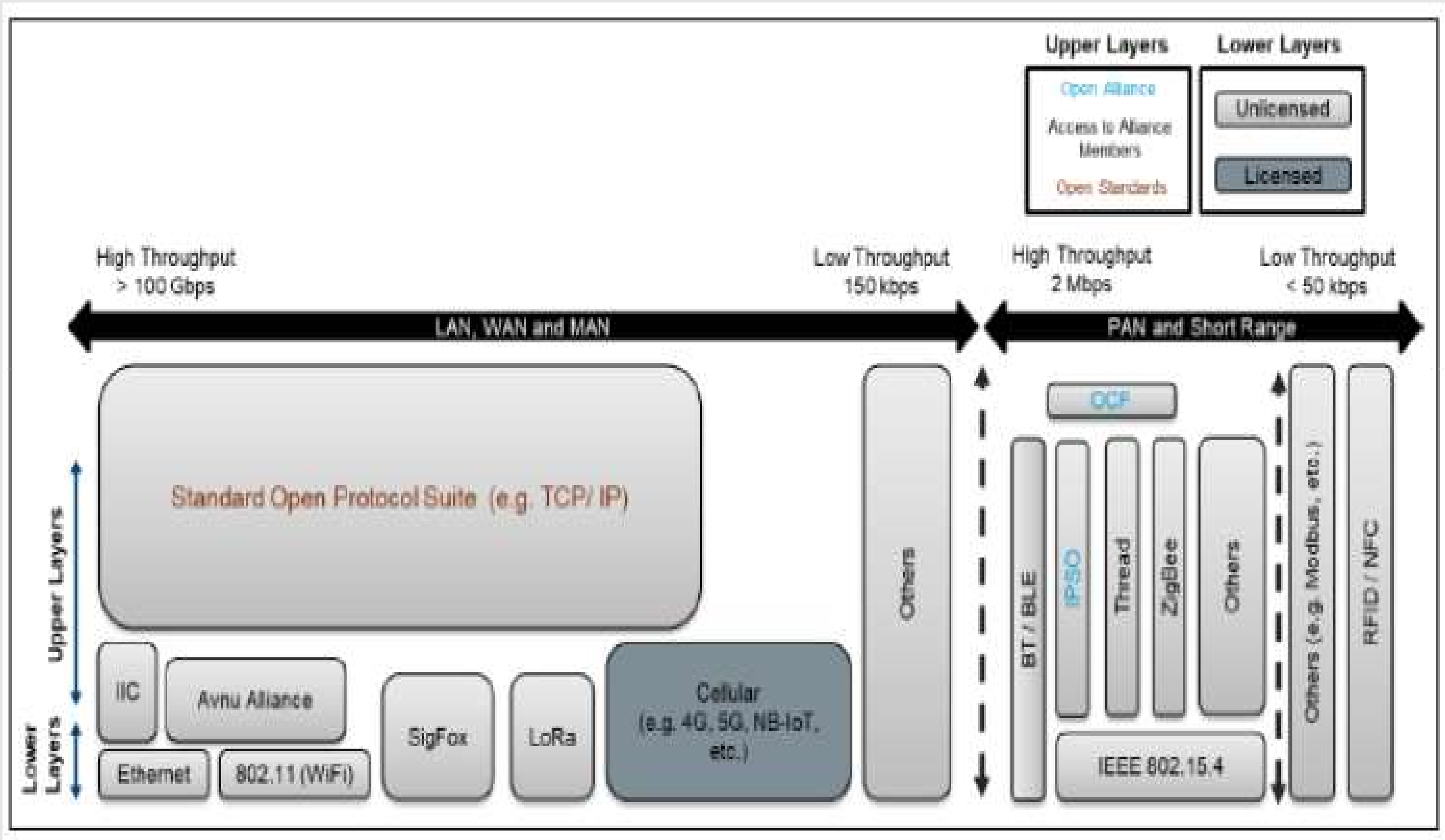
Management: IEEE 1905, IEEE 1451, TR-069, OMA-DM, LWM2M, IEEE 1377, IEEE P1828, IEEE P1856

See the list of acronyms

Sources: T.Salman, R.Jain "Networking Protocols and Standards for Internet of Things", 2015 https://www.cse.wustl.edu/~jain/cse570-15/ftp/iot_prot/, T. Salman, R.Jain, "A Survey of Protocols and Standards for Internet of Things", https://arxiv.org/ftp/arxiv/papers/1903/1903.11549.pdf

2. IoT Connectivity

- **IoT connectivity- related protocols** (cont'd)
  - **Technologies and connectivity standards**



Source: "IoT- High Level Functional Architecture"
https://www.mcmc.gov.my/skmmgovmy/media/General/pdf/MTSFB0652019-IOT-HIGH-LEVEL-FUNCTIONAL-ARCHITECTURE.pdf

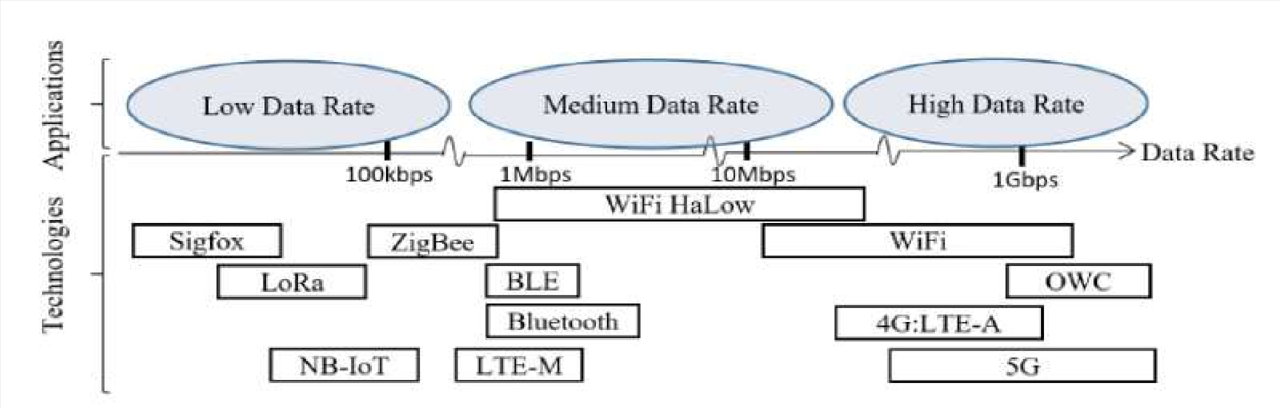
2. IoT Connectivity

- **IoT connectivity- related protocols** (cont'd)
  - **Range-related taxonomy (typical examples)**
  - **Fixed & Short Range**
    - RFID
    - Bluetooth/BLE
    - Zigbee
    - WiFi
    - IEEE 802.11ah, IEEE 802.15.4e
  - **Long Range technologies**
    - Non 3GPP Standards (LPWAN)
      - LoRaWAN
      - Sigfox
      - Weightless
      - RPMA
      - ….
    - **3GPP Standards**
      - LTE-M
      - NB-IOT
      - EC-GSM
      - 5G and IoT

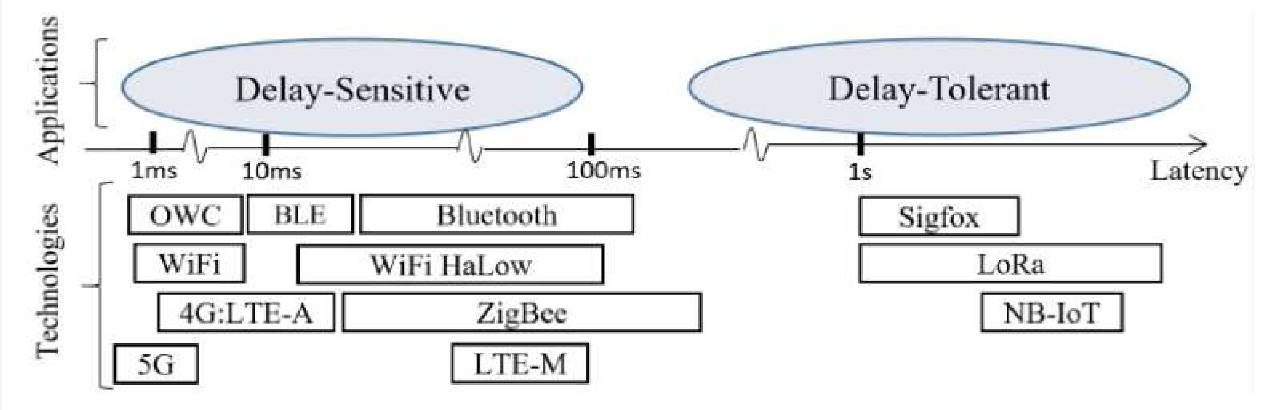
2. IoT Connectivity

- **IoT connectivity- related protocols** (cont'd)

IoT Protocols: different data rates capabilities



IoT Protocols: different latencies capabilities



Source: J.Ding, M.Nemati, C.Ranaweera, and J.Choi, "IoT Connectivity Technologies and Applications: A Survey" arXiv:2002.12646v1 [eess.SP] 28 Feb 2020.

2. Iot Connectivity

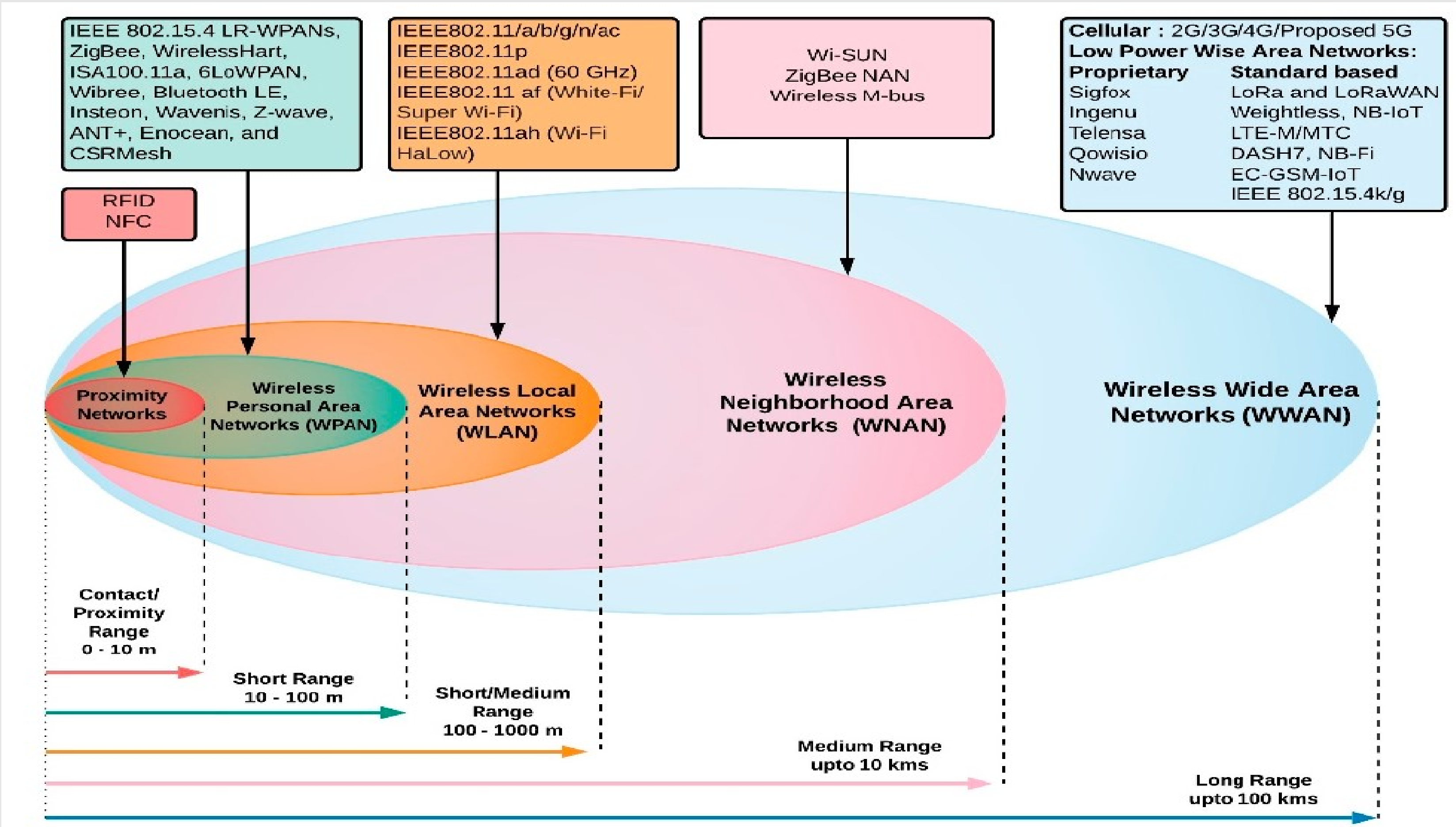
- **IoT connectivity- related protocols – quantitative comparison**

Technology	Frequency	Data Rate	Range	Power Usage	Cost
2G/3G	Cellular Bands	10 Mbps	Several Miles	High	High
Bluetooth/BLE	2.4Ghz	1, 2, 3 Mbps	~300 feet	Low	Low
802.15.4	subGhz, 2.4GHz	40, 250 kbps	> 100 square miles	Low	Low
LoRa	subGhz	< 50 kbps	1-3 miles	Low	Medium
LTE Cat 0/1	Cellular Bands	1-10 Mbps	Several Miles	Medium	High
NB-IoT	Cellular Bands	0.1-1 Mbps	Several Miles	Medium	High
SigFox	subGhz	< 1 kbps	Several Miles	Low	Medium
Weightless	subGhz	0.1-24 Mbps	Several Miles	Low	Low
Wi-Fi	subGhz, 2.4Ghz, 5Ghz	0.1-54 Mbps	< 300 feet	Medium	Low
WirelessHART	2.4Ghz	250 kbps	~300 feet	Medium	Medium
ZigBee	2.4Ghz	250 kbps	~300 feet	Low	Medium
Z-Wave	subGhz	40 kbps	~100 feet	Low	Medium

Source: "IoT Standards and Protocols", https://www.postscapes.com/internet-of-things-protocols/#protocols

2. IoT Connectivity

- **IoT connectivity- related protocols** (cont'd)
  - **Technologies comparison**



Source: B.S.Chaudhari, M.Zennaro and S.Borkar, "LPWAN Technologies: Emerging Application Characteristics, Requirements, and Design Considerations", Future Internet 2020, 12, 46; doi:10.3390/fi12030046 www.mdpi.com/journal/futureinternet

Contents

1. Introduction
2. IoT connectivity
3. Short-range technologies
4. Mid-long range technologies
5. Cellular technologies for IoT
6. 5G connectivity solutions for IoT
7. Selection of IoT communication technology
8. Conclusions

3. Short range technologies

- **Examples of short-range technologies**
- **WiFi (IEEE 802.11x)**
- **IEEE 802:11 standards** - family of technologies for wireless local area networks (WLAN).
  - IEEE 802.11 provides the last mile wireless broadband connections to the Internet with high data rates
  - **Several generations**
    - **IEEE 802:11a** (1999), max. data rate 54Mbps in 5GHz
    - **IEEE 802:11b** (1999) max data rate 11Mbps in 2.4GHz.
    - **IEEE 802:11g** (2003) max data rate of 54Mbps in 2.4GHz.
    - **IEEE 802:11n** (2008) up to 600Mbps
    - **IEEE 802:11ac** (2014) up to 7Gbps
      - wider coverage w.r.t. IEEE 802:11a/b/g by using dense modulations and MIMO technology.
- Drawback: the original WiFi standards are not suitable for IoT apps. (reason: frame overhead and high power consumption)

3. Short range technologies

- **IEEE 802:11ah (WiFi HaLow) (2017) – designed for IoT**
  - **Characteristics**
    - is a low overhead version of IEEE 802.11, lightweight to meet IoT extended coverage
    - **low-power consumption** requirements.
    - operates in the **unlicensed sub-1GHz** bands (excluding the TV white-space bands)
    - bandwidth occupation is 1MHz/2MHz – or 16MHz in some countries
    - provide connectivity to thousands of devices with coverage of **up to 1km**
    - **max data rate is about 300 Mbps** utilizing 16MHz bandwidth

  - **MAC layer features**

    - **Synchronization Frame**
      - Only valid stations with valid channel information can transmit by reserving the channel medium
      - A station can transmit if it receives the duration field packet correctly
      - If not correct reception, then it waits for a duration (*Probe Delay)*
      - *Probe Delay* can be configured by the AP in 802.11ah and announced by transmitting a sync frame at the beginning of the Tx cycle

3. Short range technologies

- **IEEE 802:11ah (WiFi HaLow) (2017)**
-
  - **MAC layer features** (cont'd)
    - **Efficient Bidirectional Packet Exchange**
      - uplink and downlink communication between Aps and the sensors
      - this feature reduces power consumption as the sensors will go to sleep as soon as they finish their communication.
    - **Short MAC Frame**
      - reduces frame size from 30 bytes in traditional IEEE 802.11 to 12 bytes
      - The frame has low less overhead frame - suitable for IoT application
    - **Null Data Packet**
      - IEEE 802.11 had (ACK) frames of 14 bytes with no data (high overhead)
      - 802.11ah solution: introducing a tiny signal (preamble), which is used in place of ACKs and is much less in size
    - **Increased Sleep Time**
      - Design for low power → it allows a long sleep period and waking up infrequently to exchange data only

3. Short range technologies

- **Bluetooth**
  - **Bluetooth IEEE 802.15.1** – (originally , from Nokia- late 90s) in-house project.
  - Now is a popular wireless technology used in a small area (~100m coverage range)
  - **Characteristics**
    - Use of short data packets over several channels of bandwidth 1MHz
    - between 2.402 GHz to 2.480 GHz
    - variable data rate : 1Mbps to 3Mbps
    - high power consumption of classic Bluetooth → impractical for IoT use-cases
  - Solution: **Bluetooth Low Energy (BLE)** introduced in **Bluetooth 4.0** for low-powered IoT devices
  - **Characteristics**
    - optimized for short burst data transmissions.
    - defines 40 usable channels divided into 3 primary advertisement channels and 37 data channels
    - two multiple access schemes – FDMA and TDMA based polling

3. Short range technologies

- **Bluetooth** (cont'd)

- **Bluetooth 5.0** – enhancement version upon BLE in terms of data rates and range, by using increased transmit power or coded physical layer
  - compared to Bluetooth 4.0, max 4x transmission range increase and a max data rate of 2Mbps
- **Bluetooth 5.1:** enhanced direction finding feature of BLE to better understand signal direction and achieve sub-meter location accuracy

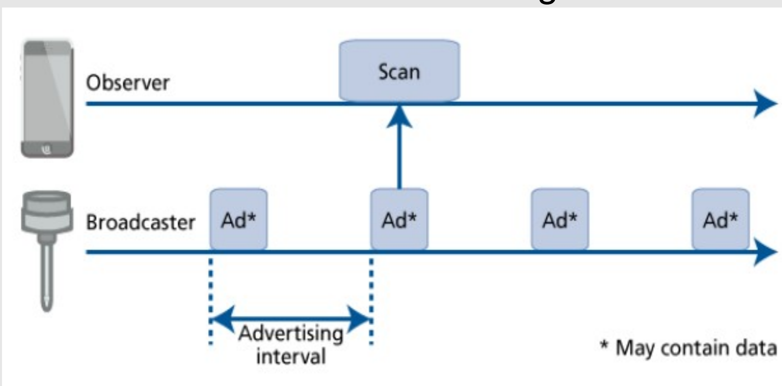
- **BLE mesh networking** – (2017)
  - BLE mesh topology operates on a managed flood routing principle for forwarding messages from one device to another
  - The maximum number of devices in any given Bluetooth mesh network is 32,767, with up to 16,384 groups. Only devices defined as relay forward received messages further into the network
  - Time-to-live (TTL) mechanisms (max TTL value=127) are used to avoid loops
  - Backwards compatibility Is defined in BLE mesh for BLE devices.
    - (the BLE devices that do not support BLE mesh still can be connected to a mesh network
  - A friendship feature enables power-limited BLE devices to become part of a mesh network with the help of battery-powered devices

  - Bluetooth and BLE frequent use cases: low-cost indoor positioning audio streaming, health and wellness monitoring, and controlling and automating

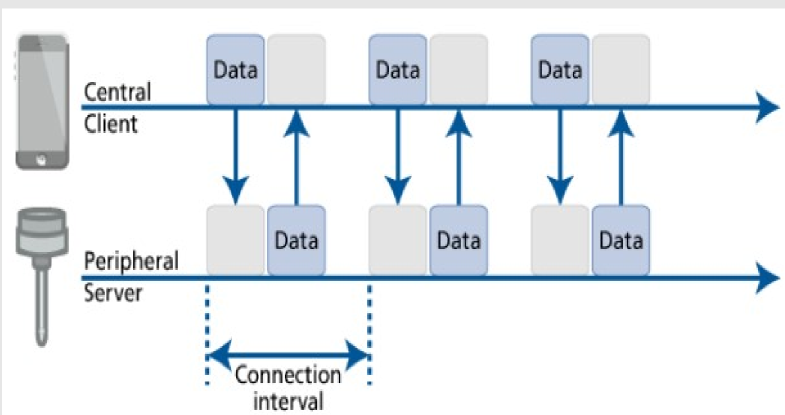
3. Short range technologies

- **BLE** (cont'd)

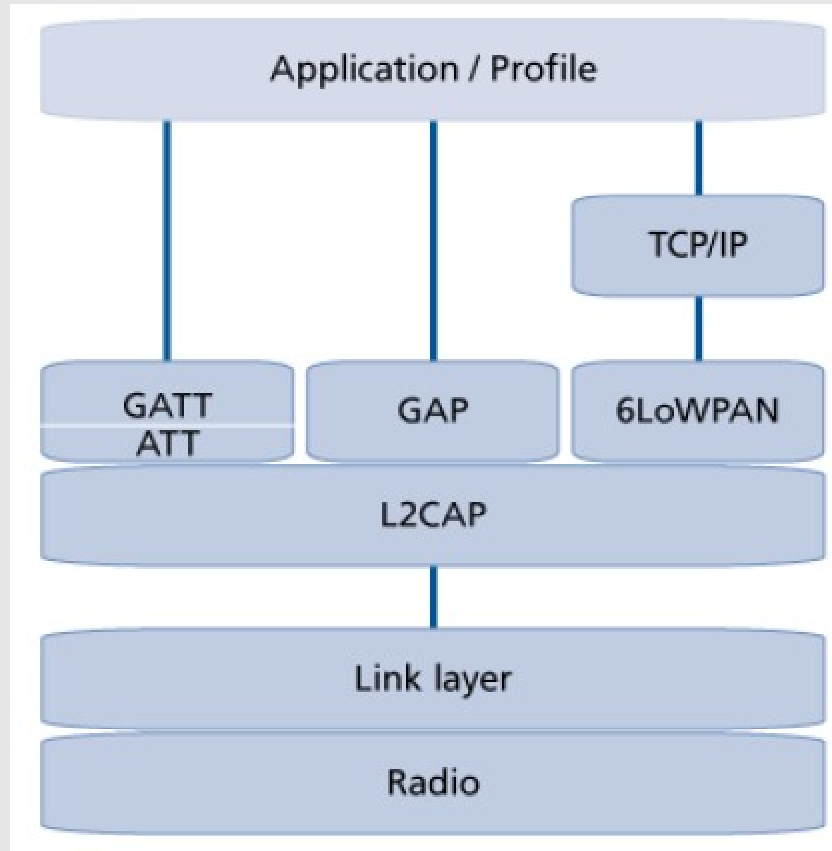
BLE advertising feature



BLE connections



BLE architectural stack



Source: M.Andersson , "Use case possibilities with Bluetooth low energy in IoT applications "White paper www.u-blox.com , UBX-14054580 - R01

3. Short range technologies

- **BLE** (cont'd)
- **BLE architectural stack**
  - **L2CAP (Logical Link Control and Adaptation Protocol).**
    - responsible for multiplexing data between various higher layer protocols as well as segmentation and reassembly of data packets
  - **GAP (Generic Access Protocol)**
    - defines the generic procedures related to device discovery and link management when connecting to Bluetooth devices.
  - **GATT (Generic Attribute Protocol)**
    - Provides profile and service discovery for BLE Bluetooth low energy
    - The described procedures show how to use the **ATT (Attribute Protocol)** for service discovery as well as how to read and write attributes (data)
    - Services and profiles are developed on top of GATT
  - **6LoWPAN (IPv6 over Low power Wireless Personal Area Networks)**
    - An alternative to GATT is to use TCP/IP with 6LoWPAN
    - 6LoWPAN can be used to compress the IP messages sent over BLE to save on size requirements and power consumption

3. Short range technologies

- **ZigBee**
- **Wireless mesh** network protocol developed by the **ZigBee Alliance**
- **Main characteristics**
  - The relationship between ZigBee and IEEE 802.15.4-2003 can be compared to that existing between Wi-Fi Alliance and IEEE 802.11
  - **one of the main IoT communication standards**
  - differs from other protocols for its ability to combine good autonomy (low power) and a fair level of security (128-bit integrated encryption)
  - used for **short range communications ;** thanks to the IEEE 802.15.4 standard, it offers a high degree of interoperability
  - **low transfer rates and low power consumption**
  - **small antennas with low power and low power consumption for WPAN** (Wireless Personal Area Networks)
  - it can support several application profiles for specific communication
    - **energy (Smart Energy)**
    - **home automation (ZigbeeLightLink)**
  - economic and **self-managed Wireless Mesh Network** for the control of a network of sensors and actuators in order to create automation and home automation scenarios

3. Short range technologies

- **ZigBee** (cont'd)
- **Standard ZigBee**
- Several versions of ZigBee
  - ZigBee 2006 specification
  - ZigBee 2007 specification with the popular ZigBee PRO feature set.

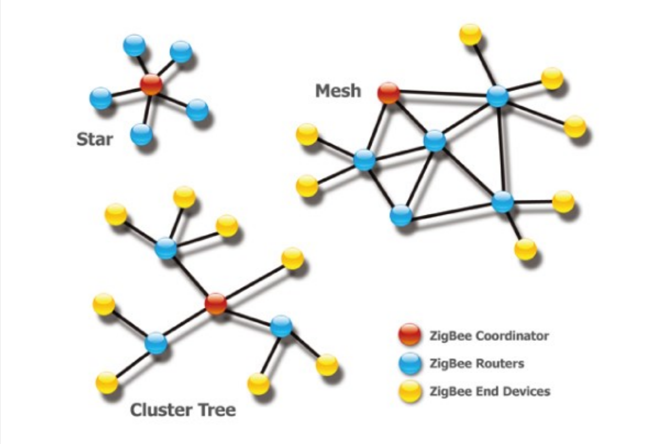
  - ZigBee PRO 2015
    - These specs have been integrated into the ZigBee 3.0 version
    - this new version eliminates all the problems that slowed down its deployment, offering full interoperability between a wide variety of devices that can now work together and interact with each other within the home
    - ZigBee 3.0 makes it easy for developers to build applications and services for the smart home and IoT
    - The standard includes: ZigBee Home Automation, ZigBee Light Link, ZigBee Building Automation, ZigBee Retail Services, ZigBee Health Care and ZigBee Telecommunication

  - ZigBee PRO 2017

3. Short range technologies

- **ZigBee** (cont'd)
- **Network topology**
- The Network layer supports three network topologies:
  - **Star**: coordinator + end nodes (devices) that communicate directly with the coordinator
  - **Tree:** the network can be extended through the use of ZigBee Routers
    - End devices can therefore be connected to both the Coordinator and the Routers
    - A hierarchical routing strategy is used in the tree network
    - beacon oriented communication can also be used
  - **Mesh:** the networks, such as tree networks, can also be extended through the use of ZigBee Routers
    - however, hierarchical routing strategies are not used, but allow full peer-to-peer communication
    - ZigBee Routers in mesh networks do not currently emit normal IEEE 802.15.4 beacons

Topologies: star, mesh, cluster tree



Source: G.Mazzi, "Zigbee Wireless Communication Protocol" 2019 EDALAB, https://edalab.it/en/zigbee-wireless-communication/

3. Short range technologies

- **ZigBee** (cont'd)
- IEEE 802.15.4 defines two types of devices:
  - **FFD (Full Function Device)**
    - nodes that can perform all the functions defined by the ZigBee standard and in particular are nodes that can act as relays
  - **RFD (Reduced Function Device)**
    - nodes ("leaf nodes") that can only perform a limited number of functions- energy saving
    - they cannot be relays but only act as sources or final recipients of traffic
- **ZigBee Node types**
  - **Coordinator**: - unique FFD type device
    - it is the first to be activated
    - acts as the IEEE 802.15.4 PAN coordinator
    - The IEEE 802.15.4 PAN Coordinator is responsible for training the network.
    - ZigBee Coordinator functions:
      - selects the channel to be used in the network
      - select the Personal Area Network (PAN) ID
      - assigns addresses to other nodes
      - allows other nodes to join or leave the network
      - takes care of transferring application packages keeps a list of nearby nodes and routers

3. Short range technologies

- **ZigBee** (cont'd)
- **ZigBee Node types (cont'd)**

  - **ZigBee Router**: (FFD type device)
    - Router-type nodes are used only in tree and mesh networks and allow to extend the network coverage
    - A router can forward packets to other nodes to find the best path
    - It can perform all the functions of a coordinator except establishing a network

  - **ZigBee End Device (**RFD type device)
    - simple devices that send and receive application packages but cannot perform other functions in the network
    - can be connected to a router or coordinator.
    - They are usually battery-operated devices that only consume power during transmission
    - the transmission time of an end device is usually short
    - an end device can join or leave a network

3. Short range technologies

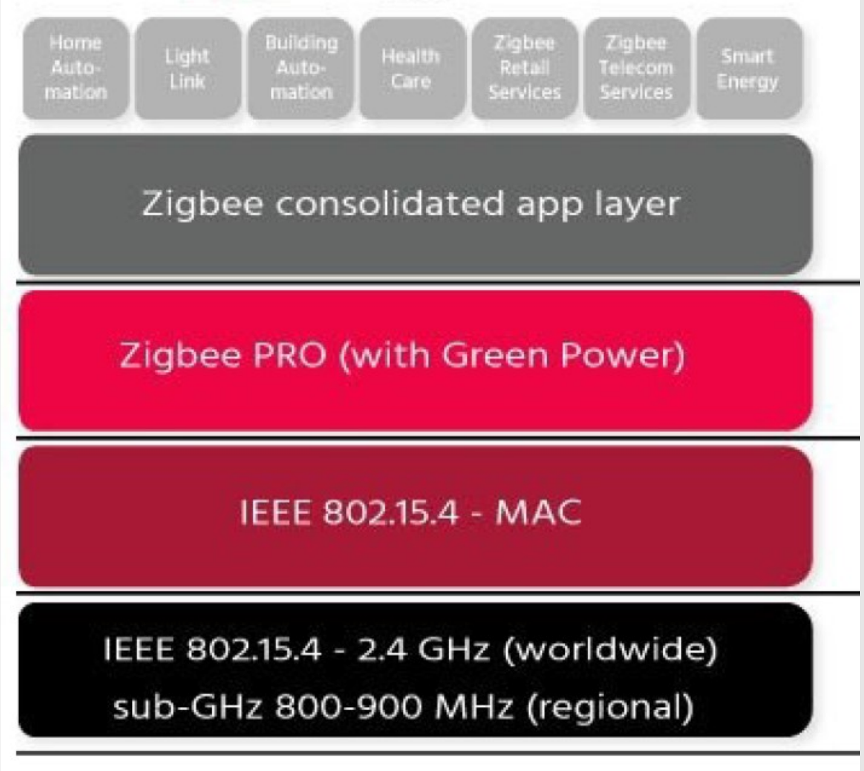
- **ZigBee** (cont'd)

▪ZigBee devices comply with IEEE 802.15.4-2003 Low-Rate Wireless Personal Area Network (WPAN) std.

▪This standard specifies the PHY and the part of MAC

▪operability in the 2.4 GHz, 915 MHz and 868 MHz bands

▪The ZigBee protocols support "beacon enabled" and "non-beacon enabled" networks



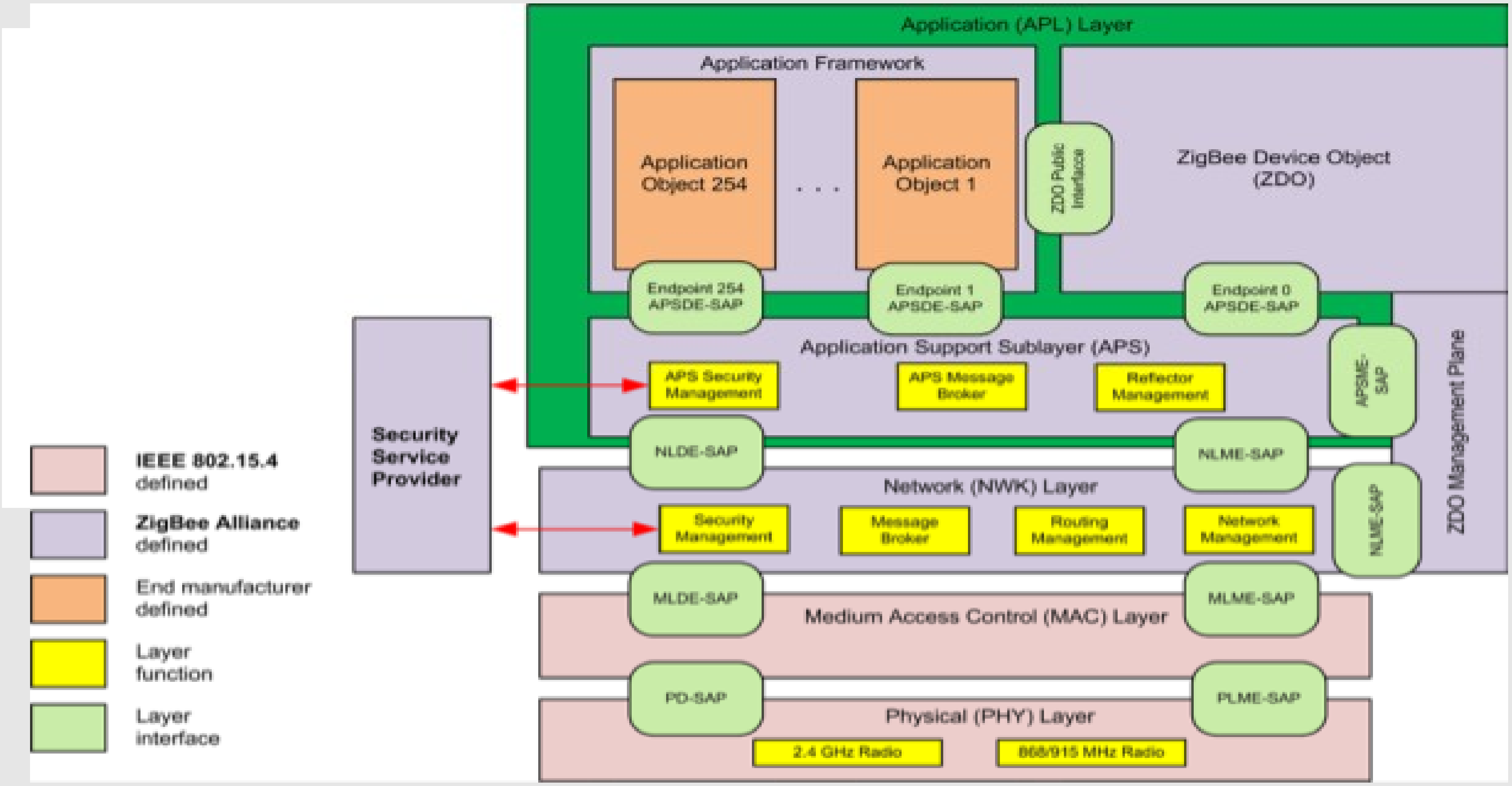
Typical ZigBee architectural stack

Source: G.Mazzi, "Zigbee Wireless Communication Protocol" 2019 EDALAB, https://edalab.it/en/zigbee-wireless-communication/

3. Short range technologies

- **ZigBee** (cont'd)

  Architectural stack



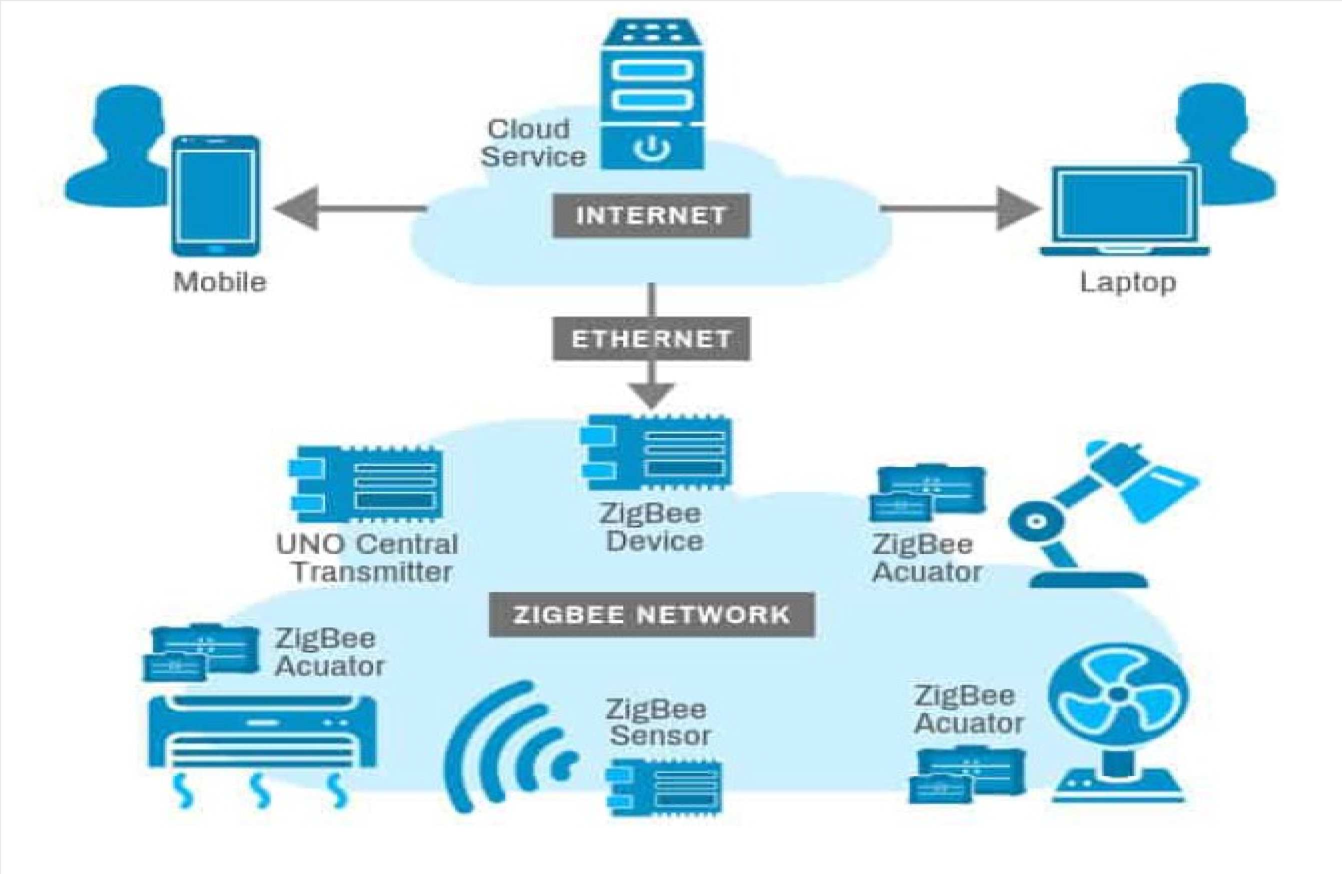
ZigBee Stack Architecture [Std-ZIG-15]

SAP- Service Access Point

Source: G.Mazzi, "Zigbee Wireless Communication Protocol" 2019 EDALAB, https://edalab.it/en/zigbee-wireless-communication/

3. Short range technologies

- **ZigBee** (cont'd)
  - **Deployment example**



Source: G.Mazzi, "Zigbee Wireless Communication Protocol" 2019 EDALAB, https://edalab.it/en/zigbee-wireless-communication/

3. Short range technologies

- **Optical wireless communication (OWC)**

  - Designed for indoor IoT device connectivity (high bandwidth and low latency
  - Using **visible light** (VL), **infrared** (IR), or **ultraviolet** (UV) spectrum
  - Low-complex optical wireless links that can operate at **multi-gigabits** per second data rate in an energy efficient manner under a typical in room environment for various applications

  - The **high-speed OWC links** provide connectivity for many IoT application where WiFi/other wireless connectivity are limited
  - Application examples: tactile Internet, wireless BANs

  - OWC links are also proposed to provide connectivity for
    - remotely operated underwater vehicles,
    - dense urban environments,
    - autonomous vehicle communications, and connecting sensors in chemical and power plants where usage of radio frequency is restricted

  - **Two major OWC technologies** can be identified
    visible light communication(VLC),
    beam-steered infrared light communication (BS-ILC)

3. Short range technologies

- **Optical wireless communication (OWC)** (cont'd)
- **Visible light communication(VLC** VLC
  - It uses the laser (LED) illumination infrastructure
  - Multi-gigabit wireless connectivity - by employing diverse modulation scheme ranging from simple on-off keying (OOK) to quadrature amplitude modulation (QAM) orthogonal frequency division multiplexing (OFDM)
  - VLC was initially standardized (2011) as IEEE 802.15.7
  - further developments
    - low data rate apps., IEEE 802.15.7m - using the optical camera communications (OCC) that support connectivity for a range of 200m
    - high data rate apps., IEEE 802.15.13 - enabling multi gigabit data rate connectivity over few tens of meters
  - Recent: 100 Gbps VLC links -using laser diodes (LD) instead of using LEDs
  - The light fidelity (LiFi) (popular) is also developed based on VLC technology
  - There are several commercial VLC products available – e.g., pure LiFi

3. Short range technologies

- **Optical wireless communication (OWC)** (cont'd)
- **Beam-steered infrared light communication (BS-ILC)**

  - Infrared light communication standardized by IrDA and IEEE in early 90s
  - It was included in the initial WiFi standard (IEEE 802.11)

  - The IR beams are turned on when needed, for example when there are applications/users to be served.
    - Multiple beams can be used to serve several users in the same room
    - Coverage of a single beam – two variants
      - a single beam is used to serve a single user application/user within a room
        - no MAC is needed - as no shared medium is used
      - multiple users are served within a wide IR beam
        - MAC protocols are needed

  - Different types of BS-ILC systems proved multi-gigabit connectivity for a range of 3m using diverse modulation formats and different beam-steering techniques using active/passive beam steering devices

3. Short range technologies

- **Comparison between short range technologies**

	Bluetooth	Zigbee	WiFi	OWC
RA protocol	TDMA based polling FDMA	CSMA/CA	CSMA/CA	CSMA/CA TDMA/CDMA
Modulation type	GFSK/DQPSK/DPSK	BPSK/OQPSK	BPSK/QPSK/QAM	OOK/OFDM
Maximum data rate	Classic: 3Mbps BLE: 2Mbps	250kbps	7Gbps	10Gbps using LED 100Gbps using LD
Coverage	Classic: 100m BLE: 240m	100m	Conv.: 100m 802.11ah: 1km	200m

Modulation types

GFSK: Gaussian frequency shift keying
DQPSK: differential quadrature phase shift keying;
DPSK: differential phase shift keying
BPSK: binary phase shift keying
OQPSK: offset quadrature phase-shift keying;
QPSK: quadrature phase shift keying
CDMA: code-division multiple access.

Source: J.Ding, M.Nemati, C.Ranaweera, and J.Choi, "IoT Connectivity Technologies and Applications: A Survey" arXiv:2002.12646v1 [eess.SP] 28 Feb 2020.

Contents

1. Introduction
2. IoT connectivity
3. Short range technologies
4. Mid-long range technologies
5. Cellular technologies for IoT
6. 5G connectivity solutions for IoT
7. Selection of IoT communication technology
8. Conclusions

4. Mid-long range technologies

- **LPWAN**
- **Low–Power, Wide-Area Networks (LPWAN)** - designed to support a major portion of the billions of devices forecasted for IoT
- **Common LPWAN characteristics**
  - **Low power** (the network and end devices should consume low energy)
  - **Communication,** deployment and management cost - essential issue
  - The whole eco-system needs strong **security** mechanism
  - **Built-in localization** is a plus for indoor deployments
  - Network deployment in dense urban areas → **Robust (interference resistance)** modulation is necessary
  - End of the day, nodes generate data and this has to be handled properly

- **Critical factors**
  - Network architecture
  - Communication range
  - Battery lifetime or low power
  - Robustness to interference
  - Network capacity (maximum number of nodes in a network)
  - Network security
  - One-way vs two-way communication
  - Variety of applications served

4. Mid-long range technologies

- **LPWAN** (cont'd)
  - **LPWAN technologies versus LAN and Cellular**

	Local Area Network Short Range Communication	Low Power Wide Area (LPWAN) Internet of Things	Cellular Network Traditional M2M
Share	40%	45%	15%
Pros	Well established standards In building	Low power consumption Low cost Positioning	Existing coverage High data rate
Cons	Battery Live Provisioning Network cost & dependencies	High data rate Emerging standards	Autonomy Total cost of ownership
Technologies	Bluetooth 4.0, ZigBee, WiFi	LoRa	GSM, 3G+ / H+, 4G

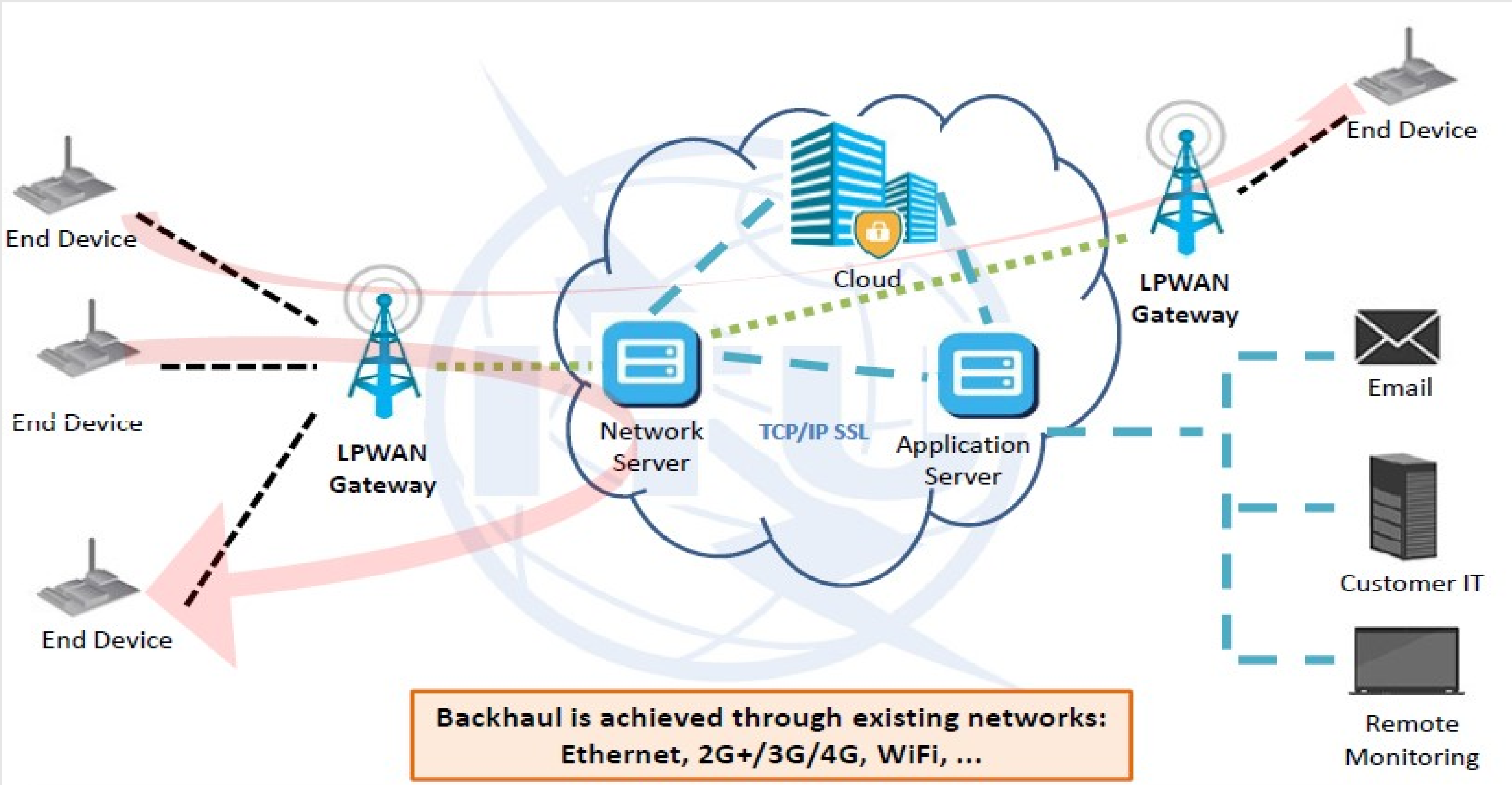
Source: Lora Alliance, "A technical overview of LoRa and LoRaWAN" Technical Marketing Workgroup 1.0, 2015, November

- **LPWAN** (cont'd)
  - **General** Requirements

Source: ITU- S.Tabanne, "IoT Standards, Part I: IoT Technology and Architecture", September 2018, Bandung – Indonesia, https://www.itu.int/en/ITU-D/Regional-Presence/AsiaPacific/Documents/Events/2018/IoT-BDG/IoT%20Standards%20Part%20I%20Sami.pdf

4. Mid-long range technologies

- **LPWAN** (cont'd)
  - **LPWAN architecture**



Source: ITU- S.Tabanne, "IoT Standards, Part I: IoT Technology and Architecture", September 2018, Bandung – Indonesia, https://www.itu.int/en/ITU-D/Regional-Presence/AsiaPacific/Documents/Events/2018/IoT-BDG/IoT%20Standards%20Part%20I%20Sami.pdf

4. Mid-long range technologies

- **LPWAN** (cont'd)
  - **LPWAN technology types**
    - **Unlicensed LPWAN**
      - employ unlicensed spectrum resources over the industrial, scientific, and medical (ISM) band.
      - LPWAN providers do not necessarily pay for spectrum licensing, as a result it reduces the cost of deployments.
      - **LoRa** and **Sigfox** are the two biggest competitors
    - **Licensed LPWAN**
      - using the licensed spectrum
      - standardized by the 3GPP
      - LTE-M and NB-IoT are the most promising stds introduced in 3GPP Rel-13 in 2016

4. Mid-long range technologies

- **LPWAN** (cont'd)
  - **Wide area M2M tecbhnologies and IoT (llicensed and unlicensed)**

Carrier frequency		Technology	Channel bandwidth	Representative data rate	Link budget target or max. range
Licensed cellular		LTE Cat. 0	20 MHz	DL: 1 Mb/s UL: 1 Mb/s	140 dB
		LTE Cat. M	1.4 MHz	DL: 1 Mb/s UL: 1 Mb/s	155 dB
		NB-IoT	200 kHz	DL: 128 kb/s UL: 64 kb/s	164 dB
		EC-GSM	200 kHz	DL: 74 kb/s UL: 74 kb/s	164 dB
Unlicensed	2.4 GHz	Ingenu RPMA	1 MHz	UL: 624 kb/s DL: 156 kb/s	500 km line of sight
	Sub-1 GHz	LoRa chirp spread spectrum	125 kHz	UL: 100 kb/s DL: 100 kb/s	15 km rural 5 km urban
	Sub-1 GHz	Weightless-N	200 Hz	UL: 100 b/s	3 km urban
	Sub-1 GHz	Sigfox	160 Hz	UL: 100 b/s	50 km rural 10 km urban

Source: H. S. Dhillon et al., "Wide-Area Wireless Communication Challenges for 4th3e Internet of Things," IEEE Communications Magazine, February 2017

4. Mid-long range technologies

- **Long Range WAN (LoRaWAN)**
- **LoRa & LoRaWAN Technologies**
  - **LoRa - the PHY layer in OSI RM** - specifies a RF modulation – PHY
    - **Frequency band ISM: 433 MHz, 868 MHz, 915 MHz**
    - LoRa modulation is a variation of chirp spread spectrum where the rate of frequency increase/decrease is modulated by symbol
    - Increases its resistance to noise
    - Allows multiple parallel transmissions in one frequency
    - Devices broadcast to all gateways. The best gateway replies back

  - **LoRaWAN**
    - LoRaWAN is a MAC standardized by LoRa Alliance which coordinates the medium
    - It solves management issues of the medium and network congestion
    - A node using LoRaWAN protocol can have features such as:
      - **Channel management, Energy efficiency, Adaptive data rate, Security, GPS-Free geolocation**
    - Centralized management and media access control using a “server”

4. Mid-long range technologies

- LoRaWAN (cont'd)
- **Long Range (LoRa) - Physical Layer**
  - **Long range** communication (up to 15 Km)
    - A single gateway or base station can cover entire cities or hundreds of square kilometers
  - Many legacy wireless systems use FSK modulation as the PHY layer (very efficient for achieving low power)
  - **LoRa modulation: a version of *Chirp Spread Spectrum*** (CSS) with a typical channel bandwidth of 125KHz
    - maintains the same low power characteristics as FSK but significantly increases the communication range
    - chirp spread spectrum has been used in military and space communication for decades
  - **High Sensitivity** (End Nodes: Up to -137 dBm, Gateways: up to -142 dBm)
  - **Strong indoor penetration**: With High Spreading Factor, Up to 20dB penetration (deep indoor)
  - Occupies the entire bandwidth of the channel to broadcast a signal, making it **robust to channel noise**
  - **Resistant to Doppler effect**, multi-path and signal weakening

4. Mid-long range technologies

- **Long Range WAN (LoRaWAN)**
- **LoRa & LoRaWAN Technologies**

- **LoRaWAN Network topology** : **star-of-stars**
  - Many existing deployed networks utilize a mesh network
    - Mesh: the individual end-nodes forward the information of other nodes
      - to increase the communication range
      - to increase cell size of the network
      - This solution also adds complexity, reduces network capacity, and reduces battery lifetime
        - as nodes receive and forward information from other nodes that is likely irrelevant for them
      - **Long range star** architecture better preserves the battery lifetime when long-range connectivity can be achieved

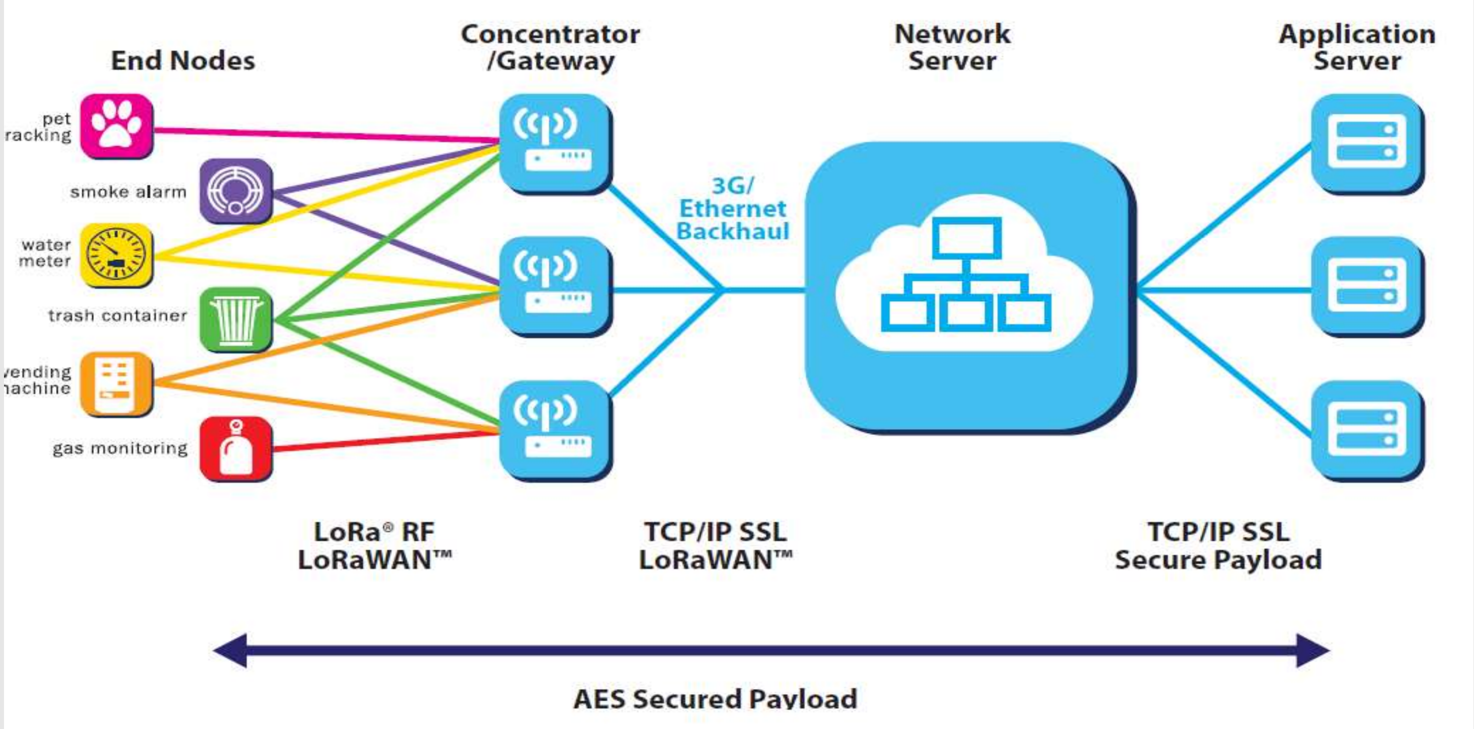
4. Mid-long range technologies

- **LoRaWAN**
- **LoRaWAN Architecture**
  - **Architectural main components**
    - **network servers,**
    - **gateways (GWs)**
    - **end nodes**
  - End nodes communicate with the network server (or data server) via GWs
  - Node-to-GW communication can be either LoRa or FSK modulation with different data rates and channels
  - Network servers manage the GWs through standard IP technology
  - Data frames sent by the end node are received by GWs and routed towards the cloud network server via some backhaul (cellular, Ethernet, Wi-Fi, or satellite)

  - The network nodes are not associated with a specific GW
    - data transmitted by a node is typically received by multiple gateways.
  - The intelligence and complexity is pushed to the **network server**, which
    - manages the network and will filter redundant received packets
    - perform security checks
    - schedule acknowledgments through the optimal gateway
    - and perform adaptive data rate, etc.
  - If a node is mobile there is no handover needed from gateway to gateway, which is a critical feature to enable asset tracking applications–a major target application vertical for IoT

4. Mid-long range technologies

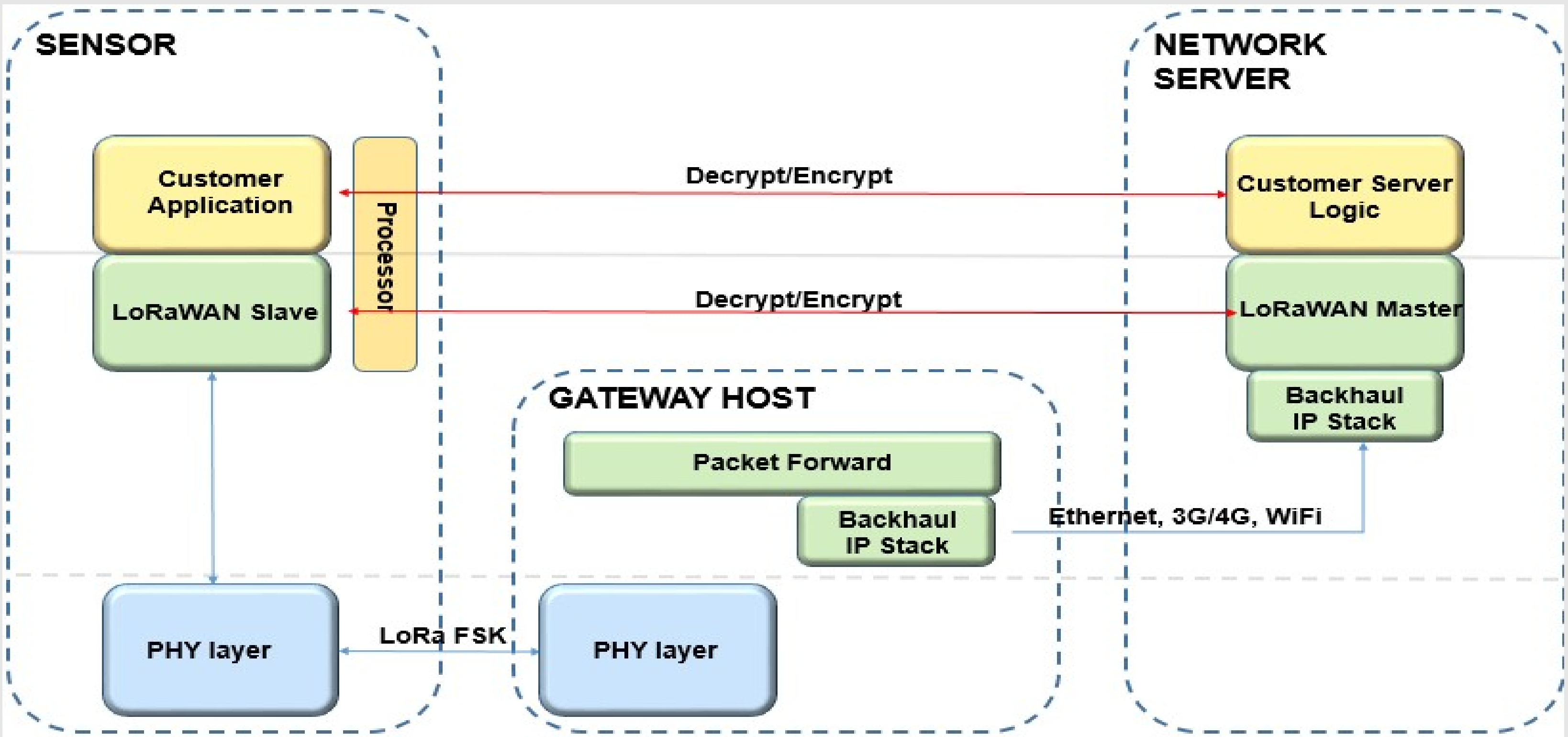
- **LoRaWAN** (cont'd)
- **General LoRaWAN Network Architecture**
  - **Several technologies (WiFi, Ethernet, 3G, 4G, 5G etc.) can serve as backhaul**



Source: Lora Alliance, "A technical overview of LoRa and LoRaWAN" Technical Marketing Workgroup 1.0, 2015, Nov

4. Mid-long range technologies

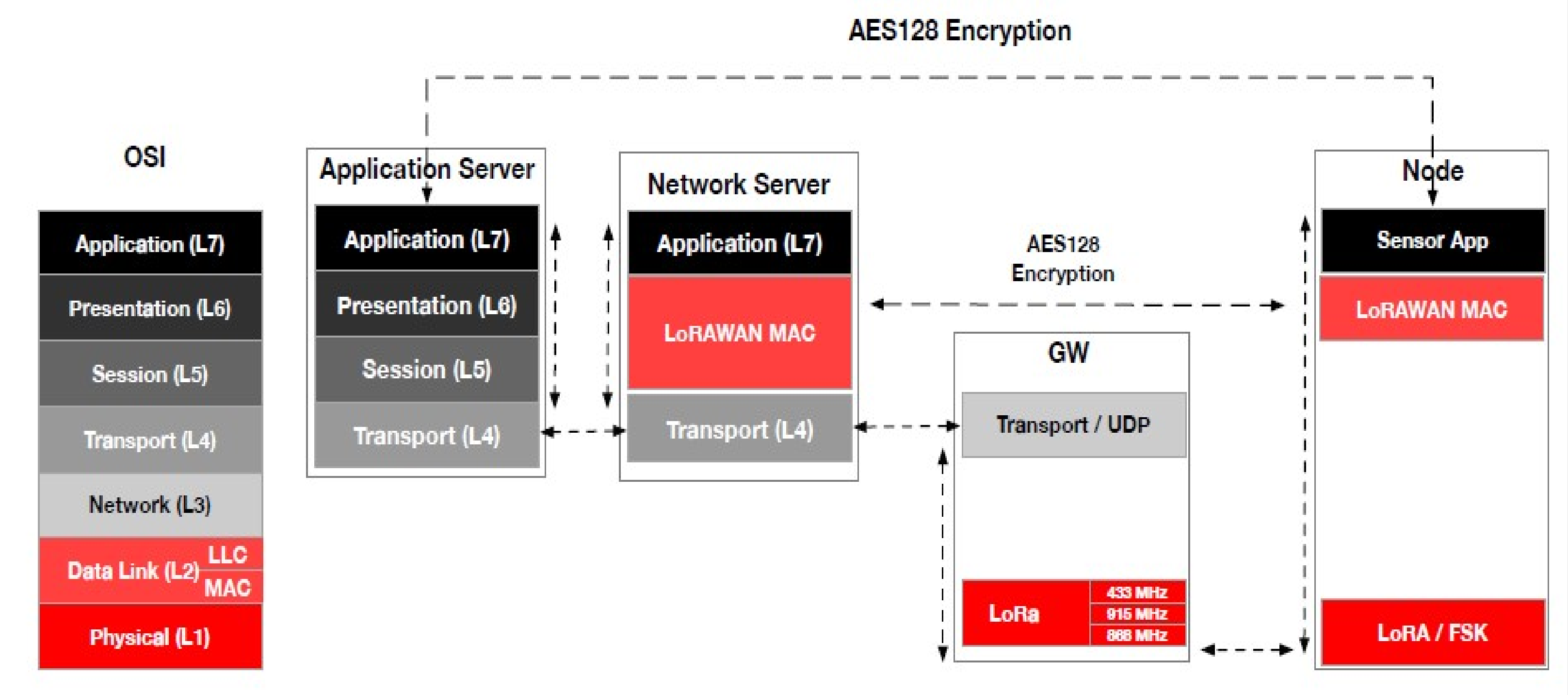
- **LoRaWAN** (cont'd)
  - **Layered architecture**



Source: J.Carvalho Silva,et al., "LoRaWAN - A Low Power WAN Protocol for Internet of Things: a Review and Opportunities", https://www.researchgate.net/publication/318866065, 2017

4. Mid-long range technologies

- **LoRaWAN** (cont'd)
- **Layered architecture versus OSI Reference Model**
  - Network servers: plain application services that operating over L4
  - All MAC layer functionalities of the whole network are controlled by the Network Server



Source: M.A.Ertürk et al., "A Survey on LoRaWAN Architecture, Protocol and Technologies", Future Internet 2019, 11, 216; doi:10.3390/fi11100216, www.mdpi.com/journal/futureinternet

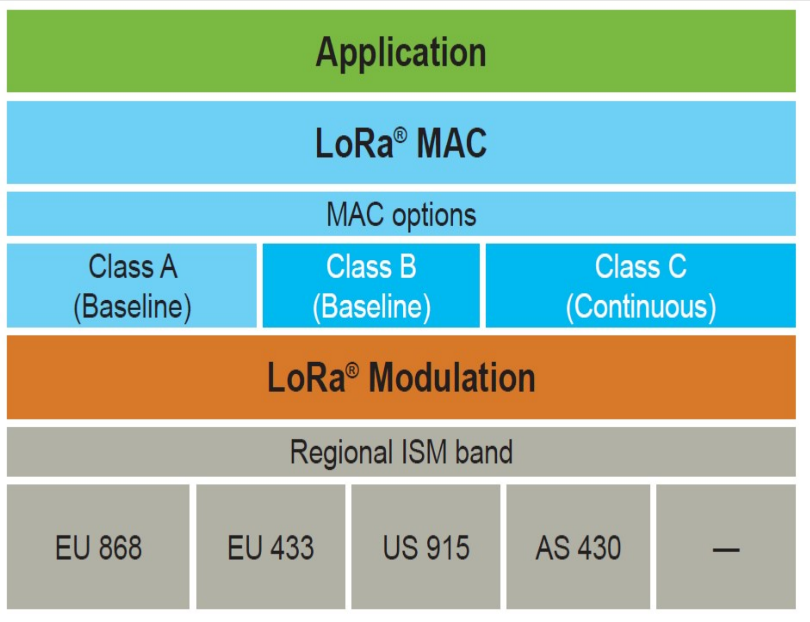
4. Mid-long range technologies

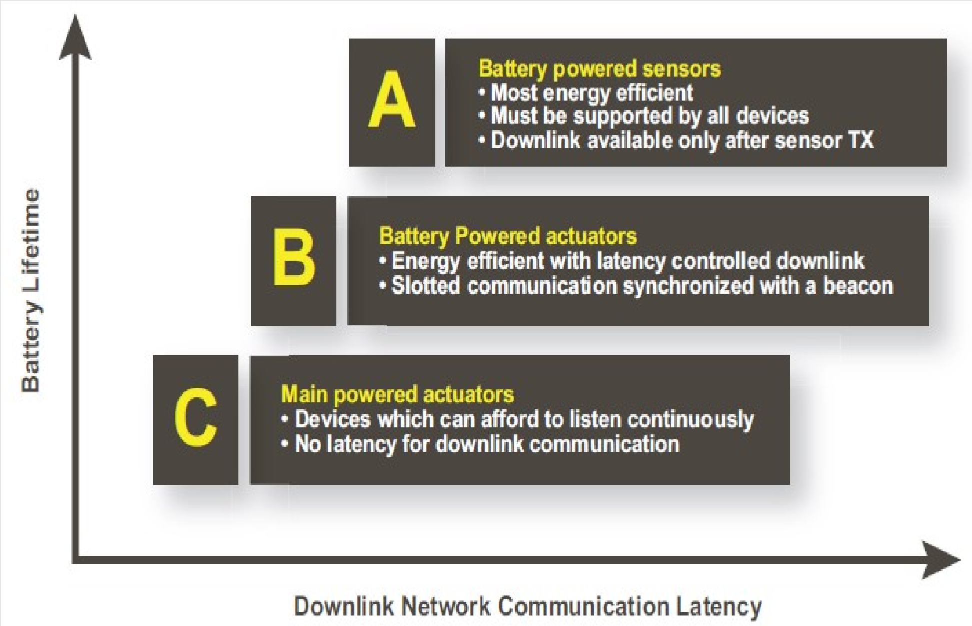
- **LoRaWAN** (cont'd)
- **NetworkCapacity**
  - The **GW** must have a **high capacity** or capability to receive messages from a very high number of nodes
  - High network capacity is achieved by
    - utilizing adaptive data rate
    - using a multichannel multi-modem transceiver in the GW so that simultaneous messages on multiple channels can be received
  - Critical factors affecting capacity
    - the number of concurrent channels,
    - data rate (time on air)
    - the payload length
    - Frequency of transmissions
  - Spread spectrum-based modulation→ the signals are practically orthogonal to each other when different spreading factors are utilized
    - As the spreading factor changes, the effective data rate also changes
      - The GW takes advantage of this property by being able to receive multiple different data rates on the same channel at the same time

4. Mid-long range technologies

- LoRaWAN (cont'd)
- **NetworkCapacity** (cont'd)
- If a node has a good link and is close to a GW, it
  - can shift the data rate higher
  - the time on air is shortened opening up more potential space for other nodes to transmit
- **Adaptive data rate** also optimizes the battery lifetime of a node
  - Symmetrical up link and down link is required with sufficient downlink capacity
  - The above features → the network has a high capacity and good scalability
- **Network extension**
  - a network can be deployed with a minimal amount of infrastructure
  - as capacity is needed, more GWs can be added, shifting up the data rates, reducing the amount of overhearing to other gateways, and scaling the capacity by 6-8x.
- **Battery Lifetime**
  - The LoRaWAN **nodes are asynchronous** and communicate when they have data ready to send whether *event-driven* or *scheduled* (Aloha method)
  - Note: in a mesh network or with a synchronous network, (e.g., cellular), the nodes frequently have to 'wake up' to synchronize with the network and check for messages
    - This consumes significant energy
    - GSMA study of the various technologies → LoRaWAN™ has a 3 to 5 times advantage compared to all other technology options

- **LoRaWAN** *(cont'd)*
  - **Device classes**
  - End-devices serve different applications with different requirements
    - therefore, LoRaWAN™ utilizes different device classes
    - they trade off network downlink communication latency versus battery lifetime
      - E.g., In a control or actuator-type application, the downlink communication latency is an important factor

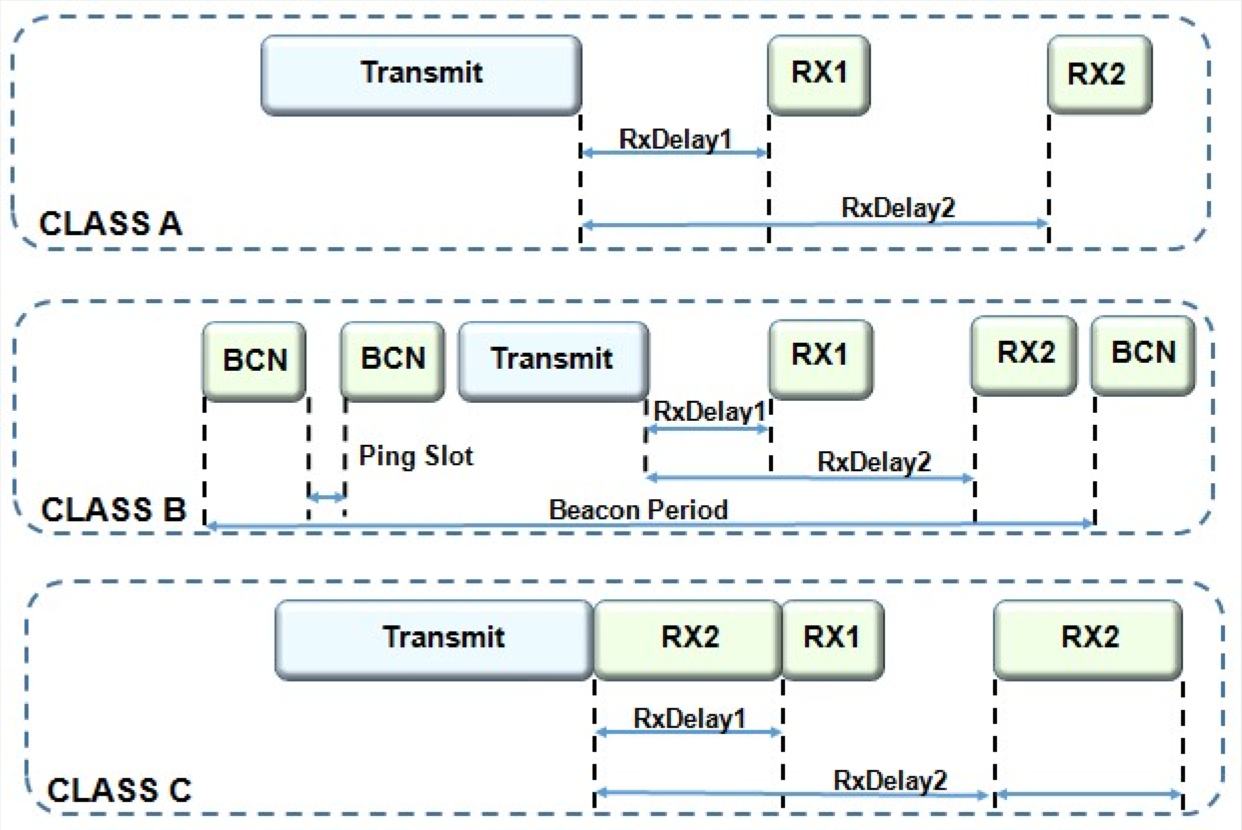




Source: Lora Alliance, "A technical overview of LoRa and LoRaWAN" Technical Marketing Workgroup 1.0, 2015, November

4. Mid-long range technologies

- **LoRaWAN** (cont'd)
  - **Classes** (cont'd)



4. Mid-long range technologies

- **LoRaWAN** (cont'd)
  - **Device classes** (cont'd)
  - **Bi-directional end-devices (Class A)**
    - Bi-directional communications; each end-device's uplink transmission is followed by two short downlink receive windows
    - the transmission slot scheduled by the end-device is based on its own communication needs with a small variation based on a random time basis (ALOHA-type of protocol)
    - Class A - the lowest power end-device system
      - for applications that only require downlink communication from the server shortly after the end-device has sent an uplink transmission
    - Downlink communications from the server at any other time will have to wait until the next scheduled uplink
  - **Bi-directional end-devices with scheduled receive slots (Class B)**
    - Additionally to the Class A random receive windows, Class B devices open extra receive windows at scheduled times
    - In order for the end-device to open its receive window at the scheduled time it receives a time-synchronized beacon from the gateway
    - This allows the server to know when the end-device is listening
  - **Bi-directional end-devices with maximal receive slots (Class C)**
    - End-devices of Class C have almost continuously open receive windows, only closed when transmitting

4. Mid-long range technologies

- **LoRaWAN** (cont'd)
  - **Device classes** (cont'd)

Classes	Description	Intended Use	Consumption	Examples of Services
A (« all »)	**Listens only after end device transmission**	Modules with **no latency constraint**	The **most economic** communication Class energetically.. **Supported by all modules. Adapted to battery powered modules**	• **Fire Detection** • **Earthquake Early Detection**
B (« beacon »)	The module listens at a **regularly adjustable frequency**	Modules with **latency constraints** for the **reception of messages of a few seconds**	**Consumption optimized.** **Adapted to battery powered modules**	• **Smart metering** • **Temperature rise**
C (« continuous »)	Module **always listening**	Modules with a ***strong reception latency constraint*** (less than one second)	Adapted to **modules on the grid** or with **no power constraints**	• **Fleet management** • **Real Time Traffic Management**

Source: S.Tabanne, "IoT Standards, Part I: IoT Technology and Architecture", September 2018, Bandung – Indonesia, https://www.itu.int/en/ITU-D/Regional-Presence/AsiaPacific/Documents/Events/2018/IoT-BDG/IoT%20Standards%20Part%20I%20Sami.pdf

4. Mid-long range technologies

- **LoRaWAN** (cont'd)
- **Regional LoRa WAN parameters**

	Europe	North America	China	Korea	Japan	India
Frequency band	867-869MHz	902-928MHz	470-510MHz	920-925MHz	920-925MHz	865-867MHz
Channels	10	64 + 8 +8	In definition by Technical Committee	In definition by Technical Committee	In definition by Technical Committee	In definition by Technical Committee
Channel BW Up	125/250kHz	125/500kHz				
Channel BW Dn	125kHz	500kHz				
TX Power Up	+14dBm	+20dBm typ (+30dBm allowed)				
TX Power Dn	+14dBm	+27dBm				
SF Up	7-12	7-10				
Data rate	250bps- 50kbps	980bps-21.9kpbs				
Link Budget Up	155dB	154dB				
Link Budget Dn	155dB	157dB				

Source: Lora Alliance, "A technical overview of LoRa and LoRaWAN" Technical Marketing Workgroup 1.0, 2015, Nov

4. Mid-long range technologies

- **LoRaWAN** (cont'd)
  - **Comparison LoRaWAN vs other technologies**

Feature	LoRaWAN	Narrow-Band	LTE Cat-1 2016 (Rel12)	LTE Cat-M 2018 (Rel13)	NB-LTE 2019(Rel13+)
Modulation	SS Chirp	UNB / GFSK/BPSK	OFDMA	OFDMA	OFDMA
Rx bandwidth	500 - 125 KHz	100 Hz	20 MHz	20 - 1.4 MHz	200 KHz
Data Rate	290bps - 50Kbps	100 bit/sec 12 / 8 bytes Max	10 Mbit/sec	200kbps – 1Mbps	~20K bit/sec
Max. # Msgs/day	Unlimited	UL: 140 msgs/day	Unlimited	Unlimited	Unlimited
Max Output Power	20 dBm	20 dBm	23 - 46 dBm	23/30 dBm	20 dBm
Link Budget	154 dB	151 dB	130 dB+	146 dB	150 dB
Batery lifetime - 2000mAh	105 months	90 months		18 months	
Power Efficiency	Very High	Very High	Low	Medium	Med high
Interference immunity	Very high	Low	Medium	Medium	Low
Coexistence	Yes	No	Yes	Yes	No
Security	Yes	No	Yes	Yes	Yes
Mobility / localization	Yes	Limited mobility, No loc	Mobility	Mobility	Limited Mobility No Loc

Source: Lora Alliance, "A technical overview of LoRa and LoRaWAN" Technical Marketing Workgroup 1.0, 2015, November

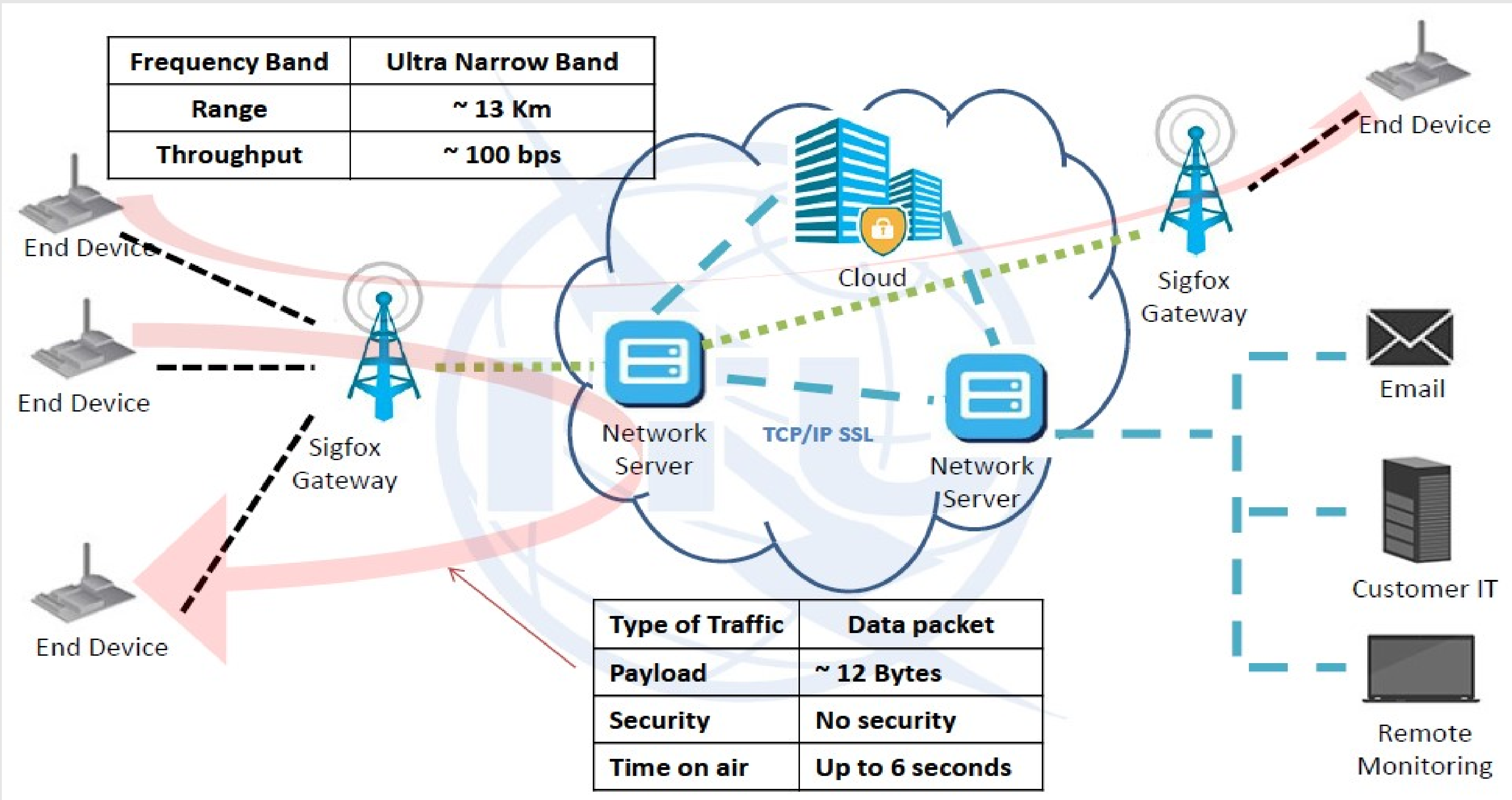
4. Mid-long range technologies

- **SigFox**
  - **Proprietary system** (SigFox Company
  - Early LPWAN technology (after – 2012)
  - Countries (2028): France, Spain, Portugal, Netherlands, Luxembourg, Ireland , Germany, UK, Belgium, Denmark, Czech Republic, Italy, Mauritius Island,Australia, New Zealand, Oman, Brazil, Finland, Malta, Mexico, Singapore, U.S., etc.

  - **Cellular system**
  - **Low throughput** (~100 bps), **Low power**
  - The end-devices connect to **base stations (BS)** equipped with software-defined cognitive radios using the BPSK (Binary Phase Shift Keying)- Ultra-Narrow band
    - Frequency band of 868MHz, dividing the spectrum into 400 channels of 100Hz; 915 MHz in USA
    - Downlink communication can only precede uplink communication after each the end device must wait for a response from the BS
  - **Coverage: 30-50 km in rural areas** and about **3-10 km in urban environments.**
  - An access point (AP) can manage around one **million of end-devices**
  - Each end-device can send ~ **140 messages per day** with a **data rate of 100 bps**
  - **Roaming capability**
  - **Subscription-based model**
  - **Cloud platform with Sigfox** –defined API for server access

4. Mid-long range technologies

- **SigFox** (cont'd)
  - **Architecture**



Frequency Band	Ultra Narrow Band
Range	~ 13 Km
Throughput	~ 100 bps

Type of Traffic	Data packet
Payload	~ 12 Bytes
Security	No security
Time on air	Up to 6 seconds

Source: S.Tabanne, "IoT Standards, Part I: IoT Technology and Architecture", September 2018, Bandung – Indonesia, https://www.itu.int/en/ITU-D/Regional-Presence/AsiaPacific/Documents/Events/2018/IoT-BDG/IoT%20Standards%20Part%20I%20Sami.pdf

4. Mid-long range technologies

- **LoRaWAN vs SigFox**
  - **Common:**
    - proprietary technology
    - use 900/868 MHz ISM band
    - use star network architecture
    - multiple base stations/gateways listen to the packets from IoT devices

Issue	LoRa	Sigfox
Business Model	Sell LoRa chips and silicon	Network as a Service Royalty from network service providers
Technology	LoRa Modulation	Ultra-narrowband (100 kHz) with BPSK
Symmetry	Uplink = Downlink	12 B payload in uplink 8 B payload in downlink 140 Messages/day/device uplink 4 messages/day/device downlink
Cost	Gateway and end points cost comparable	Expensive base stations Cheap end-points
Openness	Any one can make either or both end devices	Anyone can make end-points. Sigfox makes the basestations.
Service Provider	Anyone can setup a network	Sigfox sets up the network
Location	Can use everywhere	Only in markets where Sigfox has a network

Source: Raj Jain, "Low Power WAN Protocols for IoT: IEEE 802.11ah, LoRaWAN, Sigfox", http://www.cse.wustl.edu/~jain/cse574-18/

Contents

1. Introduction
2. IoT connectivity
3. Short range technologies
4. Mid-long range technologies
5. ➡ Cellular technologies for IoT
6. 5G connectivity solutions for IoT
7. Selection of IoT communication technology
8. Conclusions

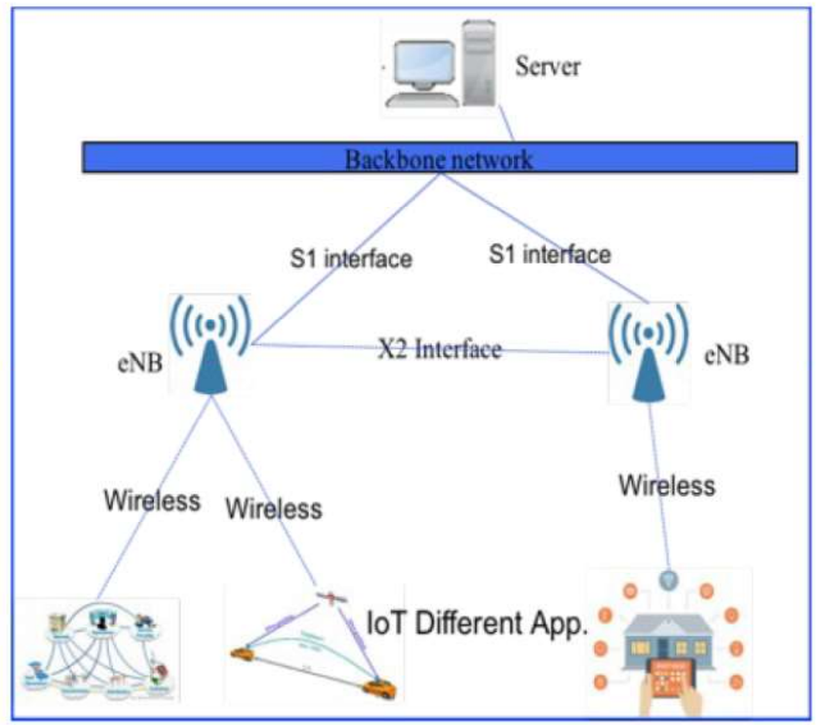
5. Cellular technologies for IoT

- **LTE- 4G-5G**
  - LTE and 5G -important technologies to support IoT
  - Standardized (4G), LTE/LTE-Advance (LTE-A)
    - ITU, 3GPP main standardization actors
    - successfully deployed worldwide
    - however, it was mainly designed to support conventional high speed HTC
  - **5G – major advantages over 4G** *(see Chapter 4, for details)*
    - Throughput, latency, density of terminals, coverage, power efficiency, etc.
    - Flexibility (multi-tenant, multi-domain, multi-oprator)
    - Advanced management and control (based on NFV, SDN, virtualization)
    - 5G slicing concept

Connectivity characteristics – comparison LTE – 5G

	LTE/LTE-A	5G
Round trip latency	15ms	1ms
Peak data rate	1Gbps	20Gbps
Available spectrum	3GHz	30GHz
Channel bandwidth	20MHz	100MHz below 6GHz 400MHz above 6GHz
Frequency band	600MHz to 5.925GHz	600MHz to 80GHz
Uplink waveform	SC-FDMA	Option for CP-OFDM

- **LTE- A general architecture**
  - **Core network- (CN)**
    - contains the architectural planes : data, control, management
    - controls the mobile devices , realizes Internet connection, control of mobile devices, performs complex management and control actions
  - **Radio Access Network (RAN)**
    - essentially contains architectural planes data and control
    - assures the connectivity (L1, L2, L3) via radio interfaces between mobile nodes and base stations (eNB)
- **Mobile devices**



Source: T.Salman, R.Jain, A Survey of Protocols and Standards for Internet of Things, Advanced Computing and Communications, Vol. 1, No. 1, March 2017.

3. Cellular technologies for IoT

- **LTE IoT**
- **3GPP** : a suite of two **complementary** narrowband **LTE IoT** technologies in Rel13:
  - **eMTC (enhanced Machine-Type Communication),** also known as LTE-M (Machine-Type Communication)
  - **NB-IoT (NarrowBand-Internet of Things)**
  - collectively referred to as LTE IoT
  - optimized for lower complexity/power, deeper coverage, and higher device density
  - seamlessly coexisting with other LTE services

Source: 5G Americas white Paper, "5G A future of IoT", July 2019, https://www.5gamericas.org/5g-the-future-of-iot/

5. Cellular technologies for IoT

- **Low Power WAN (LPWAN) – licensed spectrum**
  - Standardized by the 3GPP
  - **LPWAN, LTE-M** and **NB-IoT** – promising standards (see the 3GPP Rel-13 in 2016)
  - both standards are developed based on LTE
  - Random access procedure (RA) of a terminal to access the network – similar to LTE
    - using the contention-based physical random access channel (PRACH) for initial access of the mobile terminal to the network
- **LTE-M**
  - Is an LTE simplified version low cost, low power –attractive for IoT
  - **Main LTE-M characteristics:**
    - support for MTC and also for voice communications
    - uses OFDMA in downlink and SC-FDMA in uplink
    - low bandwidth 1.4MHz (reduced hardware cost)
    - working mode: half duplex or full duplex

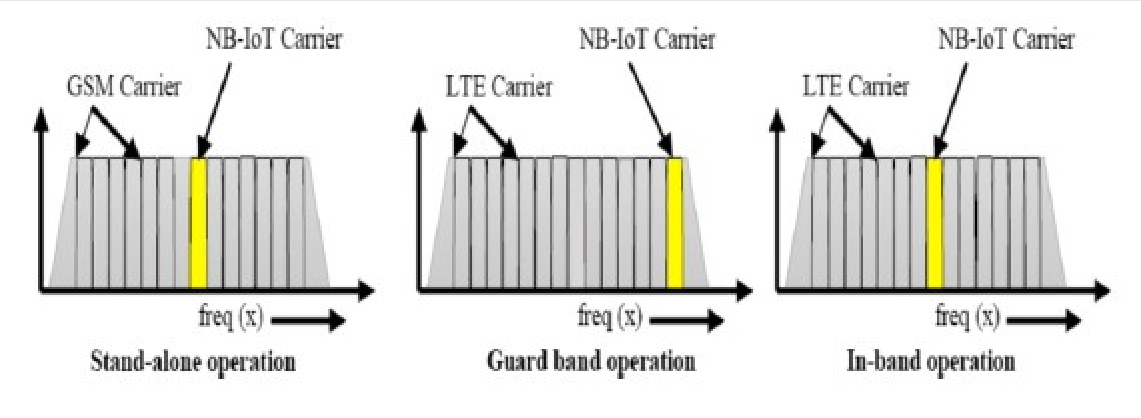
    - 3GPP Rel-14 and Rel-15 have added enhanced capabilities related to data rate, latency, coverage

5. Cellular technologies for IoT

- **Low Power WAN (LPWAN) – licensed** (cont'd)
- **NB-IoT**
- It is a **LTE based system**, using a single narrow band (200KHz), with low complexity of the baseband functions
  - designed to serve a large area, low-cost terminals, high density of terminal devices and procedures which can allow a long battery life
  - **NB-IoT characteristics**:
    - OFDMA with 15KHz spacing between subcarriers on downlink
    - SC-FDMA with 15KHz or 3.75 KHz on *uplink*
    - half-duplex mode
    - larger coverage area w.r.t LTE
    - three operation modes *inband*, *standalone* and *guard-band*
      - *inband* – one or more LTE resource blocks (*physical resource blocks (PRBs) within an LTE carrier*) are reserved for IoT
      - *standalone*- NB-IoT can be deployed inside one or more global mobile communication systems (e.g., GSM)
      - *guard-band- NB* –IoT can be used inside the guard-band LTE

5. Cellular technologies for IoT

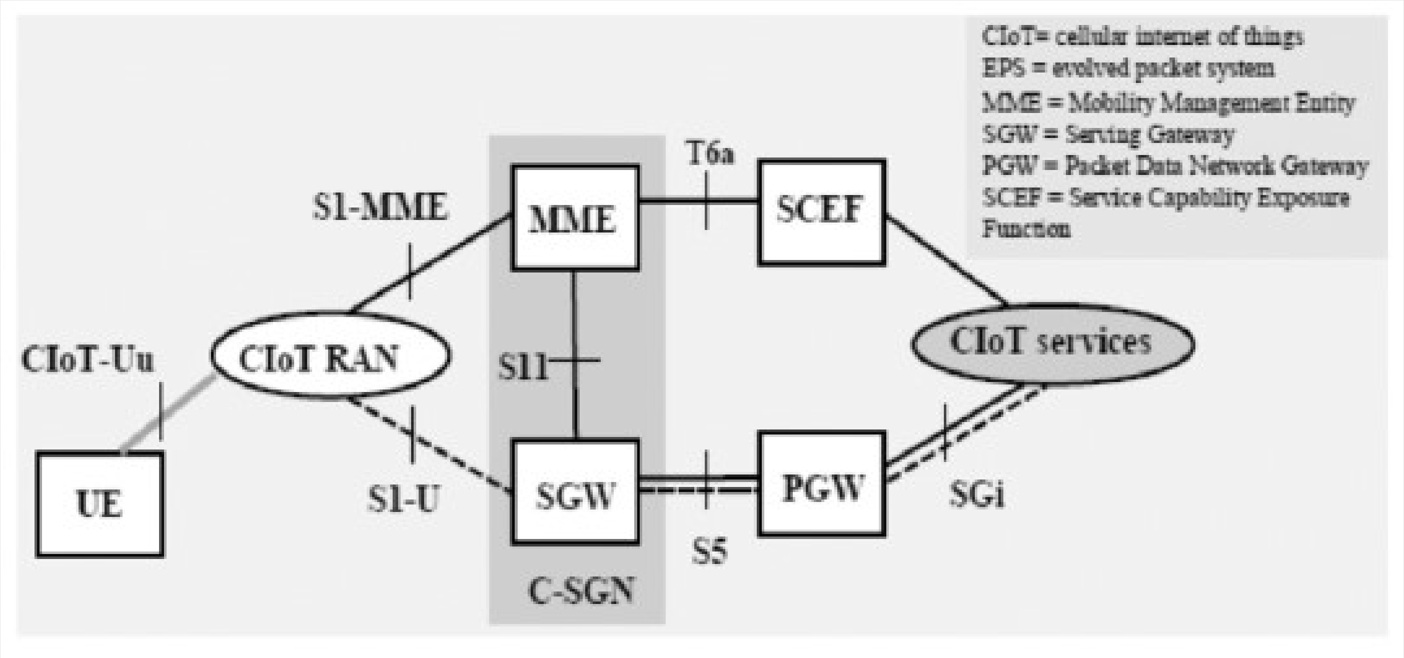
- **Low Power WAN (LPWAN) – licensed** (cont'd)
- **NB-IoT**
  - to increase the battery life, two mechanisms exist (in both NB-IoT and in LTE-M)
    - *power saving mode (PSM)* – maintains a terminal registered to the network, but allows it to enter in sleep mode and disable some functions like *paging listening* or *link quality measurements*
    - *expanded discontinuous reception (eDRX)* - allows a mobile terminal to negotiate when to enter the sleep state and for how long



Source: R.S.Sinha, Y.Wei, S.Hwang, "A survey on LPWA technology: LoRa and NB-IoT", ICT Express 3 (2017) 14–21, www.elsevier.com/locate/icte

5. Cellular technologies for IoT

- **Low Power WAN (LPWAN) – licensed (cont'd)**
- **NB-IoT (cont'd)**
  - **NB-IoT Network** architecture
    - LTE functional blocks are present in the Core network
    - The CIoT RAN can be customized for IoT applications



Source: R.S.Sinha, Y.Wei, S.Hwang, "A survey on LPWA technology: LoRa and NB-IoT", ICT Express 3 (2017) 14–21, www.elsevier.com/locate/icte

5. Cellular technologies for IoT

- **Low Power WAN (LPWAN) – licensed** (cont'd)
- **LTE-M versus NB-IoT comparison**

	LTE-M	NB-IoT
RA protocol (based on PRACH)	Slotted-ALOHA	Slotted-ALOHA
Modulation type	QPSK/QAM	BPSK/QPSK
Frequency	Licensed LTE bands	Licensed LTE bands
Bandwidth	1.4MHz	200kHz
Bidirectional	Full/Half-duplex	Half-duplex
Link budget	153dB	164dB
Maximum data rate	1Mbps	250kbps
Maximum payload length	1000bits	1000bits
Coverage	Few kilometers	1km (urban), 10km (rural)
Interference immunity	Low	Low
Battery life	10 years	10 years
Localization	Yes	Yes
Mobility	Yes	Yes

Source: J.Ding, M.Nemati, C.Ranaweera, and J.Choi, "IoT Connectivity Technologies and Applications: A Survey" arXiv:2002.12646v1 [eess.SP] 28 Feb 2020.

5. Cellular technologies for IoT

- **Low Power WAN (LPWAN) – licensed** (cont'd)
- Comparison of cellular NB-IoT vs LoRaWAN, Sigfox, and others

	Sigfox	NB-IoT	LoRaWAN	WiFi	ZigBee	Bluetooth
Standards	Sigfox	3GPP	LoRa Alliance	IEEE 802.11	IEEE 802.15.4	Bluetooth SIG
Modulation	BPSK	QPSK	CSS	DSSS, OFDM	DSSS, QPSK	GFSK
Frequencies	ISM: 433 MHz, 868 MHz, 915 MHz	Licensed under LTE	ISM: 433 MHz, 868 MHz, 915 MHz	ISM: 2.4 GHz, 5 GHz	ISM: 868 MHz, 2.4 GHz	2.4 GHz
Coverage	10–40 km	2–20 km	1–10 km	10–100 m	10–100 m	10–100 m
Bandwidth	100 Hz	200 kHz	125 kHz, 250 kHz	20 MHz, 40 MHz, 80 MHz, 160 MHz	2 MHz	1 MHz
TX Limit	140 Packets per Day	Unlimited	Duty Cycle Lim.	Unlimited	Unlimited	Unlimited
Max Data Rate	100 bps	200 kbps	50 kbps	Gbps	250 kbs at 2.4 GHz	2 Mbps
Private Deployments	No	No	Yes	Yes	Yes	Yes
Energy Consumption	Low	Low	Low	High	Low	Low
Security	Low	High	High	Low-High	High	Low-High

Source:PM.A.Ertürk, et al., "A Survey on LoRaWAN Architecture, Protocol and Technologies", Future Internet 2019, 11, 216; doi:10.3390/fi11100216

Contents

1. Introduction
2. IoT connectivity
3. Short range technologies
4. Mid-long range technologies
5. Cellular technologies for IoT
6. 5G connectivity solutions for IoT
7. Selection of IoT communication technology
8. Conclusions

6. 5G connectivity solutions for IoT

- **Three views/sets-of-requirements for 5G**
  - ***user-centric*** (uninterrupted connectivity and communication services, smooth consumer experience)
  - ***service-provider-centric*** (connected intelligent systems, multi-tenant, multi-domain capabilities, large area of IoT services, critical monitoring/tracking services)
  - ***network-operator-centric*** (scalable, energy-efficient, low-cost, efficiently managed, programmable, and secure - communication infrastructure)
- **5G: evolution of mobile *broadband networks* + *new unique network and service capabilities*:**
  - It will ensure *user experience continuity* in various situations
    - high mobility (e.g. in trains)
    - very dense or sparsely populated areas
    - regions covered by heterogeneous technologies
- **5G - key enabler for the Internet of Things, M2M**

6. 5G connectivity solutions for IoT

- **5G Key technological characteristics**
  - Heterogeneous set of integrated air interfaces
  - Cellular and satellite solutions
  - Simultaneous use of different **Radio Access Technologies (RAT)**
    - **Seamless (vertical) handover** between heterogeneous RATs
  - Ultra-dense networks with numerous small cells
    - Need new interference mitigation, backhauling and installation techniques
  - **Driven by SW**
    - unified OS in a number of PoPs, especially at the network edge

  - To achieve the required performance, scalability and agility it will rely on
    - Software Defined Networking (SDN)
    - Network Functions Virtualization (NFV)
    - Cloud/Mobile Edge Computing (MEC) /Fog Computing (FC)

  - **Optimized network management** operations, through
    - **cognitive features**
    - **advanced automation** of operation through proper algorithms
    - Data Analytics and Big Data techniques -> monitor the users' QoE

6. 5G connectivity solutions for IoT

- **Network softwarization:** represents sets of functions assuring **programmability** of
  - network devices
  - **network functions (NF)-** virtual or physical
  - **network slices** – logical, on demand, customized networks
  - network services and applications
  - **architectural planes**: data/user, control, management
- **Shift** from network of entities, to **network of (virtual) functions** /capabilities.
  - NFs become units of networking
- **Separation** of concerns between
  - control/ management/ softwarization/ services
  - logical / physical resources functions (connectivity, computing and storage) and network capabilities
- **On demand composition** of NFs and network capabilities
- Develop network softwarization capabilities in all network segments and network components.

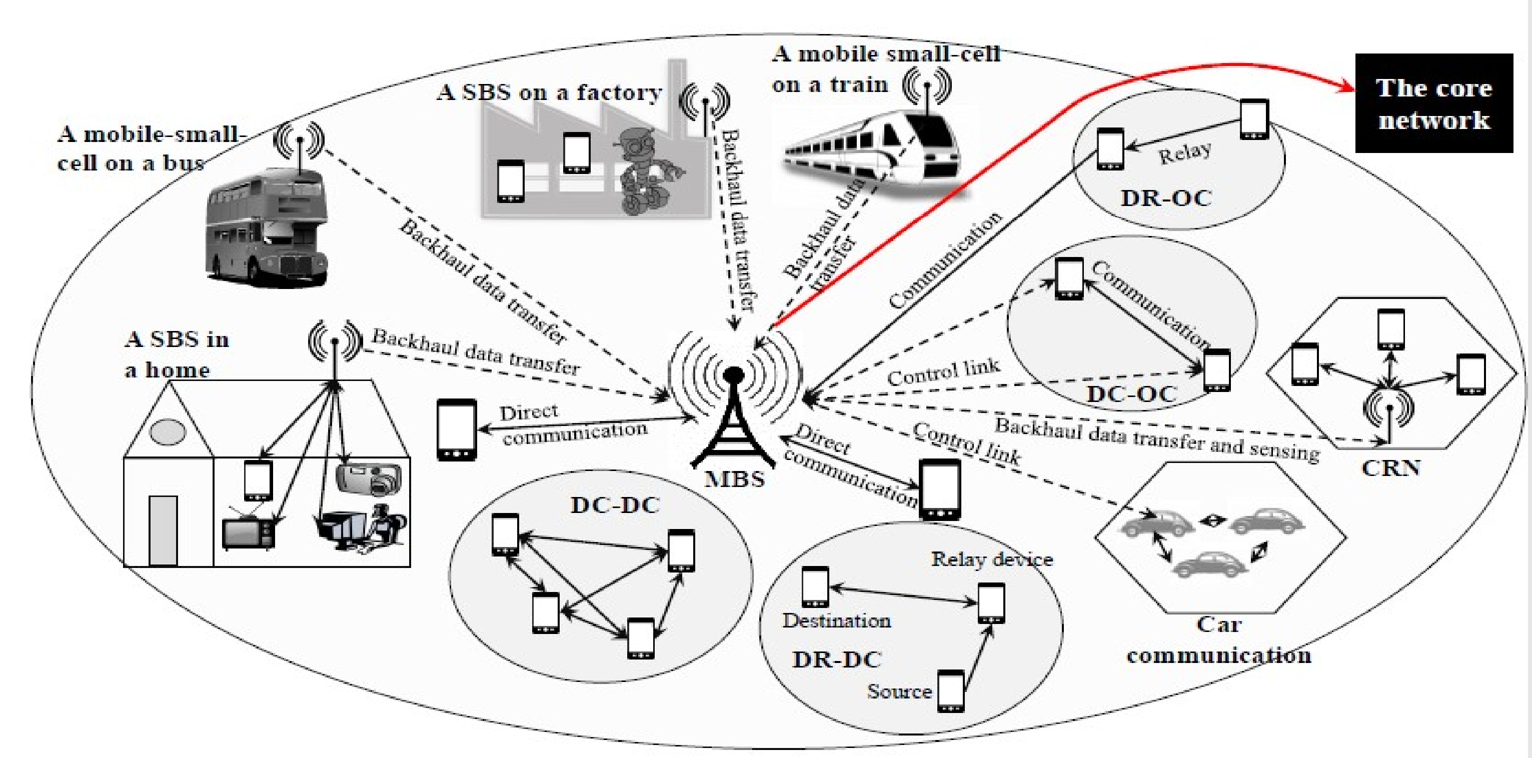
6. 5G connectivity solutions for IoT

- **Summary of 5G figures - strong goals:**
  - **1,000 X in mobile data volume** per geographical area reaching a target ≥ 10 Tb/s/km2
  - **1,000 X in number of connected devices** reaching a density ≥ 1M terminals/km2
  - **100 X in user data rate** reaching a peak terminal data rate ≥ 10Gb/s
  - **1/10 X in energy** consumption compared to 2010
  - **1/5 X in E2E latency reaching 5 ms** for e.g. tactile Internet and radio link latency reaching a target ≤ 1 ms, e.g. for Vehicle to Vehicle (V2V) communication
  - **1/5 X in network management** OPEX
  - **1/1,000 X in service** deployment time, reaching a complete deployment in ≤ 90 minutes

6. 5G connectivity solutions for IoT

- **5G Generic Architecture**
  - multi-tier arch.: small-cells, mobile small-cells, and D2D- and Cognitive Radio Network (CRN)

DR-OC - Device relaying with operator controlled link establishment
DC-OC - Direct D2D communication with operator controlled link establishment
DR-DC - Device relaying with device controlled link establishment
DC-DC - Direct D2D communication with device controlled link establishment

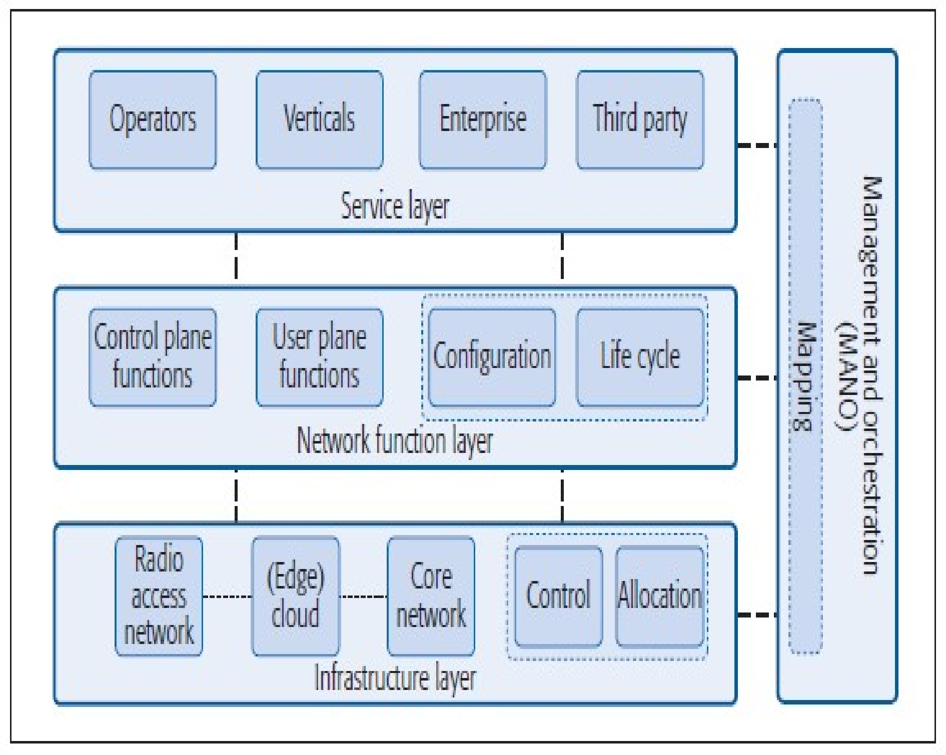


Source: Panwar N., Sharma S., Singh A. K. ‚A Survey on 5G: The Next Generation of Mobile Communication'. Accepted in Elsevier Physical Communication, 4 Nov 2015, http://arxiv.org/pdf/1511.01643v1.pdf

6. 5G connectivity solutions for IoT

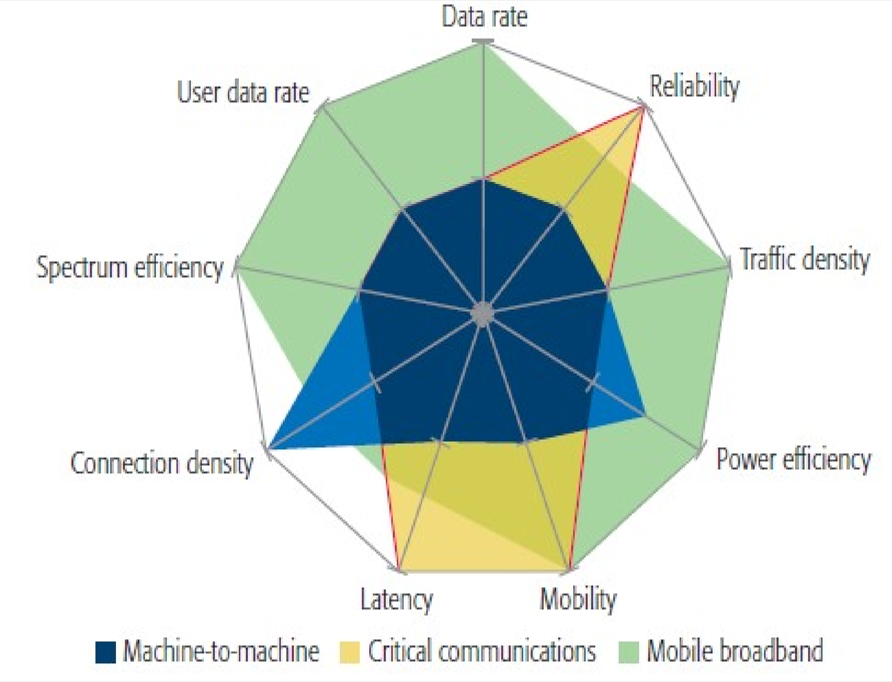
5G Layered Functional Architecture

- **Generic layered architecture**
  - High level representation



Key 5G use cases and their requirements

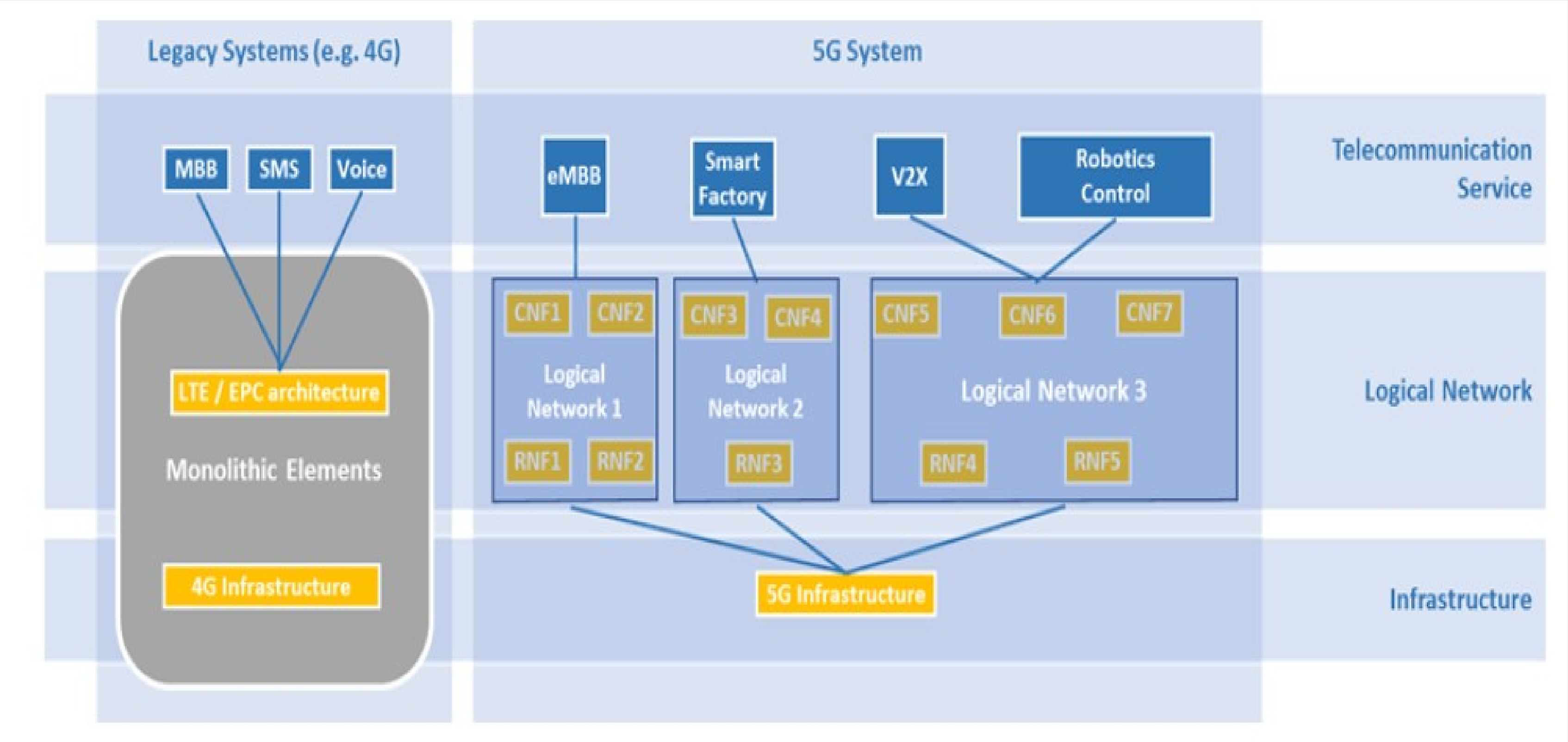
- difficult for a traditional unique arch to meet all of them
- **dedicated slicing can be the solution**



Source: X. Foukas, G. Patounas, A.Elmokashfi, and M.K. Marina, Network Slicing in 5G: Survey and Challenges, IEEE Communications Magazine, May 2017, pp.94-100

6. 5G connectivity solutions for IoT

- **4G versus 5G concepts**



MBB - Mobile Broadband;
LTE - Long Term Evolution (4G) ;
V2X - vehicle to X ; **CNF**- Core Network Functions;

SMS - Short Messages service;
EPC- Evolved Packet Core
RNF- RAN network Functions

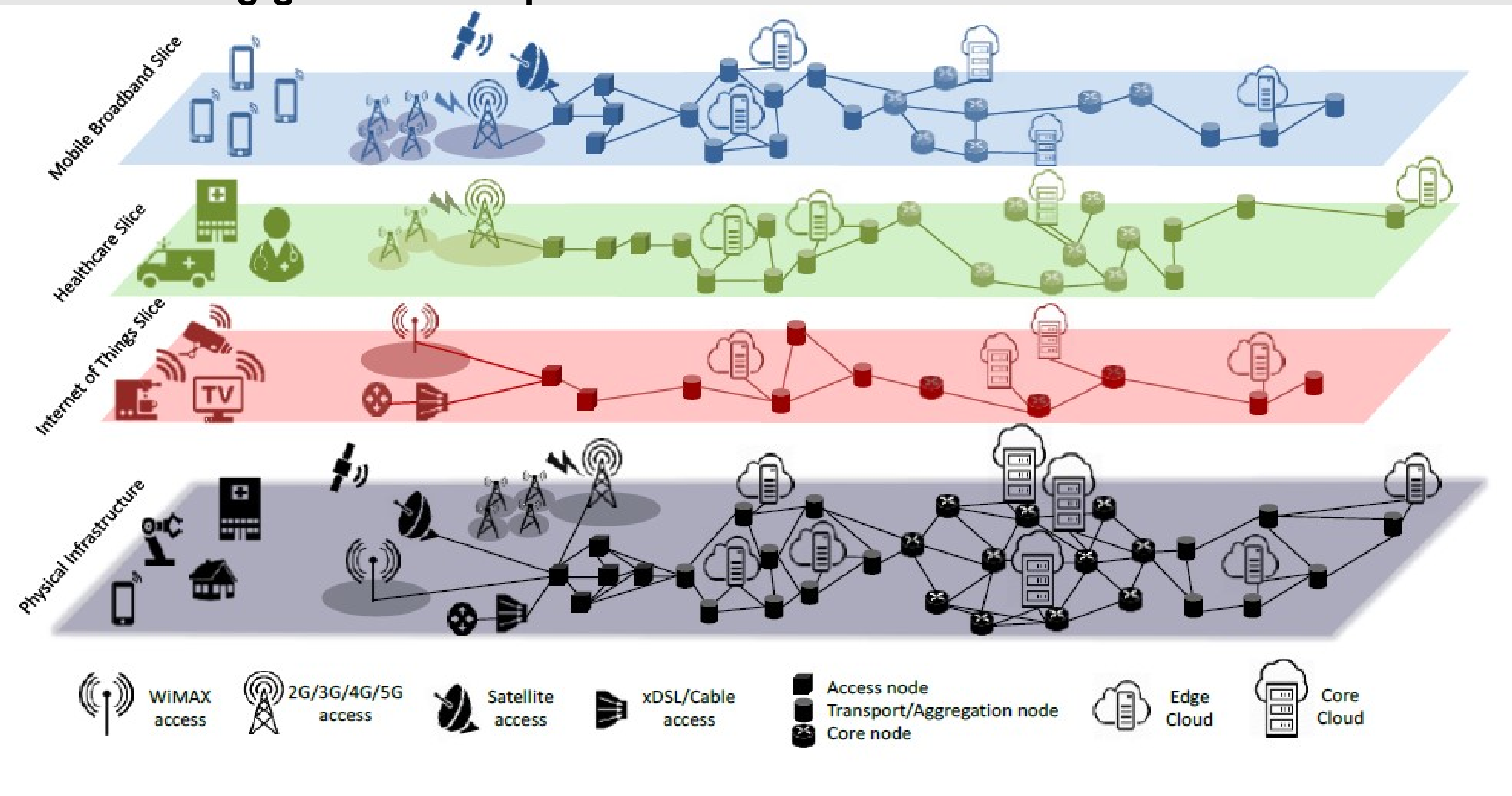
6. 5G connectivity solutions for IoT

▪ **5G Network slicing concepts**

- **E2E concept:** covering all network segments : radio, access/edge, wire, core, transport and edge networks.
- **concurrent deployment of multiple E2E logical, self-contained and independent shared or partitioned networks** on a common infrastructure platform
- **Slices**
  - created **on demand**, running on a common underlying (P/V) network, mutually isolated with independent M&C
  - **composition** of adequately configured NFs, network apps., and the underlying cloud infrastructure (PHY/virtual/ emulated resources, etc.)
  - **resources are bundled together** to meet specific UC reqs. (e.g., bandwidth, latency, processing, resiliency) coupled with a business purpose
- **SDN and NFV** – support technologies providing virtualization, programmability, flexibility, and modularity to create **multiple network slices** each tailored for a given UC

6. 5G connectivity solutions for IoT

- **5G Network slicing concepts** (cont'd)
  - **5G slicing generic example**



Source: J. Ordonez-Lucena, P. Ameigeiras, D. Lopez, J.J. Ramos-Munoz, J. Lorca, J. Folgueira, Network "Slicing for 5G with SDN/NFV: Concepts, Architectures and Challenges" , IEEE Communications Magazine, 2017, Citation information: DOI 10.1109/MCOM.2017.1600935

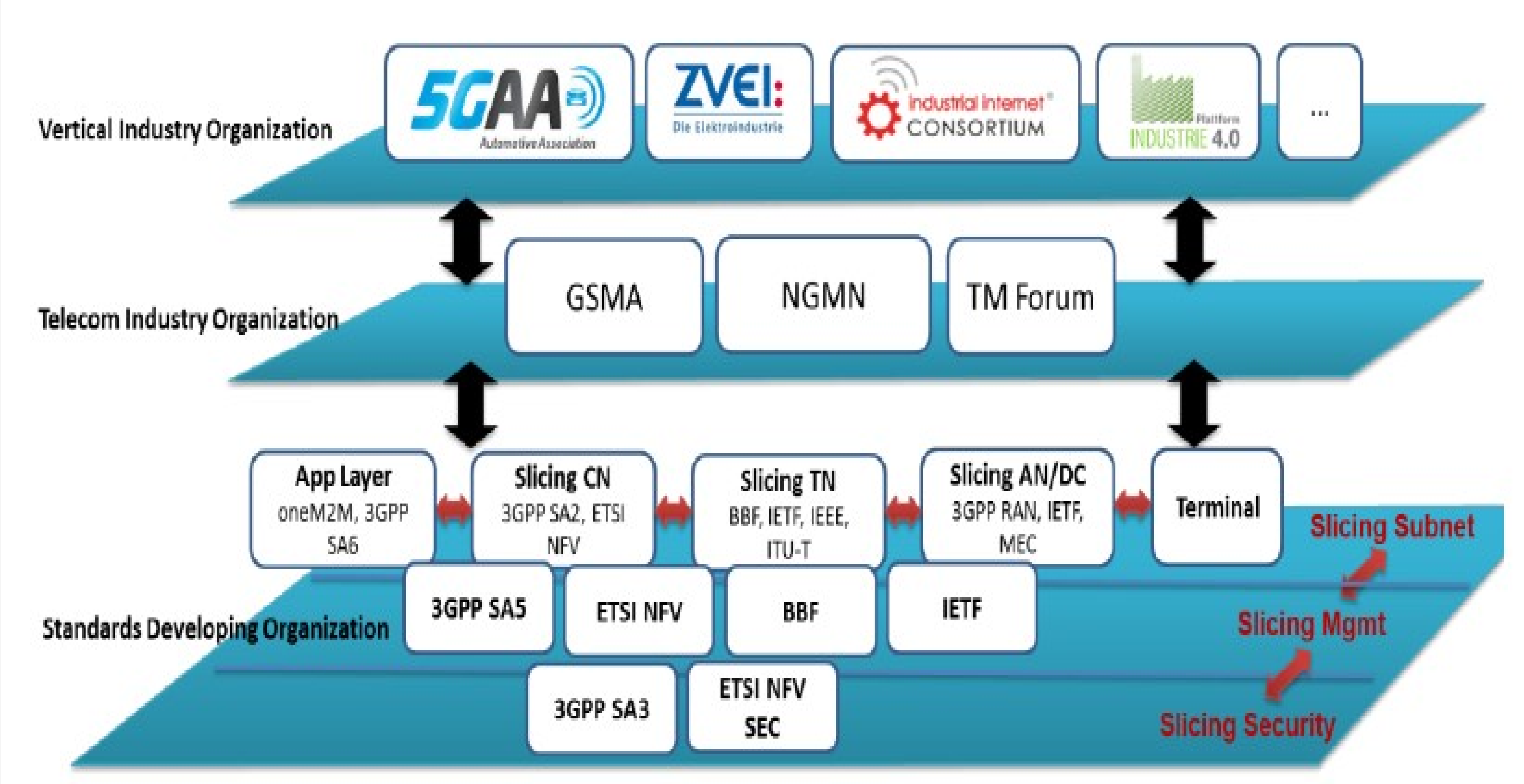
6. 5G connectivity solutions for IoT

- **Standardization work oriented to slicing**

- **European Telecom Std. Institute (ETSI)** –**Next Generation Protocols (NGP)** – Technology independent approach to slicing
  - **ETSI- Network Function Virtualization (NFV)–** studies on SDN and NFV support for slices
- **3rd Generation Partnership Project (3GPP)** – contributions on RAN, Services and architectures, Core networks and terminals, Mgmt. and orchestration
- **5G-PPP** – details the roles and relationships between different parts of the 5G
- network.
- **Next Generation Mobile Networks (NGMN)** –Slicing concept for 5G with IMT2020
- **Int'l Telecom Union (ITU-T)** – Works on Slices in IMT-2020, SG13 and SG15: management & transport aspects; alignment with 5G
- **Open Networking Foundation (ONF) , Broadband Forum (BBF)**
- **Internet Engineering Task Force (IETF)** – focused more on fixed network and management of network slicing
- **GSM Association (GSMA)-** business aspects, use cases, etc.

6. 5G connectivity solutions for IoT

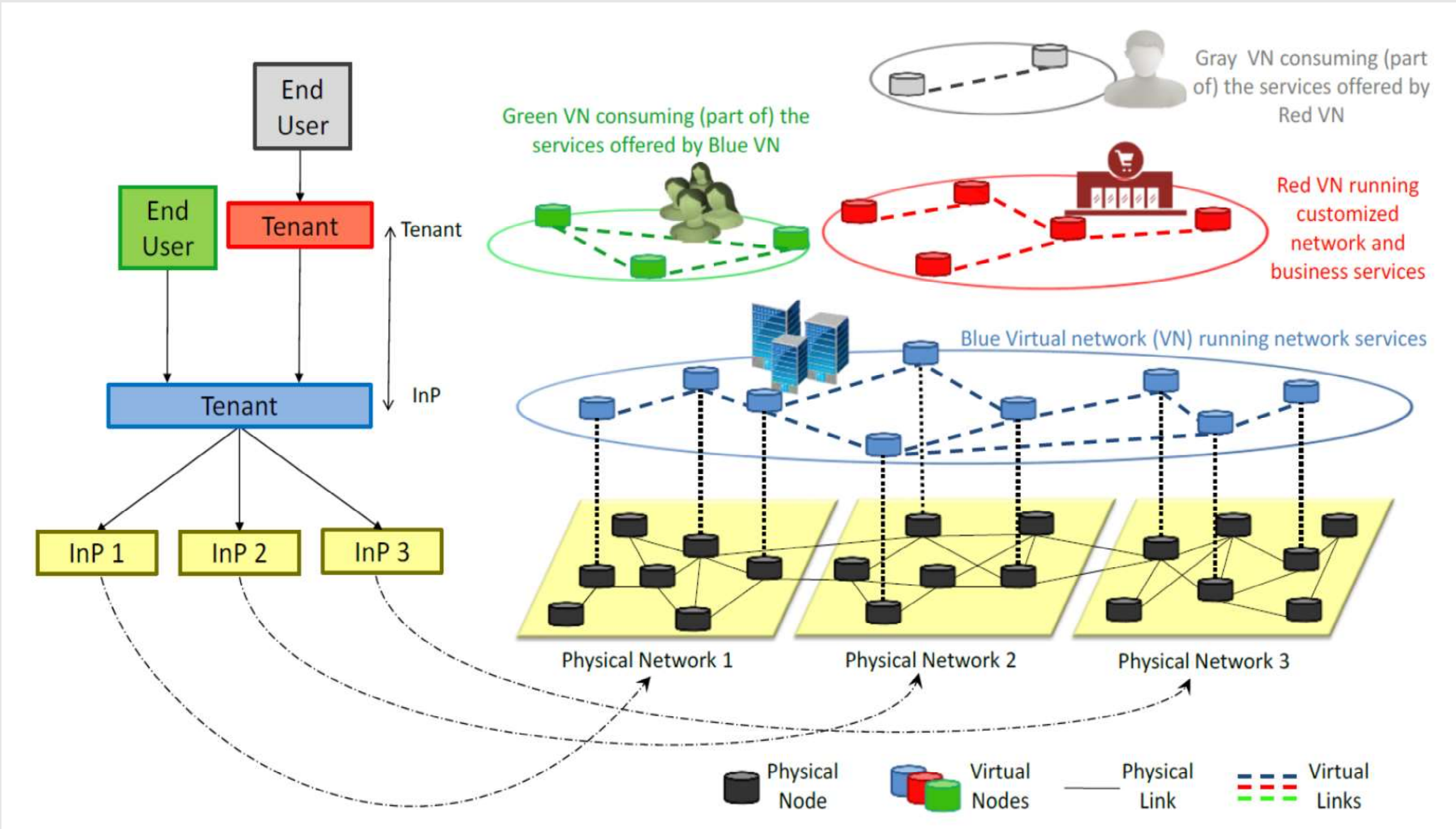
- **Standardization effort oriented to slicing** (cont'd)



Source: GSMA, Network Slicing, - Use Cases and Requirements , April 2018

6. 5G connectivity solutions for IoT

- **Business model (actors) - example**
  - **Recursive model**



Source: J. Ordonez-Lucena, P. Ameigeiras, D. Lopez, J.J. Ramos-Munoz, J. Lorca, J. Folgueira, Network "Slicing for 5G with SDN/NFV: Concepts, Architectures and Challenges" , IEEE Communications Magazine, 2017

6. 5G connectivity solutions for IoT

- **Categories of 5G fundamental – slicing scenarios**
  - **Massive machine type communication (mMTC) – aiming to IoT apps.**
  - **Ultra reliability low latency communication (URLLC)**
  - **Enhanced mobile broadband (eMBB)**
  - **different requirements on 5G: functional** (e.g. priority, charging, policies, security, and mobility) and **performance** (e.g. latency, mobility, availability, reliability and data rates) -→ **dedicated slices can be constructed**

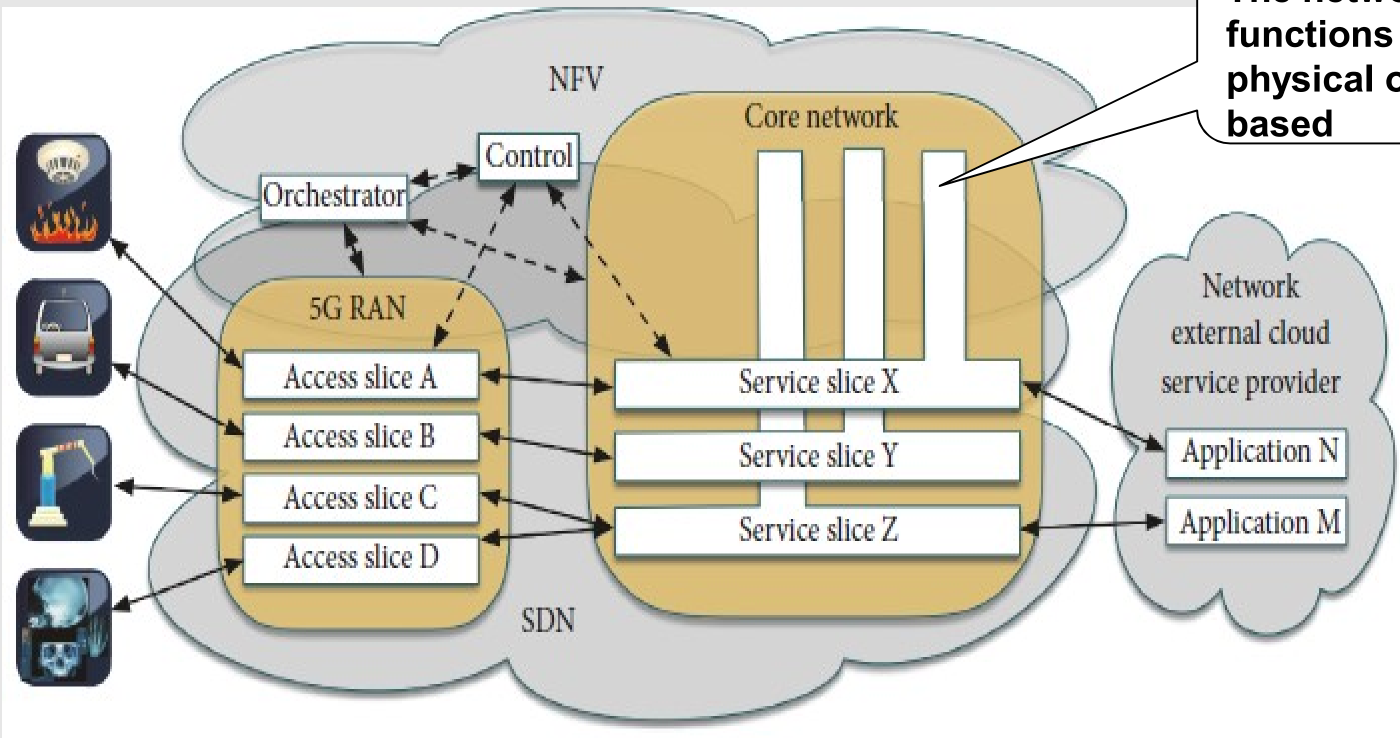
Characteristics	mMTC	URLLC	eMBB
Availability	Regular	Very High	Regular (baseline)
E2E latency	Not highly sensitive	Extremely sensitive	Not highly sensitive
Throughput type	Low	Low/med/high	Medium
Frequency of Xfers	Low	High	High
Density	High	Medium	High
Network coverage	Full	Localized	Full

Source: End to End Network Slicing – White paper 3 Outlook 21, Wireless World , Nov 2017

6. 5G connectivity solutions for IoT

- **Generic slicing architecture with SDN and NFV support**
- **Potential solution scenarios for support of multiple slices per UE**
  - Three groups of solutions defined by 3GPP

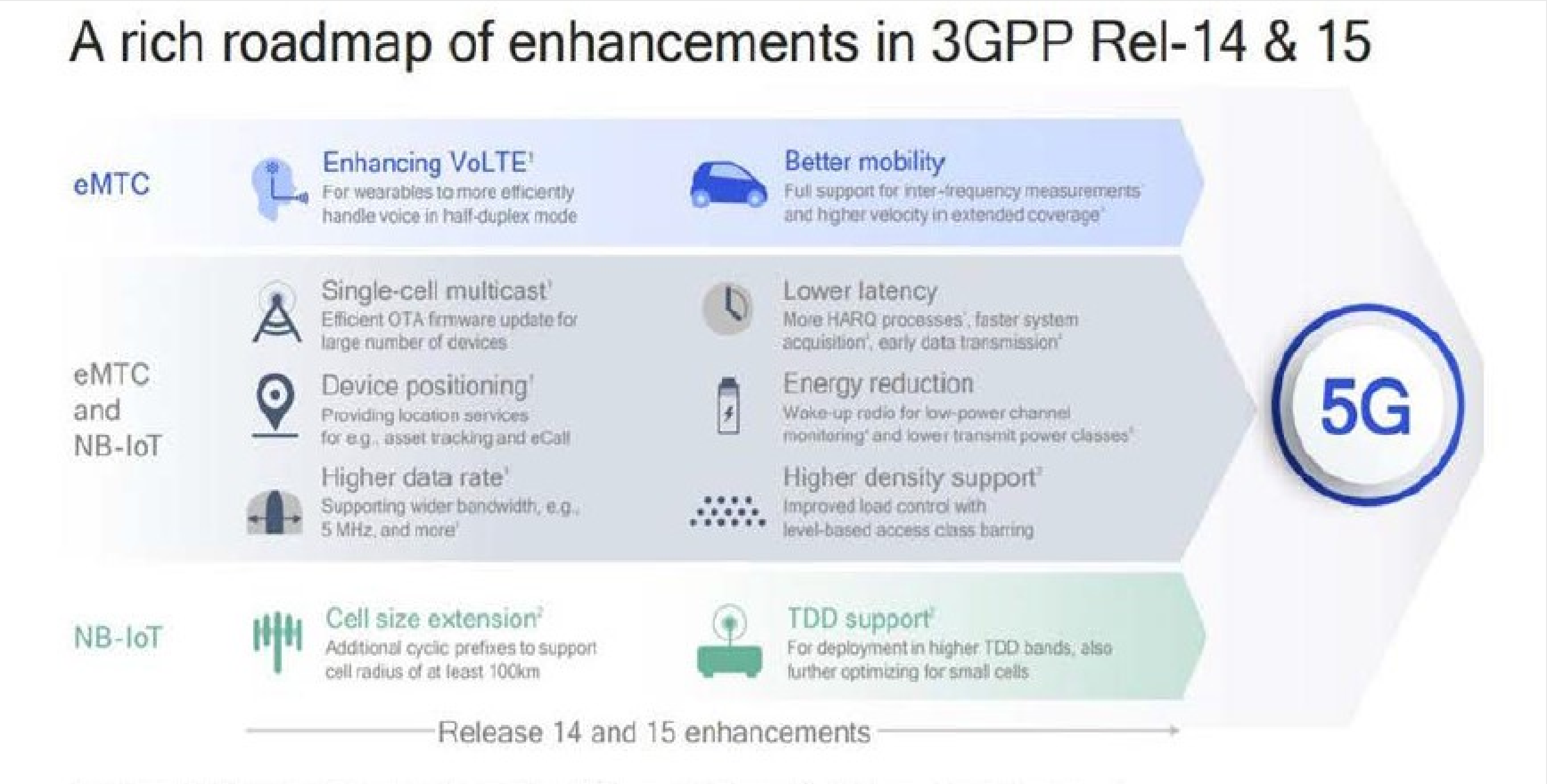
The network functions can be physical or NFV-based



Source: G. Nencioni et al., Orchestration and Control in Software-Defined 5G Networks: Research Challenges, Wiley, Wireless Communications and Mobile Computing Volume 2018, Article ID 6923867, pp. 1-19, https://doi.org/10.1155/2018/6923867https://www.hindawi.com/journals/wcmc/2018/6923867/

6. 5G connectivity solutions for IoT

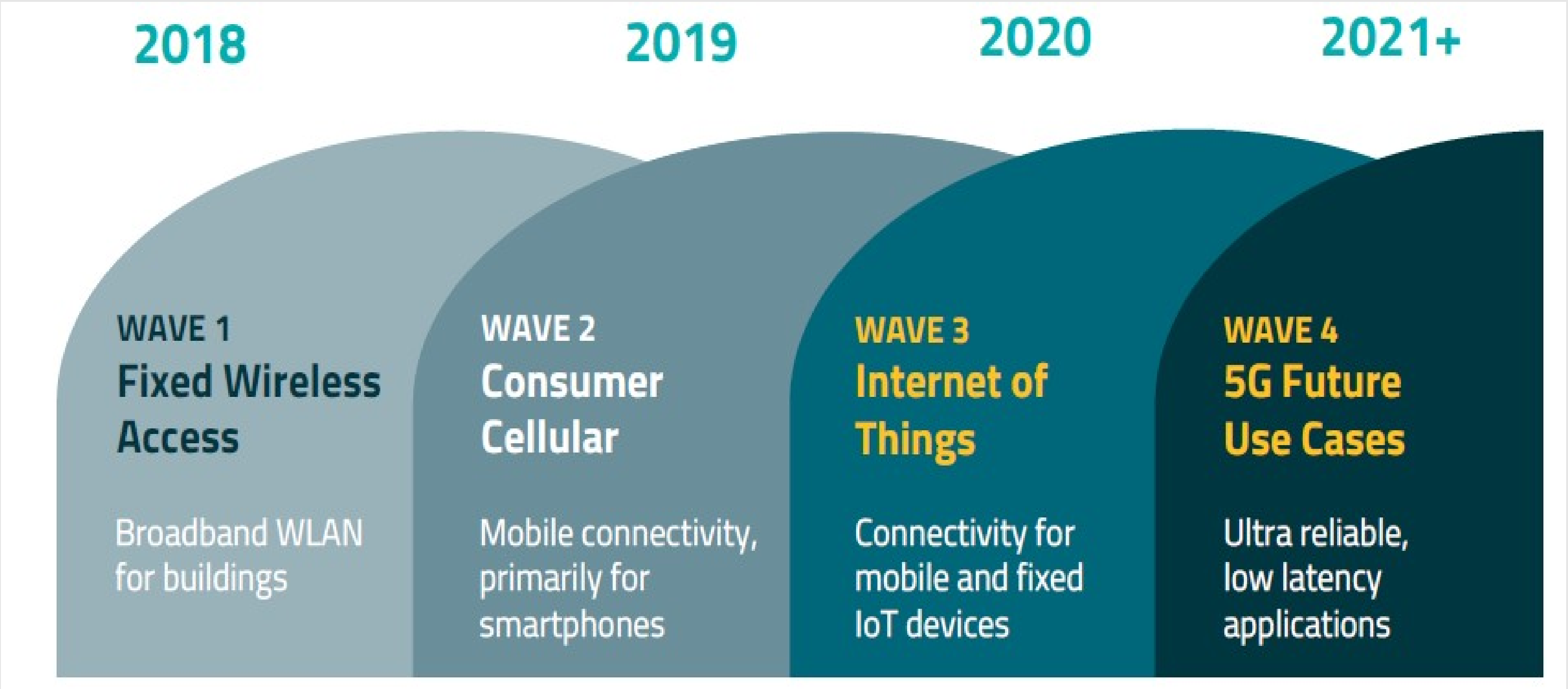
- **3GPP enhancement towards 5G**



Ref: 5G Americas white Paper, "5G A future of IoT", July 2019, https://www.5gamericas.org/5g-the-future-of-iot/

6. 5G connectivity solutions for IoT

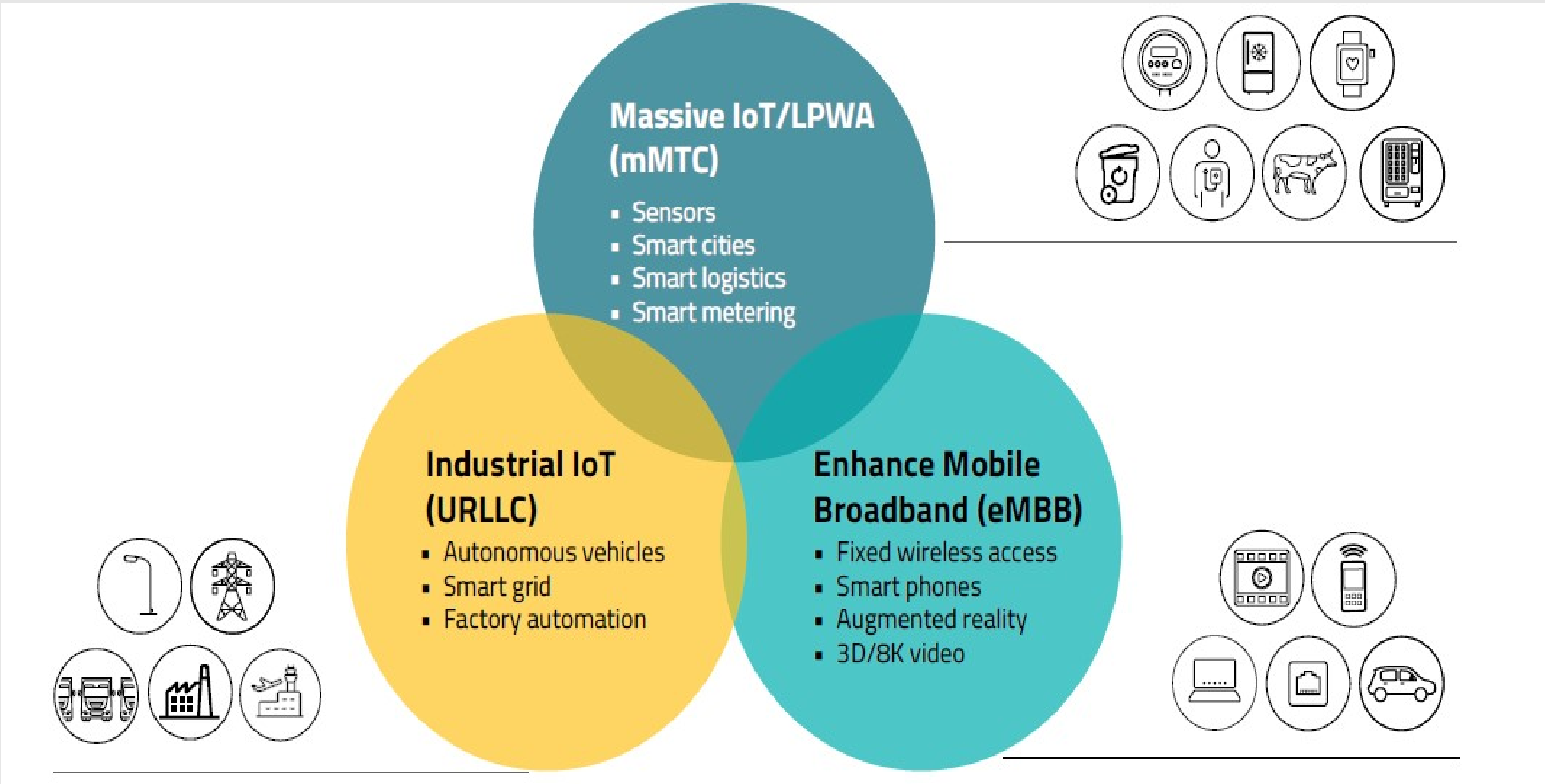
- **5G Commercialization Timeline**
  - **Wave 3 → IoT**



Source: SIERRA WIRELESS White Paper, "5G for IoT?", https://www.sierrawireless.com/resources/white-paper/5g-for-iot/

6. 5G connectivity solutions for IoT

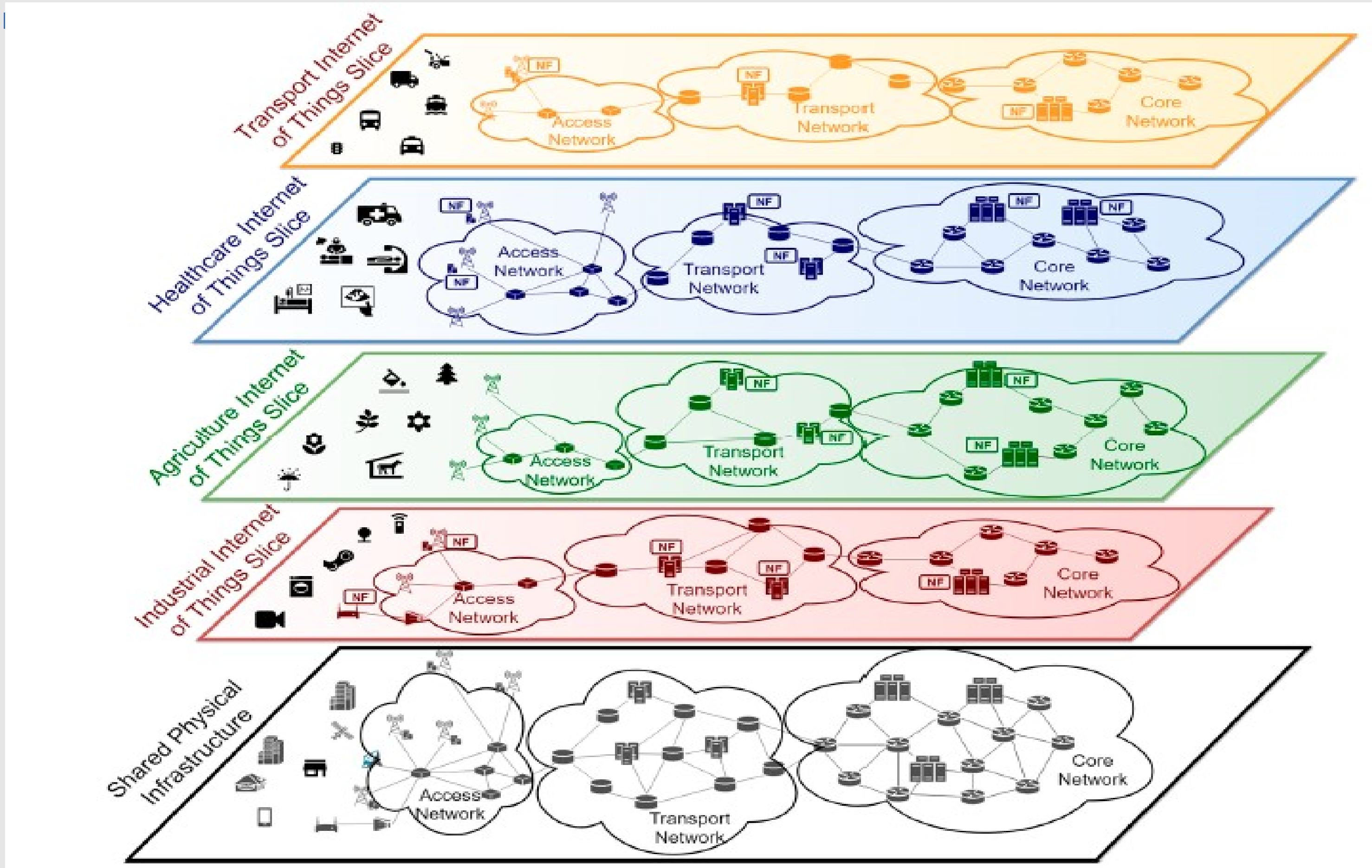
- **5G -Current and Future Use Cases in Consumer and IoT Markets**



Source: SIERRA WIRELESS White Paper, "5G for IoT?", https://www.sierrawireless.com/resources/white-paper/5g-for-iot/

6. 5G connectivity solutions for IoT

- **5G –slices for IoT - examples**



Source: J.M Fernandez I.Vidal and F.Valera, "Enabling the Orchestration of IoT Slices through Edge and Cloud Microservice Platform", Sensors 2019, 19, 2980; doi:10.3390/s19132980, www.mdpi.com/journal/sensors

6. 5G connectivity solutions for IoT

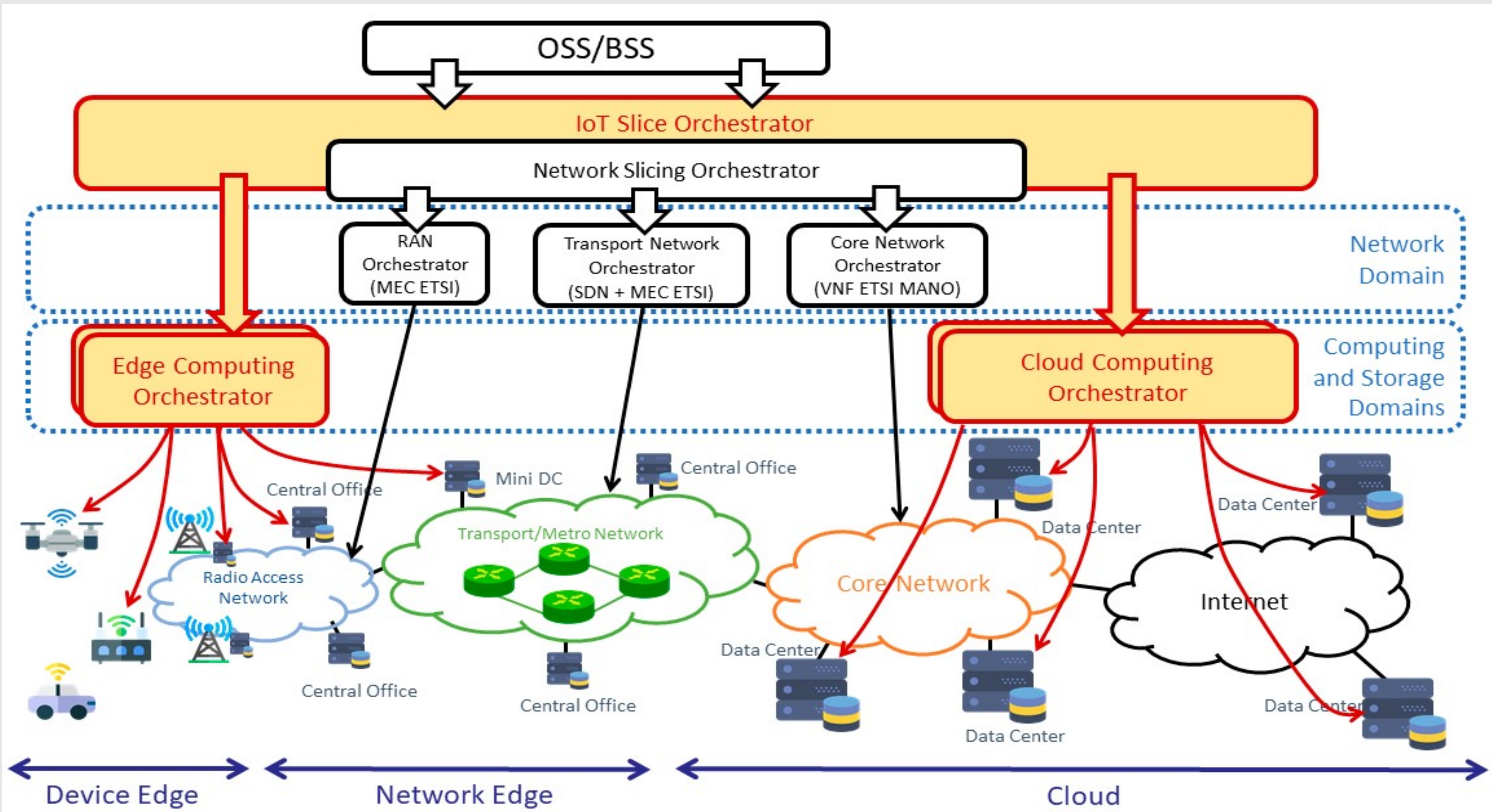
- **5G –slices for IoT – general slice orchestration solution -** example

  Source : J.M Fernandez I.Vidal and F.Valera, "Enabling the Orchestration of IoT Slices through Edge and Cloud Microservice Platform", Sensors 2019, 19, 2980; doi:10.3390/s19132980, www.mdpi.com/journal/sensors

  - *(See next slide)*
  - **Domains:**
    - Radio Access Networks (RAN)
    - Aggregation and transport networks (ATN)
    - Core networks (CN)
    - Edge/cloud infrastructures (ECI)
  - **Slice types:** End to End, Multi-tenant
- **Why IoT slice orchestration?**
  - **IoT slice orchestrator – main orchestration entity in the system**
    - coordinates the deployment and configuration of the software entities (e.g., case network functions) composing an IoT service, and their inter- connectivity
    - provides an interface to the Operations Support System/Business Support System (OSS/BSS)
      - The OSS/BSS may request to IoT Orchestrator to create IoT slices with specific requirements.
    - includes a *network slice coordinator function* (Network Slicing Orchestrator NSO)
      - NSO coordinates the operation of the diverse (regional) network orchestrators operating locally at each network domain.

6. 5G connectivity solutions for IoT

- **5G –slices for IoT – general slice orchestration solution** example (cont'd)



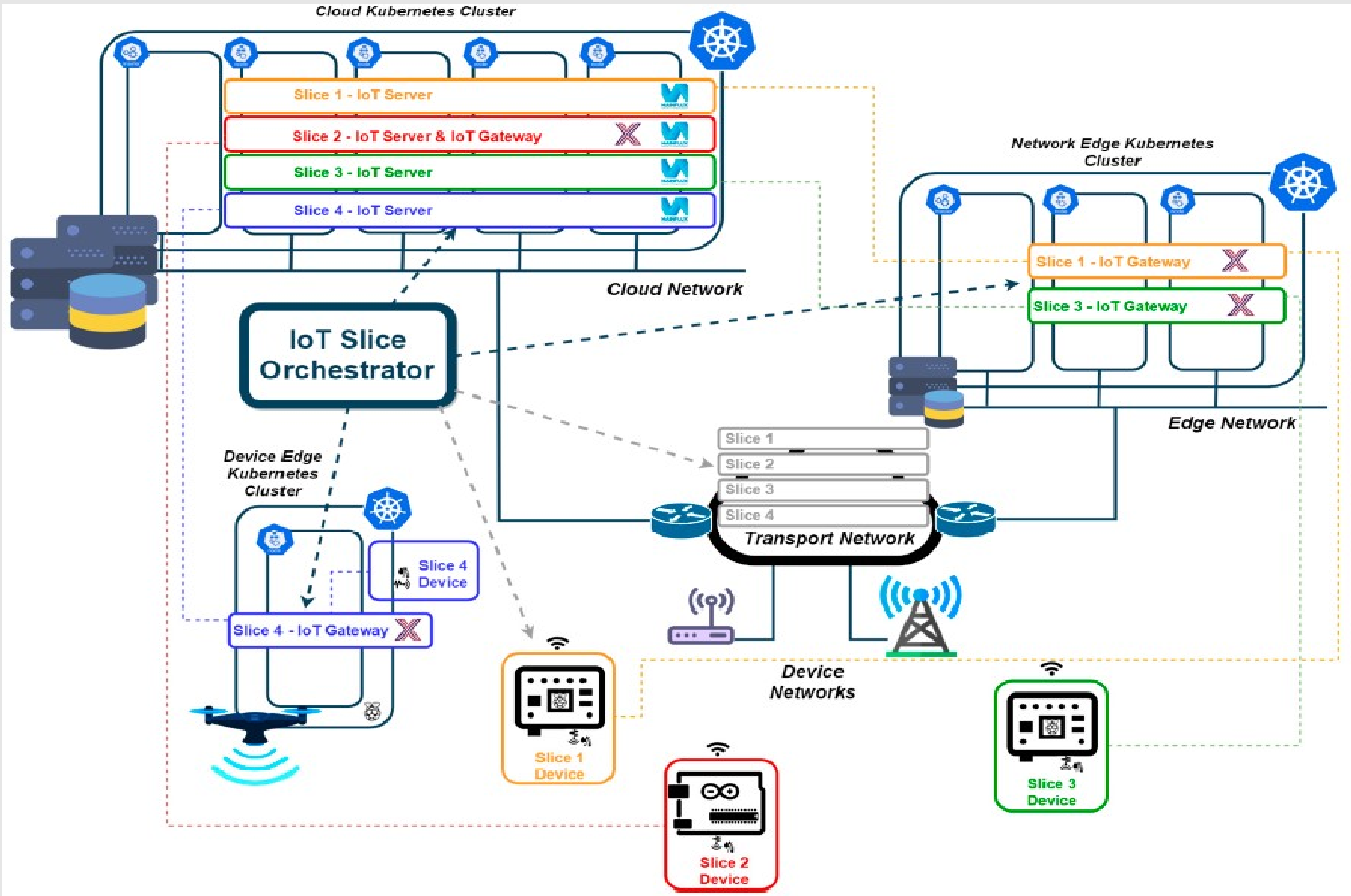
Source : J.M Fernandez I.Vidal and F.Valera, "Enabling the Orchestration of IoT Slices through Edge and Cloud Microservice Platform", Sensors 2019, 19, 2980; doi:10.3390/s19132980, www.mdpi.com/journal/sensors

6. 5G connectivity solutions for IoT

- **5G –slices for IoT – general slice orchestration solution** example (cont'd)
- **Orchestration entities – hierarchy**
  - **IoT Slice Orchestrator**
  - **Network Slicing Orchestrator** - master
  - **Network domains orchestrators**
    - RAN Orchestrator
      - Possible technology : *Multi-access Edge Computing (MEC-ETSI)*
    - Transport network orchestrator – here one can use technologies like
      - *Software Defined Networking (SDN)* to control the connectivity
      - *MEC- ETSI* for edge cloud computing resources
    - Core network orchestrator
      - *Network Function Virtualization* technologies
      - *ETSI Management and Orchestration* functions - ETSI MANO
  - **Edge Computing Orchestrator**
    - under control of the IoT Slice Orchestrator
    - orchestrates the edge computing functions (in RAN and Transport networks)
  - **Cloud Computing Orchestrator**
    - under control of the IoT Slice Orchestrator
    - orchestrates the central cloud computing functions (Data Ceters connected to Core network or Internet)

6. 5G connectivity solutions for IoT

- **5G –slices for IoT – general slice orchestration solution** (cont'd)
  - **Implementation example**



Source : J.M Fernandez I.Vidal and F.Valera, "Enabling the Orchestration of IoT Slices through Edge and Cloud Microservice Platform", Sensors 2019, 19, 2980; doi:10.3390/s19132980, www.mdpi.com/journal/sensors

6. 5G connectivity solutions for IoT

- **5G –slices for IoT – general slice orchestration solution** (cont'd)
- **Implementation example (cont'd)**
  - **Principles: microservices**
  - **IoT Gateway** functions (e.g., Edge X Foundry)
  - **IoT Server** functions (e.g. Mainflux)
  - **Implementation Support example**
    - *Kubernetes*
      - System for management of *open source* containers for implementaion automation, scaling and application distribution
      - It offers an automation platform for containerised systems (e.g., . Docker)
      - REST interfaces related to IoT functions orchestration and mcroservces which compose these functions
    - The IoT Orchestrator IoT can deploy *deploy*) IoT servers and IoT Gateways in different locations *(edge/cloud)*
      - In previous slide example the locations are *Kubernetes clusters;* however, any infrastructure (which could host virtualized applications) could be used instead
    - The *cloud network*, *transport network* si *edge network are organized in slices*
    - The IoT Slice Orchestrator controls the subordinate entities in a hub style

6. 5G connectivity solutions for IoT

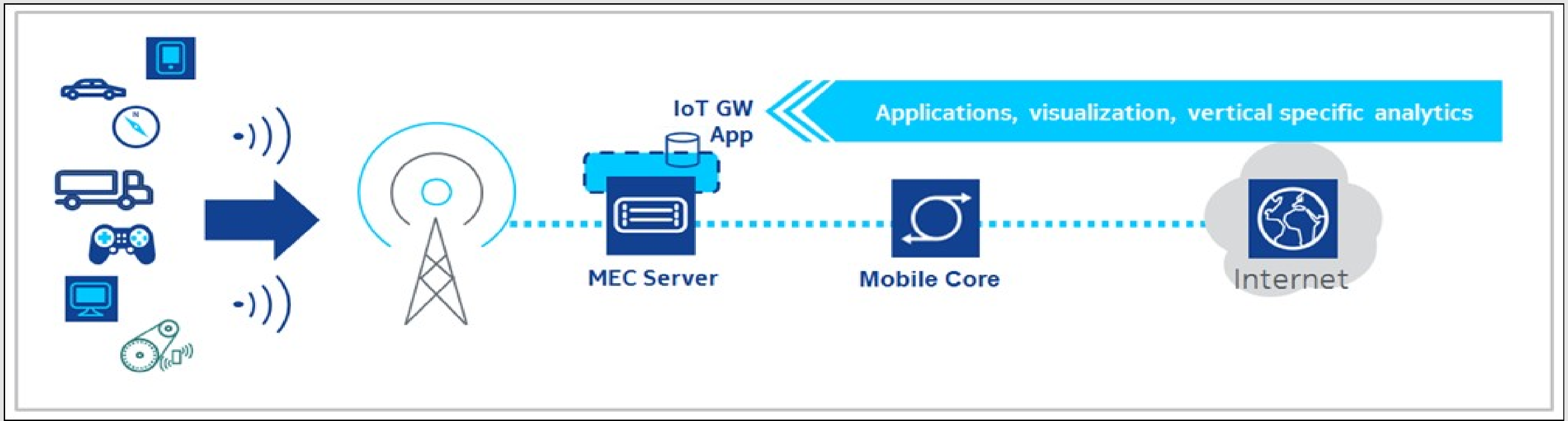
- **5G – IoT and Multi-access Edge Computing (MEC)**

- **Multi-access Edge Computing (** former Mobile Edge Computing)
  - currently being standardized in an ETSI ISG)
  - provides an IT service environment and cloud-computing capabilities at the edge of the mobile network, within the RAN and in close proximity to mobile subscribers
  - **low latency, proximity, high bandwidth, and real-time insight into radio network information and location awareness**
  - natural development in the evolution of mobile base stations and the convergence of IT and telecommunications networking
  - based on a virtualized platform
  - recognized by the **European 5G PPP** (5G Infrastructure Public Private Partnership) as one of the **key emerging technologies for 5G networks** together with
    - Network Functions Virtualization (NFV)
    - Software-Defined Networking (SDN)

  - **IoT is one of the most important MEC application instances**
  - benefits of employing MEC into IoT systems
    - E.g. lowering the amount of traffic passing through the infrastructure and reducing the latency for applications and services
    - Environment/location awareness

6. 5G connectivity solutions for IoT

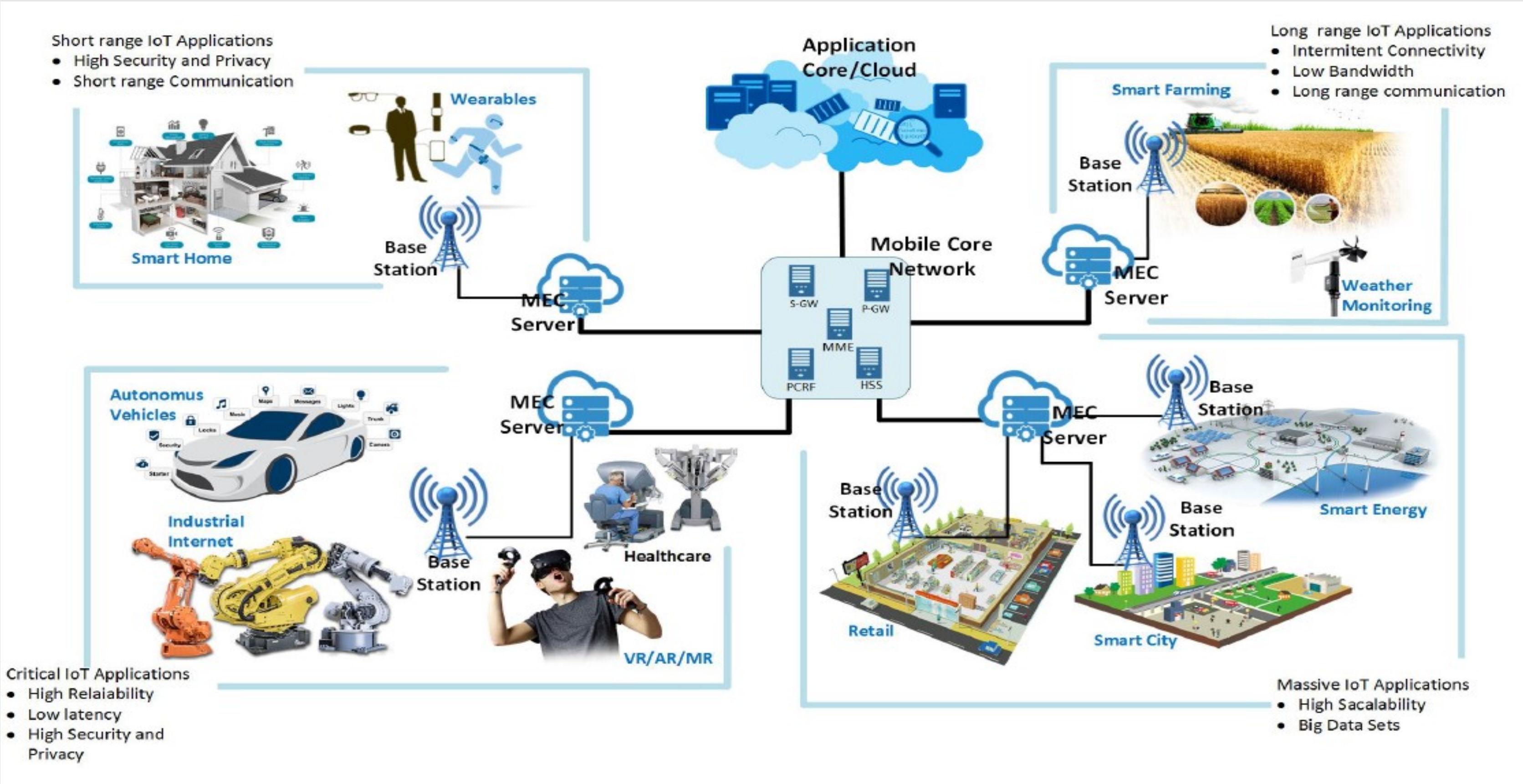
- **5G – IoT and Multi-access Edge Computing**
  - **Example 1: IoT Gateway**
  - IoT requires gateways to aggregate the messages and ensure low latency and security.
  - a real time capability is required and a grouping of sensors and devices is needed for efficient service.
  - IoT devices are resource constrained
    - need to aggregate various IoT device messages connected through the mobile network close to the devices
    - This also provides an analytics processing capability and a low latency response time
    - **MEC could be the solution**



Source: Y.-C. Hu, M. Patel, D. Sabella, N. Sprecher, and V. Young, "Mobile Edge Computing A Key Technology Towards 5G," ETSI White Paper, vol. 11, no. 11, pp. 1–16, 2015.

6. 5G connectivity solutions for IoT

- **5G – IoT and Multi-access Edge Computing** (cont'd)
  - **Example 2:Using MEC for different IoT applications…**



Source: Y.-C. Hu, M. Patel, D. Sabella, N. Sprecher, and V. Young, "Mobile Edge Computing A Key Technology Towards 5G," ETSI White Paper, vol. 11, no. 11, pp. 1–16, 2015.

Contents

1. Introduction
2. IoT connectivity
3. Short range technologies
4. Mid-long range technologies
5. Cellular technologies for IoT
6. 5G connectivity solutions for IoT
7. ⇨ Selection of IoT communication technology
8. Conclusions

7. Selection of IoT communication technology

- **Selection problem**
- **Many IoT application types, many available technologies for communication and IoT platforms → selection problems**
  - The developers’ decision process should be based on a methodology that would make the decision process repeatable and sustainable
  - The methods should consider *pros* and *cons* of several points of view that affect the decision process
  - Estimating and choosing the wireless communication technology (WCT) is a complicated process for reasons, such as:
    - **Multi-criteria evaluation** in the WCT selection- factors
      - Set of use cases to be developed
      - Business model/ecosystem
      - Economical factors (costs, CAPEX, OPEX)
      - Technical (availability, complexity, coverage, security, scalability, inter-operability, etc.)
    - preliminary consideration of all possible stages of decision making
    - considering all important criteria when choosing a solution
    - determination of the priority of the criteria and their weight coefficients

7. Selection of IoT communication technology

- **Some more popular communication protocols (on hype 2018-2019)**
  - IEEE 802.11ax: Successor to IEEE 802.11ac
  - Li-Fi: Light Fidelity. Optical wireless at 100+ Gbps1
  - IEEE 802.11ah
  - Thread: Networking over 802.15.4 using IPv6 over 6LowPAN3
  - LPWA: Low Power Wide Area Network4
  - Lora: Long-Range, LoRaWAN
  - Sigfox
  - RPMA: Random Phase Multiple Access. Proprietary LPWA
  - Cellular: 5G, NB-IoT, LTE-M
  - OneM2M: Consortium of eight standards organization for M2M IoT

7. Selection of IoT communication technology

- **IoT applications**, **use-cases** and appropriate **connectivity technologies**

Requirement	App. category	Use-cases (e.g.,)	Connectivity technologies
End-user-type	Human-oriented	Smart phone	Legacy cellular technologies, LTE/LTE-A, 5G, WiFi/WiFi HaLow, OWC
	Machine-oriented	Monitoring sensors	Bluetooth/BLE, ZigBee, LPWAN, WiFi/WiFi HaLow, OWC
Data rate	High data-rate	Streaming video cameras	LTE/LTE-A, 5G, OWC, WiFi
	Medium data-rate	Connected cooking systems	Bluetooth/BLE, ZigBee, LTE-M, WiFi HaLow
	Low data-rate	Energy & water meters	NB-IoT, Sigfox, LoRa, ZigBee
Latency	Delay-sensitive	Autonomous vehicles, health-care sensors	LTE/LTE-A, 5G, OWC, WiFi/WiFi HaLow, Bluetooth/BLE, LTE-M
	Delay-tolerant	Waste management sensors	ZigBee, Sigfox, NB-IoT, LoRa
Coverage	Long-range	UAVs, smart farming sensors	LTE/LTE-A, 5G, LoRa, Sigfox, NB-IoT, LTE-M, WiFi HaLow
	Short-range	Smart home appliances	Bluetooth/BLE, ZigBee, OWC, WiFi
Power	Low power	Tracking sensors, smart retail sensors	Bluetooth, ZigBee, LTE/LTE-A, 5G, WiFi
	Ultra low power	Pollution monitoring sensor	BLE, WiFi HaLow, LPWAN: LoRa, Sigfox, LTE-M, NB-IoT
Reliability	Mission critical	Real-time patient surveillance, autonomous vehicles	LTE/LTE-A, 5G, WiFi/WiFi HaLow, OWC
	Mission non-critical	Smart farming sensors	LPWAN: LoRa, Sigfox, LTE-M, NB-IoT
Mobility	High mobility	Autonomous vehicles	LTE/LTE-A, 5G
	Low mobility	Smart traffic lights	LPWAN, Bluetooth/BLE, ZigBee

Source: J.Ding, M.Nemati, C.Ranaweera, and J.Choi, "IoT Connectivity Technologies and Applications:A Survey" arXiv:2002.12646v1 [eess.SP] 28 Feb 2020.

7. Selection of IoT communication technology

- **Network/ Communication selection criteria (requirements) for IoT LPWAN deployment**
  - Low Power Wide Area Networks (LPWANs) are the fastest growing IoT communication technology and are a key driver for global IoT connections.
  - With various LPWAN solutions and vendors available today, choosing the right technology for is a complex task.
  - The LPWAN solution determine its performance in the criteria discussed below
  - Selecting the right solution requires weighing these criteria according to wanted IoT application requirements and measure different LPWAN options based on the defined criteria.
  - **Network Capacity**
    - A large network capacity allows scaling with growing demand in data acquisition points without compromising QoS.
    - As the radio range is similar across LPWAN technologies, network capacity becomes an important indicator of infrastructure capability.
    - Efficient use of the limited radio spectrum, or spectrum efficiency, is important in achieving a large network capacity
    - An ultra-narrowband approach with minimal bandwidth usage provides a very high spectrum efficiency, allowing more messages to fit into an assigned frequency band without overlapping each other.
    - LPWAN systems employing asynchronous communication need a mitigation scheme to prevent packet collisions (*i.e.* self-interference) as the number of messages and transmission frequency increase

7. Selection of IoT communication technology

- **Network/ Communication selection criteria (requirements) for IoT LPWAN deployment** (cont'd)
- **Data Rates**
  - Most IoT remote monitoring applications are rather latency tolerant and only need to transmit data periodically
  - As faster data rates often come with trade-offs in range and power consumption, opting for the solution that best balance these criteria will benefit the Return-on-Investment (ROI)
- **Variable Payload Size**
  - Payload or user data size should be driven by actual application needs rather than fixed by a certain technology
  - LPWAN solutions with variable payload size allow users to seamlessly integrate new use cases into their existing network infrastructure—regardless of the payload requirement
- **Reliability**
  - For LPWAN, operating in the increasingly congested, license-free spectrum interference resilience is a prerequisite to ensure high reliability
  - An LPWAN's communication technology should be able to avoid interference or packet collisions when the traffic is high
  - A robust technology combines a number of versatile approaches like narrow bandwidth usage, short on-air radio time, frequency hopping techniques and forward error correction to minimize contention likelihood

7. Selection of IoT communication technology

- **Network/ Communication selection criteria (requirements) for IoT LPWAN deployment** (cont'd)
- **Security**
  - Multi-layer, end-to-end encryption should be natively embedded in the network to protect message confidentiality against eavesdropping and potential breaches
  - Advanced Encryption Standard (AES) is a lightweight, powerful cryptographic algorithm for data encryption in IoT networks
  - Typically, 128-bit AES can be used to establish network-level security for data communications over the air interface from end nodes to the base station.
  - Transport Layer Security (TLS) protocol for backhaul connection provides a complementary security layer to protect IP-based data transfer to the cloud
  - The most secure LPWAN technologies should also incorporate message authentication mechanisms to confirm message authenticity and integrity
- **Operating Frequency**
  - Due to the high-cost barrier of licensed bands, most LPWAN vendors leverage license-free ISM frequency bands for faster technology development and deployment
  - There are many ISM bands available today, but there are some differences between 2.4 GHz band and sub-GHz bands.
  - LPWAN operating at 2.4 GHz provides higher data throughput at the expense of shorter range and battery life.
  - 2.4 GHz radio waves have weaker building penetration and are exposed to much higher co-channel interference

7. Selection of IoT communication technology

- **Network/ Communication selection criteria (requirements) for IoT LPWAN deployment** (cont'd)
- **Mobility Support**
  - Mobility support is necessary in some applications
  - Moving devices, moving BS or moving obstacles along the propagation path → Doppler shifts and deep fading leading to packet errors
  - LPWAN technologies that lack resistance against Doppler effects can only support data communications from stationary or slow-moving end devices
  - This limits their applicability in specific IoT use cases such as fleet management
  - These networks may fail to connect nodes operating in fast-changing environments (e.g. vehicular 100km/hour speed)

- **Battery Life**
  - LPWAN technologies share some common approaches to reduce power consumption
  - However, battery life is different in different systems.
  - One should consider those solutions that provide sufficiently long life of the batteries
  - E.g., . in cellular-based LPWANs, synchronous communications with heavy overheads and handshaking requirements also quickly drain power

7. Selection of IoT communication technology

- **Network/ Communication selection criteria (requirements) for IoT LPWAN deployment** (cont'd)
- **Public vs Private Network**
  - One need to consider which one suits the requirements better—a public or a private network
  - The advantage of public LPWANs run by network operators is infrastructure cost savings
  - However, public LPWANs create dependency on the provider's network
  - Public LPWANs leave coverage gaps in many areas and nodes operating at the network edge often suffer from unreliable connections
  - Another major drawback of public networks is data privacy concern over the centralized back-end and cloud server
  - Private networks allow for rapid deployments by end users with flexibility in network design and coverage based on their own needs.

- **Proprietary vs. Standard**
  - Industry-standard LPWAN technologies with a software-defined approach help avoid the problem of vendor lock-in while promoting long-term interoperability
  - Adopters have the flexibility to adapt to future technological trends and changing corporate needs
  - The solutions standardized and recognized by a Standards Development Organization also deliver guaranteed credibility and Quality-of-Service

7. Selection of IoT communication technology

- **Selection of an IoT platform- general factors to consider**
- Apart from communication technology, the (IoT) function need software, including middleware, known as an IoT or **IoT cloud platform**
- As a form of middleware, an IoT platform, sits between the layers of IoT devices and IoT gateways (and thus data) on one hand and applications, which it enables to build, on the other (hence why IoT platforms are also called Application Enablement Platforms or AEPs
- An IoT platform enables IoT device and endpoint management, connectivity and network management, data management, processing and analysis, application development, security, access control, monitoring, event processing and interfacing/integration

- The market of IoT platforms is complex as IoT projects, applications and solutions come with different architectures, communication technology (IoT device management), possibilities to manage and analyze data, capabilities to build applications and options to leverage IoT for any given IoT use case in any given context: consumer applications, enterprise IoT applications and Industrial IoT or Industry 4.0

- **The success of an IoT system depends strongly also on the selection of a “good” IoT platform**

- The selection problem is actually a multi-criteria one, so multi-criteria decision algorithms could be used to systematically select a solution among the available ones.

Adapted from source: M.Ullah, et al., "Twenty-one key factors to choose an IoT platform: Theoretical framework and its applications", arXiv:2004.04924v1 [eess.SY] 10 Apr 2020

7. Selection of IoT communication technology

- **Selection of an IoT platform- general factors to consider**
- Apart from communication technology, the (IoT) function need software, including middleware, known as an IoT or **IoT cloud platform**
- As a form of middleware, an IoT platform, sits between the layers of IoT devices and IoT gateways (and thus data) on one hand and applications, which it enables to build, on the other (hence why IoT platforms are also called Application Enablement Platforms or AEPs
- An IoT platform enables IoT device and endpoint management, connectivity and network management, data management, processing and analysis, application development, security, access control, monitoring, event processing and interfacing/integration

- The market of IoT platforms is complex as IoT projects, applications and solutions come with different architectures, communication technology (IoT device management), possibilities to manage and analyze data, capabilities to build applications and options to leverage IoT for any given IoT use case in any given context: consumer applications, enterprise IoT applications and Industrial IoT or Industry 4.0

- **The success of an IoT system depends strongly also on the selection of a "good" IoT platform**

- The selection problem is actually a multi-criteria one, so multi-criteria decision algorithms could be used to systematically select a solution among the available ones.

Adapted from source: M.Ullah, et al., "Twenty-one key factors to choose an IoT platform: Theoretical framework and its applications", arXiv:2004.04924v1 [eess.SY] 10 Apr 2020

7. Selection of IoT communication technology

- **Selection of an IoT platform- general factors to consider**

- **Business and development factors**
  - **Pricing model and business case**
    - some platform have a low price at the start of a contract agreement, after which the price increases
    - some providers offer a low price, but the contract includes limited features and additional features have a significant cost if included

  - **Time-to-market**
    - the platform provider should support during the action sequence from product conception to sale
    - some IoT platform providers offer quick-start packages which can reduce time-to-market

  - **Stability**
    - taking care that many platforms are in the market, with possible open issues
    - need to choose a platform having high chances of survival in the market
    - information can be obtained from previous customers using the same platform
    - the IoT platform should support integration with open source ecosystems

Adapted from source: M.Ullah, et al., "Twenty-one key factors to choose an IoT platform: Theoretical framework and its applications", arXiv:2004.04924v1 [eess.SY] 10 Apr 2020

7. Selection of IoT communication technology

- **Selection of an IoT platform- general factors to consider**
- **Business and development factors (cont'd)**
  - **Platform provider previous experience**
    - check whether the IoT platform provider has previous successful experience of work similar to that wanted for the new IoT system development
  - **Backward compatibility**
    - Generally, IoT devices are designed to work with a variety of infrastructure systems.
    - One should evaluate how new generations of technology can cooperate with legacy technology
  - **Data ownership**
    - to consider that different jurisdictions have different laws and legal interpretations (e.g., EU versus US)
    - get knowledge of data rights and the territorial scope of data protection for the IoT platform provider
  - **Cloud infrastructure ownership**
    - the HW infrastructure cost is high --> some smaller IoT platform providers only offer the software layer
    - some providers certify their platform on single or multiple leading public cloud providers and mostly run their services on a single leading platform
    - to check the compatibility of the broader enterprise cloud with the IoT platform provider
  - **Interoperability**
    - the IoT platform solution is a middleware
    - the data collected are used by many applications and may not be available on the platform itself

7. Selection of IoT communication technology

- Selection of an IoT platform- general factors to consider (cont'd)
- **Technical factors**
  - **Scalability and flexibility**
    - a company will expand its IoT business in time; therefore the IoT platform provider should support the business throughout its development
      - the platform should be scalable to new business needs
      - the platform should be flexible w.r.t rapid changing technology
  - **Security factors and requirements**
    - device to-cloud network security, data encryption
    - application authentication, secure session initiation
    - application authentication
    - cloud security
    - device security (authentication and up-to-date certification)
  - **Data analytics and visualization tools**
    - identify the data analysis and information visualization requirements
    - establish which platform offers better agregation, analysis and visualization of data
    - how the IoT platform integrates leading analytics toolsets and uses them to replace built-in functionality

7. Selection of IoT communication technology

- **Selection of an IoT platform- general factors to consider** (cont'd)
- **Technical factors**
  - **Higher layer protocols**
    - Apart from connectivity related protocols, also the higher layer ones are important
      - (e.g., MQTT, HTTP, AMQP, CoAP)
      - Example: binary nature- MQTT is lightweight (lower overheads)
    - new devices are coming onto the market --> the selected IoT platform should support new protocols or upgrading actions
  - **System performance**
    - automatic event-triggered signaling should be possible
    - analysis of platform capabilities to process large number of events
    - time response for critical missions
  - **Redundancy and disaster recovery**
    - either natural or man-made eventscan occur
    - IoT platform should have dedicated infrastructure to handle data during such occurrences
    - consideration of the the data backup plan schedule and whether the IoT platform has failover cluster provision

7. Selection of IoT communication technology

- **Selection of an IoT platform- general factors to consider** (cont'd)
- **Technical factors**
  - **Application environment**
    - which applications are deployable on the platform
    - what are the characteristics of the application development environment
    - what are the common interfaces
  - **Hybrid cloud**
    - some IoT platforms can fit with existing IT systems hosted on company premises
    - so, a hybrid cloud is useful
      - mission critical processes can be handled locally
      - public and less critical operations can be managed by the platform
  - **Friendly interfaces**
    - They should be simple and user friendly
    - all the services offered to the customers should be easy to access.

7. Selection of IoT communication technology

- **Selection of an IoT platform- general factors to consider** (cont'd)
- **Technical factors**

  - **Platform migration**
    - as a company grows, a bigger IoT platform provider may be needed
    - one should ensure that the selected IoT platform provider provides clearly documented interfaces, schema, and API for any possible future migration to other IoT platforms

  - **Network bandwidth**
    - the IoT platform needs low latency and high bandwidth networking.
    - it should be ascertained that a potential IoT platform provider has a large data pipe and sufficient room to grow

  - **Edge intelligence and processing capabilities**
    - The future systems will be more distributed
    - IoT platforms should have have offline and edge intelligence to make local decisions instead of waiting for every decision from the cloud
    - it should be checked if the IoT platform could support new topologies and utilize edge intelligence

Contents

1. Introduction
2. IoT connectivity
3. Short range technologies
4. Mid-long range technologies
5. Cellular technologies for IoT
6. 5G connectivity solutions for IoT
7. Selection of IoT communication technology
8. Conclusions

8. Conclusions

- **IoT connectivity** subsystem – essential part of the IoT assembly
- Large set of technologies and protocols are available
  - Usually adapted for low bit rate, low power devices
  - Short, medium and long ranges
  - Protocols of different layers
  - Working in licensed or unlicensed bands

- **Low power technologies** - attractive (802.11x, ZigBee, BLE, OWC, LPWAN, ..)
  - Low cost, low complexity
  - Criteria of selection: fitness to applications, data-rate, short-mid-long range, open/proprietary, security, etc

- **Cellular systems** – strong candidates to support IoT connectivity in complex systems
  - LTE-A (NB-IOT, LTE-M, ..)
  - Emergent 5G – able to support
    - Many terminals, High bit rates
    - High density, Low power devices (possible)
    - Flexibility, virtualization
    - ….

8. Conclusions

- **5G-IoT Research challenges and future directions**
  - Scalability
  - Security and privacy
  - Management of resources at lower layers
  - Network and services management
  - Interoperability (with other IoT technologies)and heterogeneity
  - Network mobility and coverage

  - **Many 5G slicing and MEC topics - still open research issues - in IoT environment**
    - Multi-domain
    - Multi-tenant
    - Multi-operator
    - E2E
    - Slice creation, isolation, maintenance
    - ….

Thanks!
Questions?

eugen.borcoci@elcom.pub.ro

References – selective list

1. L.Atzori, A.Iera, G.Morabito, “Understanding the Internet of Things: definition,potentials, and societal role of a fast evolving paradigm”, Elsevier, 2016. DOI: http://dx.doi.org/10.1016/j.adhoc.2016.12.004
2. R,Khan et al., “Future Internet: The Internet of Things Architecture, Possible Applications and Key Challenges”, Dec. 2012, https://www.researchgate.net/publication/261311447
3. K. Rose, S.Eldridge, L.Chapin, "IoT: An Overview" WWW.INTERNETSOCIETY.ORG, 2015
4. ITU-T S.Tabanne, “IoT systems overview”, 30 Sept.-03 Oct. 2019, Bangkok, Thailand, https://www.itu.int/en/ITU-D/Regional-Presence/AsiaPacific/SiteAssets/Pages/Events/2019/ITU-ASP-CoE-Training-on-/IoT%20systems%20overview.pdf
5. J.Ding, M.Nemati, C.Ranaweera, and J.Choi, "IoT Connectivity Technologies and Applications:A Survey" arXiv:2002.12646v1 [eess.SP] 28 Feb 2020.
6. “IoT Standards and Protocols”, https://www.postscapes.com/internet-of-things-protocols/#protocols
7. ITU-T, S.Tabanne, "Internet of Things: A technical overview of the ecosystem", “Developing the ICT ecosystem to harness Internet-of-Things (IoT)”, 28-30 June 2017, Mauritius
8. 5G-PPP Architecture Working Group, “View on 5G Architecture”, Version 3.0, June, 2019, https://5g-ppp.eu/wp-content/uploads/2019/07/5G-PPP-5G-Architecture-White-Paper_v3.0_PublicConsultation.pdf, [retrieved June, 2020].
9. 5G Americas white Paper, “5G A future of IoT”, July 2019, https://www.5gamericas.org/5g-the-future-of-iot/
10. SIERRA WIRELESS White Paper, "5G for IoT?", https://www.sierrawireless.com/resources/white-paper/5g-for-iot/
11. Y.-C. Hu, M. Patel, D. Sabella, N. Sprecher, and V. Young, “Mobile Edge ComputingA Key Technology Towards 5G,” ETSI White Paper, vol. 11, no. 11, pp. 1–16, 2015.
12. https://www.slideshare.net/butler-iot/butler-project-overview-13603599
13. T.Salman, R.Jain “Networking Protocols and Standards for Internet of Things”, 2015 https://www.cse.wustl.edu/~jain/cse570-15/ftp/iot_prot/
14. T.Salman, R.Jain, “A Survey of Protocols and Standards for Internet of Things, Advanced Computing and Communications,” Vol. 1, No. 1, March 2017.
15. P.Porambage,et.al., "Survey on Multi-Access Edge Computing for IoT Realization", arXiv:1805.06695v1 [cs.NI] 17 May 2018
16. J.M Fernandez I.Vidal and F.Valera, "Enabling the Orchestration of IoT Slices through Edge and Cloud Microservice Platform“, Sensors 2019, 19, 2980; doi:10.3390/s19132980, www.mdpi.com/journal/sensors

References – selective list

16. ITU-R M.2083, IMT 2020 Vision - Framework and overall objectives of the future development of IMT for 2020 and beyond, December 2017.
17. ITU-R M.2412-0, Guidelines for evaluation of radio interface technologies for IMT-2020, December 2017.
18. ITU-R M.2410-0, Minimum requirements related to technical performance for IMT-2020 radio interface(s), December 2017. 3GPP TR 38.913, Study on Scenarios and Requirements for Next Generation Access Technologies, August 2016.
19. 3GPP TS 22.368, “Service requirements for machine-type communications (mtc),” V13.1.0, 2014.
20. B.S.Chaudhari, M.Zennaro and S.Borkar, "LPWAN Technologies: Emerging Application Characteristics, Requirements, and Design Considerations", Future Internet 2020, 12, 46; doi:10.3390/fi12030046 www.mdpi.com/journal/futureinternet
21. EdgeX Foundry Documentation. Available online: https://docs.edgexfoundry.org/index.html (accessed March 2019).
22. Mainflux Documentation. Available online: https://mainflux.readthedocs.io/en/latest/ (accessed March 2019).
23. Kubernetes Documentation. Available online: https://kubernetes.io/docs/home/ (accessed March 2019).
24. G. A. Akpakwu et al., "A Survey on 5G Networks for the IoT : Communication Technologies and Challenges", IEEE Access, February 2018, Digital Object Identifier 10.1109/ACCESS.2017.2779844
25. M.Andersson , “Use case possibilities with Bluetooth low energy in IoT applications “White paper www.u-blox.com , UBX-14054580 - R01
26. G.Mazzi, "Zigbee Wireless Communication Protocol" 2019 EDALAB, https://edalab.it/en/zigbee-wireless-communication/
27. M.Ullah, et al., "Twenty-one key factors to choose an IoT platform: Theoretical framework and its applications", arXiv:2004.04924v1 [eess.SY] 10 Apr 2020
28. R.Contreras-Masse1,et al., "Selection of IoT Platform with Multi-Criteria Analysis: Defining Criteria and Experts to Interview", Research in Computing Science 148(11), 2019, https://www.researchgate.net/publication/339918356_Selection_of_IoT_Platform_with_Multi-Criteria_Analysis_Defining_Criteria_and_Experts_to_Interview
29. S.Tabanne, "IoT Standards, Part I: IoT Technology and Architecture", September 2018, Bandung – Indonesia, https://www.itu.int/en/ITU-D/Regional-Presence/AsiaPacific/Documents/Events/2018/IoT-BDG/IoT%20Standards%20Part%20I%20Sami.pdf
30. A. Hakifaz Mohd Amanm "A Survey on Trend and Classification of IoT Reviews", IEEE Acces, 2020, DOI 10.1109/ACCESS.2020.3002932

References – selective list

31. M.A.Ertürk, et al., "A Survey on LoRaWAN Architecture, Protocol and Technologies", Future Internet 2019, 11, 216; doi:10.3390/fi11100216
32. Srinivasa A H, Dr.Siddaraju, "A Comprehensive Study Of Architecture, Protocols And Enabling Applications In Internet Of Things (Iot)", ,INTERNATIONAL JOURNAL OF SCIENTIFIC & TECHNOLOGY RESEARCH VOLUME 8, ISSUE 11, NOVEMBER 2019 ISSN 2277-8616, 1767, IJSTR©2019, www.ijstr.org
33. H. S. Dhillon et al., "Wide-Area Wireless Communication Challenges for 4th3e Internet of Things," IEEE Communications Magazine, February 2017
34. Raj Jain, "Low Power WAN Protocols for IoT: IEEE 802.11ah, LoRaWAN, Sigfox", http://www.cse.wustl.edu/~jain/cse574-18/

List of Acronyms

3GPP 3rd Generation Partnership Project (3GPP)
6Lo IPv6 over Networks of Resource Constrained Nodes
6LoWPAN IPv6 over Low Power Wireless Personal Area Networks
6TiSCH IPv6 over Time Slotted Channel Hopping Mode of IEEE 802.15.4e
ALME Abstraction Layer Management Entity
AMQP The Advanced Message Queuing Protocol
AV Audio-Visual
CA Collision Avoidance
CARP Channel-Aware Routing Protocol
CoAP Constrained Application Protocol
CoRE Constrained RESTful Environment
CORPL Cognitive RPL
CRC Cyclic redundancy check
CSMA Carrier Sense Multiple Access
CSMA/CA Carrier Sense Multiple Access with Collision Avoidance
DAO Destination Advertisement Object
DAO-ACK DAO Acknowledgment
DASH7 Named after last two characters in ISO 18000-7
DDS Data Distribution Service
DECT Digital Enhanced Cordless Telephone
DECT/ULE Digital Enhanced Cordless Telephone with Ultra Low Energy

List of Acronyms

DODAG Information Object
DIS DODAG Information Solicitation
DODAG Destination Oriented Directed Acyclic Graph
eNB E-UTRAN Node B (4G Base station)
EUI-64 Extended Unique Identifier 64-bit
ETSI- European Telecom Std. Institute
FCAPS Fault, Configuration, Accounting, Performance and Security
FDMA Frequency division multiple access
HART Highway Addressable Remote Transducer Protocol
HomePlug-AV HomePlug Audio-Visual
HomePlugGP HomePlug GreenPHY
IBM International Business Machine Corporation
ICMPv6 Internet Control Message Protocol Version 6
ID Identifier
IEEE Institution of Electrical and Electronic Engineers
IETF Internet Engineering Task Force
IoT Internet of Things
IP Internet Protocol
IPv6 Internet Protocol version 6
ISM Industrial, Scientific and Medical frequency band
ITU-T International Telecommunications Union - Telecommunications
ITU International Telecommunications Union
L2CAP Logical Link Control and Adaptation Protocol
LoRA Long Range
LoRaWAN Long Range Wide Area Network

List of Acronyms

LTE-A Long-Term Evolution Advanced
LTE Long-Term Evolution
MANO Management and Orchestration
M2M Machine to Machine
MAC Media Access Control
MQTT Message Queue Telemetry Transport
NFC Near Field Communication
NFV Network Function Virtualization
OASIS Advancing Open Standards in the Information Society
OFDM Orthogonal Frequency Division Multiplexing
OMG Object Management Group
PA Process Automation
PHY Physical Layer
QoS Quality of Service
RAN Radio Access Network
REST Representational State Transfer
RESTful Representational State Transfer based
RFC Request for Comments
RFID Radio-frequency identification
RPL Routing Protocol for Low-Power and Lossy Networks
SDN Software Defined Networking
SIG Special Interest Group
SMQTT Secure MQTT
SOA Services Oriented Architecture

List of Acronyms

SSL Secure Socket Layer
TCP Transmission Control Protocol
TDMA Time Division Multiple Access
TDMA Time Division Multiple Access
TEDS Transducer Electronic Data sheets
TLS Transport Level Security
TSCH Time-Slotted Channel Hopping
UDP User Datagram Protocol
ULE Ultra-Low Energy
VNF Virtualized Network Function
WIA-PA Wireless Networks for Industrial Automation Process Automation
WiFi Wireless Fidelity
WirelessHART Wireless Highway Addressable Remote Transducer Protocol
WPAN Wireless Personal Area Network
XML Extensible Markup Language
XMPP Extensible Messaging and Presence Protocol