FACULTY
OF INFORMATICS
Masaryk University

Wireless communication

IoT technologies

PV284

Overview I

Overview II

This presentation is intended to introduce IoT aspects, so it does not contain all the details. Change of the content is reserved. The first part introduces the basic principles of wireless communication to understand the terms used. The next part then contains a presentation of IoT.

Basic introduction to radio communication and principles

Knowledge of PV169 and PA151 is an advantage (Written in Czech only)

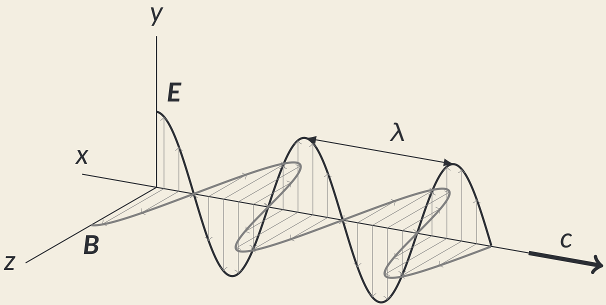
The wireless age, more than 1 and a half centuries have passed

- 1873 – James Clerk Maxwell, mathematical theory of electromagnetic waves
- 1887 – Heinrich Hertz, demonstration of the existence of electromagnetic waves
- 1901 – Guglielmo Marconi, wireless communication
- 1906 – wireless music streaming
- 1920 – Pitsburgh, radio broadcasting (radio)
- 1946 – USA, public mobile telephony network
- 1980 1G, 1990 – 2G, 2000 – 3G public mobile telephony networks
- 2002 – there are more mobile phones than fixed lines
- 202? 6G – Intelligent Mobile Networks
- Parallel development of MAN, LAN, PAN, sensor networks, IoT, . . .

Wireless Transmission

Data is transmitted by the propagation of electromagnetic waves in the environment.

Electromagnetic waves are characterized by three properties – wavelength, frequency and speed of propagation



$$c = \frac{E}{B} \qquad \lambda = \frac{c}{f} \qquad f = \frac{c}{\lambda}$$

E = electric field (amplitude)
B = magnetic field (amplitude)
c = propagation speed in vacuum ($3 \times 10^8 \mathrm{m/s}$)
λ = wavelength
f = frequency

The basic concepts

Wavelength

Wavelength λ [m, cm, mm, ...] – the distance of the two nearest points of a wave oscillating in phase

Frequency

Frequency f [Hz] – number of oscillations per second

Propagation speed

- In a vacuum, the elmag waves propagates at a speed of $c = 3 \times 10^8\ m \cdot s^{-1}$, i.e. 30 cm/ns
- In a transmission medium, the elmag waves propagates at a lower speed, depending on the frequency

The basic concepts

Decibel

is the unit of measure of the ratio between 2 signal levels, decibel gain/loss (attenuation), $G_{dB} = 10\log_{10}\frac{P_{in}}{P_{out}}$, where P denotes power. The decibel is a relative measure, a dimensionless unit, an abstract mathematical unit, not a physical unit. It expresses the relative strength of a signal at two points or the relative strength of two signals

Radio propagation

is the behaviour of radio waves as a form of electromagnetic radiation affected by the phenomena of reflection, refraction, diffraction, absorption, polarization, and scattering.

Radio propagation model

is an empirical mathematical formulation for the characterization of radio wave propagation as a function of frequency, distance and other conditions (Friis transmission equation, Egli models, . . .)

The basic concepts

Bandwidth

as a property of the transmission medium the difference between the highest and lowest frequencies that the medium transmits

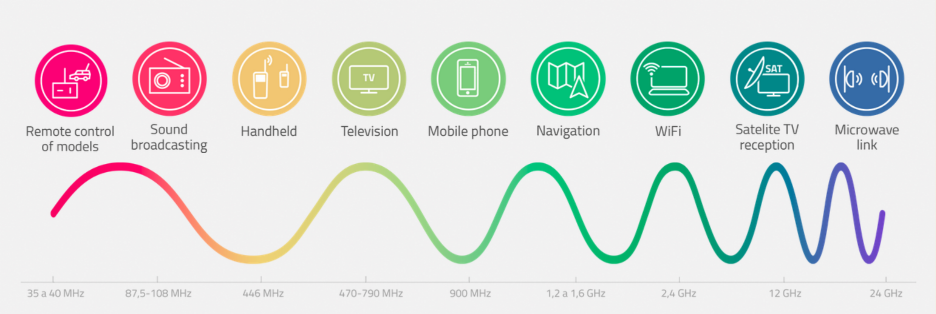


Figure: Radio spectrum utilization. Resource: `https://spektrum.ctu.cz/en/`

ISO RM OSI, where the matter of wireless transmissions is addressed

Layer		Protocol data unit (PDU)	Function
7	Application	Data	Distributed IT services, applications
6	Presentation		Supports application independence on data representation (syntax)
5	Session		Establishes, maintains and terminates connections (sessions) between processes (applications)
4	Transport	Segment, Datagram	Organizes data into/from transport (t)-segments. QoS transfers between end nodes (flow control errors). Addresses processes on the network node
3	Network	Packet	Organizes t-segments into/from packets. Defines the packet flow path between non-neighboring nodes.
2	**Data link**	**Frame**	**Organizes the bit stream into frames. Controls media access, flow and error correction during frame transfer.**
1	**Physical**	**Bit, Symbol**	**The transmission of a stream of bits through a channel regardless of their meaning. Displays 1 and 0 to/from signal elements.**

Internet of Things, IoT

Primary target

- connect (to the Internet) all objects in the home, office, . . . , everywhere in everyday life that can transmit and receive information. Objects – end devices, sensors, . . .
- connect wirelessly
- IoT is changing the vision of sensor networks, these can still be a closed network, but also be open to the Internet

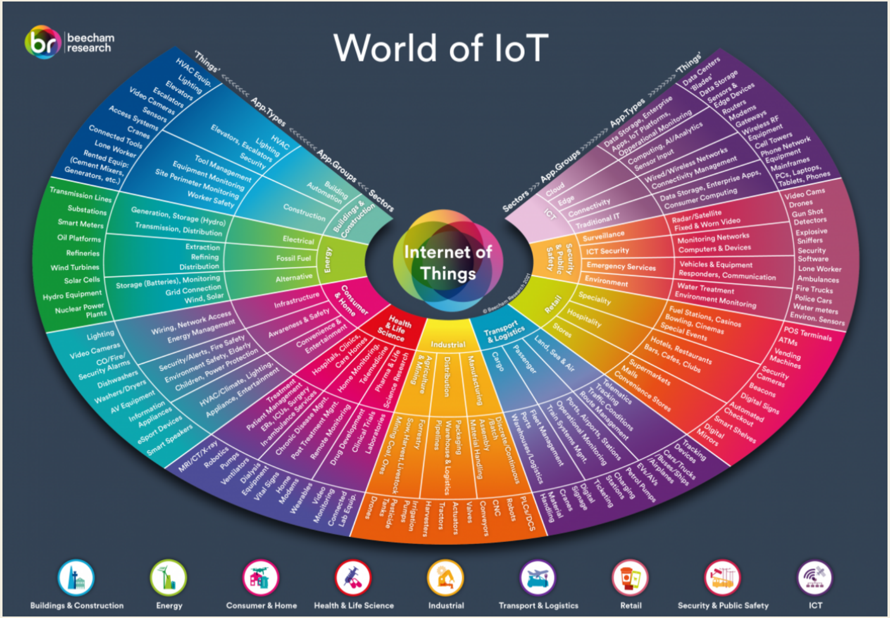
It is not possible to directly integrate „small things" into the Internet, they're not powerful enough to support TCP/IP. Specific gateways and techniques are being developed to connect smart „garbage" to the Internet.

Internet of Things, IoT – application domains

The IoT technologies are used in process automation, home automation, smart cars, decision analytics, smart grids, . . .

- **IoT Sensors** - consist of sensors connected to circuit boards such as Arduino or Raspberry. The circuit boards can be programmed to measure a range of data collected from a sensor device such as temperature, humidity, pressure, vibration, . . .
- **IoT Tracking and Monitoring System** – IoT asset tracking devices use GPS or radio frequency (RF) to track and monitor properties. The smart devices can be used for long-range identification and verification of assets.
- **IoT Connected Factory** – solution such as Azure IoT for management of industrial IoT devices. The connected cloud software can be populated with different resources that allow control of a range of devices.
- **Smart Grid** – is another industrial application of IoT. The grid allows real-time monitoring of data regarding supply and demand of electricity. It involves the application of computer intelligence for the efficient management of resources
- . . .

Internet of Things, IoT – application domains



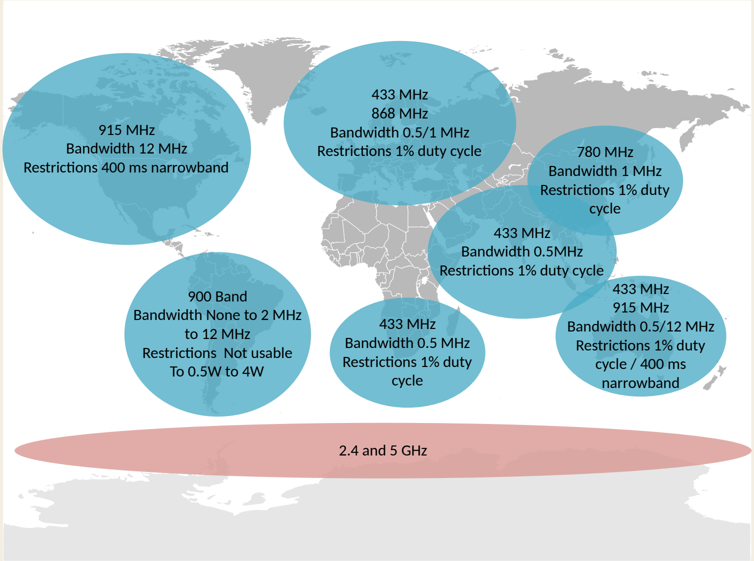
Band Frequencies – Spectrum available for IoT applications

IoT devices have a flexible range of both wired and wireless connectivity options. IoT protocols **mostly use** ISM band frequencies of 433 MHz, 915 MHz, 2.4 GHz to 5 GHz.

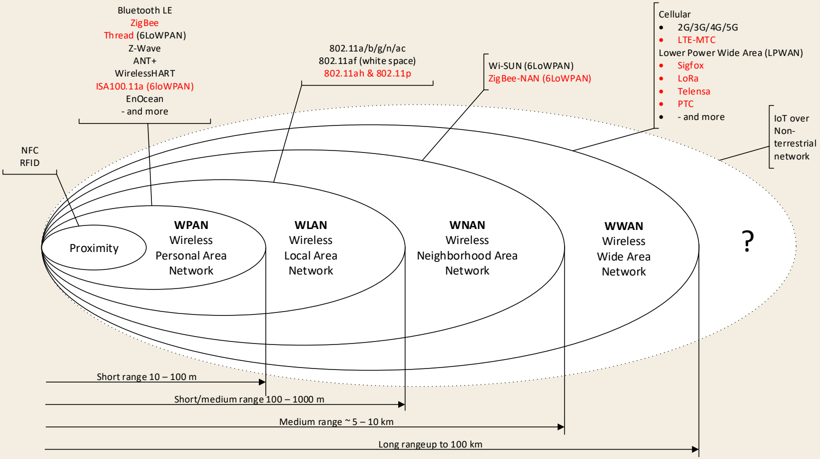
- **ISM** – Industrial, Scientific and Medical frequency band. This is a band of radio and microwave frequencies reserved and designated for industrial, scientific and medical equipment that use RF
- **The 2.4 GHz** – the most common, no need for licensing devices to use it
- **Other ISM frequencies** – can be as high as 24.125 GHz or even as low as 13.56 MHz depending on the location and local acceptance

Allocation of ISM radio frequencies is stipulated by the International Telecommunication Union (ITU). ITU has documented a worldwide ISM allocation table which varies slightly depending on the region

Band Frequencies – Spectrum available for IoT applications



IoT – Wireless Technologies



No stringent definition of what is considered WPAN, WLAN, WWAN. The figure shows a not complete list of radio formats. Emerging IoT technologies.

NFC/RFID

- NFC/RFID is a short-range radio and standards-based wireless connectivity technology that enables communication between devices held or positioned a relatively short distance from one another
- NFC/RFID works over a distance of a few inches up to a meter
- The technology uses inductive coupling, a process that transfers energy through a shared magnetic field between two devices

`https://rfid.atlasrfidstore.com/hubfs/rfid-vs-nfc-infographic.jpg`

2.4 GHz ISM Band – Bluetooth (IEEE 802.15.1)

- PAN, WPAN wireless technology
- Universal short-range wireless connectivity, connects devices (*gadgets*) in a small (personal) area up to 10 m
- Uses 2.45 GHz license-free band
- Connected devices can share speeds up to 2.1 Mbps or 24 Mbps
- Real time voice, data, video
- Ad hoc networking, complete elimination of any cabling
- Standardization of Bluetooth 2.0, 2.1, 3.0, 4.0, latest 5.3 (2021) – improved channel classification, improved encryption key size management

Bluetooth Smart, Bluetooth 4.0, Bluetooth Low Energy

- Suitable standard for IoT
- Same band as Bt BR/EDR (Basic Rate/Enhanced Data Rate), 2.4 GHz
- 150 m range in an open field
- Output power only 10 mW vs. 100 mW for Bt BR/EDR
- New advertising mechanism for efficient device discovery
- New asynchronous connectionless MAC to provide low delay and fast transactions
- New generic attribute protocol to provide a simple client/server model
- New generic attribute profile to efficiently collect data from sensors
- Suitable for fitness devices, smart metering, healthcare devices
- **Advantages** – easy to implement, low power, powered by coin cell, longer battery life
- **Limitations** – small data packets

IEEE 802.15.4

- a standard of inexpensive low speed „always present" WSN
- defines physical layer and data link layer according to OSI, physical layer has multiple variants (DSSS and QPSK/BPSK/ASK)
- for slow devices with low power consumption (battery for months to years), power management ensures low power consumption
- in star topology can be used for collision-free communication real-time reservation of TDM time slices other communications are handled by CSMA/CA contention, error-free data receiving is optionally ensured by acknowledgement
- communication can be secured (encryption, CRC, . . .)
- distance between nodes up to few tens of meters, speed up to 250 kb/s
- communication frequency bands 868 MHz, 915 MHz and 2.4 GHz

802.15.4 – Wireless Thread

- IPv6-based wireless protocol, IP-based
- run by a board of directors that includes representatives from Google, Apple, Amazon, Samsung SmartThings, Qualcomm, NXP, Assa Abloy, Lutron, and more
- uses the 802.15.4 radio technology
- similar to existing smart home protocols Zigbee and Z-Wave
- low-bandwidth devices, such as door locks and motion sensors
- **Advantages** – lower latency in opposite to Zigbee and Bluetooth, especially in large networks with many devices, it doesn't need a central hub or bridge
- **Limitations** – Not for high-bandwidth use

`https://www.threadgroup.org/support#specifications`

802.15.4 – ZigBee

- Standard *Zigbee alliance* (Honeywell, Emerson, Freescale, Texas Instuments, OKI, . . .) Defines a generic framework and application profiles
- Unlicensed bands including 2.4 GHz, 900 MHz and 868 MHz
- ZigBee 3.0, multiple network topologies, 128-bit AES encryption, DSSS up to 65,000 nodes per network
- Addition (extension) of 802.15.4 for routing, security, self-correction, self-organization, and interfaces to applications on star or *mesh* networks
- Target – a network for networking applications with secure low-speed radio communications, with the need for long battery life
- **Advantages** – low resource requirements – 32 kB ROM (4 kB for simple devices), 8 kB RAM (1 kB or less for simple devices), communicate data through noisy RF environments

6LoWPAN

IPv6 over Low power Wireless Personal Area Networks (6LoWPAN) provides the upper layer system for use with low power wireless communications for IoT and M2M, originally intended for 802.15.4, it is now used with many other wireless standards

- An open standard defined by the Internet Engineering Task Force, IETF in their document RFC 6282 updated by RFC 8066
- Defined the encapsulation and compression mechanisms that enable the IPv6 data to be carried of the wireless network

IPv6 – MTU at least 1280 bytes in length **>** IEEE802.15.4's standard packet size of 127 octets
Solution – IPv6 nodes are given 128 bit addresses in a hierarchical manner. Devices may use either of IEEE 64 bit extended addresses or 16 bit addresses that are unique within a PAN after devices have associated. There is also a PAN-ID for a group of physically co-located IEEE802.15.4 devices

802.11p – Dedicated Short Range Communication, DSRC

- based on IEEE 802.11p WLAN standards, called as Wireless Access in Vehicular Environment (WAVE)
- working in the frequency range 5.850 - 5.925 GHz (with 75 MHz band ie 7 channel of 10 MHz each and 5 MHz reserved) in USA and with 30 MHz in Europe
- low latency, Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) communication
- DSRC (WiFi based) is in use in Europe, Japan, USA. China is moving to use C-V2X Rel.14/15 (LTE uplink).
- Vehicle Safety service, commerce transaction via cars, traffic management, etc, …

Wired IoT – just a note

IoT is not only wireless technology. IoT based on Ethernet technology is used in the automotive industry to transport in-car data, poe remote cameras in public spaces, connected FVE systems, etc . . .

Examples:

- **IEEE 802.3cg** – runs over a single twisted pair. Enables a higher speed connection, without the use of gateways, for field switches, sensors and actuators.
- **IEEE 802.3bt** – PoE standard can provide up to 100 W over the UTP cabling. PoE is also critical to wireless access points and supporting Wi-Fi.

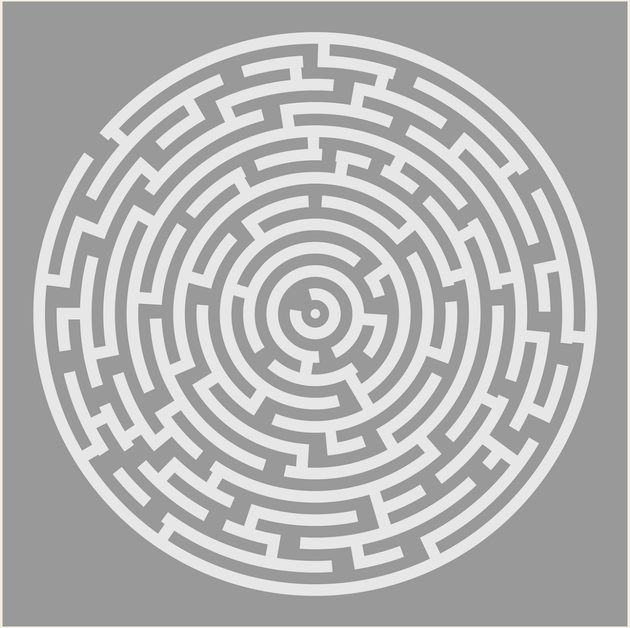
Wirepas

- A low-power wireless connectivity protocol
- Three radio profiles – 5G Mesh, Mesh 2.4 GHz and Mesh Sub-GHz for massive indoor or deep indoor applications (unlicensed frequencies – 2.4 GHz, 865 MHz, 868 MHz, 870 MHz and 915 MHz)
- Combined time-division and multiple access (TDMA) and Frequency division multiple access (FDMA) operation for efficient spectrum usage
- 5G Mesh
  - non-cellular 5G connectivity network for enterprise IoT (5G Mash)
  - free global dedicated spectrum at 1.9 GHz
  - city-wide 5G network for other applications like parking and sewer monitoring
  - **Advantages** – for massive Machine Type Communications (mMTC)

SDK available at `https://developer.wirepas.com/support/home`

WiFi, Wifi HaLow (802.11ah)

- Referred as Long range, low power Wi-Fi for IoT – from the IoT perspective itself, as Medium range
- Wi-Fi HaLow enables the low power connectivity necessary for applications including sensor networks and wearables
- Sub-1 GHz spectrum operation, Narow band OFDM channels
- Several device power saving models, native IP support, latest Wi-Fi security
- Advantages – Long range: approx 1 km, penetration trough walls and other obstacles, no need for proprietary hubs or gateways



Low-Power Wide-Area technologies – LPWA

LPWA (Low-Power Wide-Area) Technologies: carry a very small data to a large distance

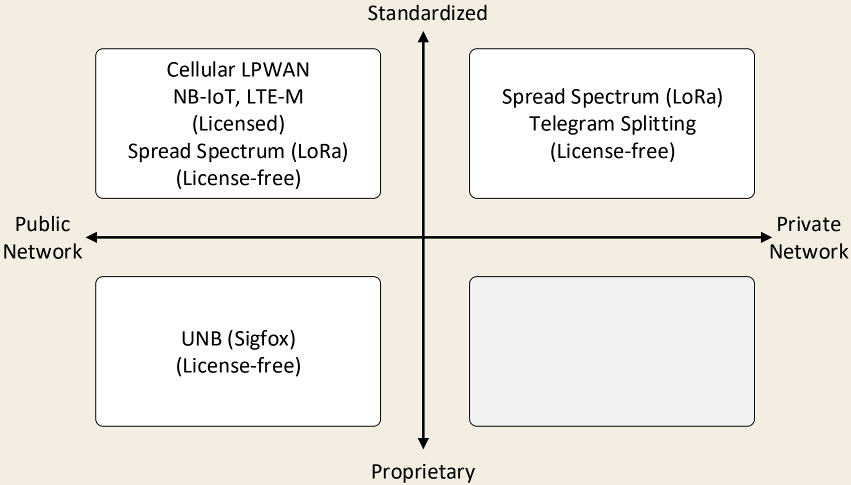
LPWA technologies may be categorized as :

- Cellular (3GPP) LPWA(N) (Networks) : Based on 3GPP Rel 13 onwards specifications, cellular networks may have LTE MTC, NB-IoT, EC-GSM and 5G
- Non cellular (Non 3GPP) LPWA(N) (Networks) : LoRa, Sigfox, Weightless, RPMA and others

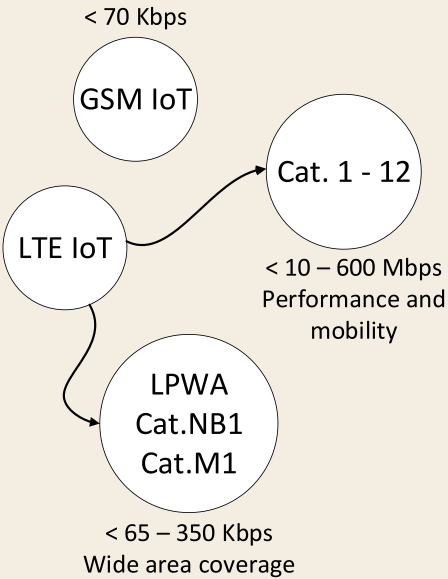
LPWA technologies – a bit of history

- 1990 - 2000s – AlarmNet – build by ADEMCO, a 900 MHz network to monitor alarm panels. Owned by Honeywell.
- 1990 - 2000s – ARDIS – built specifically for data-only applications, wireless wide-area network owned by Motorola in the 1980s
- late 1990s – migration to 2 G
- 2000s – 2 G, 3 G
- 2010s – ONRAMP, **SIGFOX**, CYCLEO
- 2014 - 2016 – **LoRa**, GENU, Waviot, LinkLabs, **3GPP**

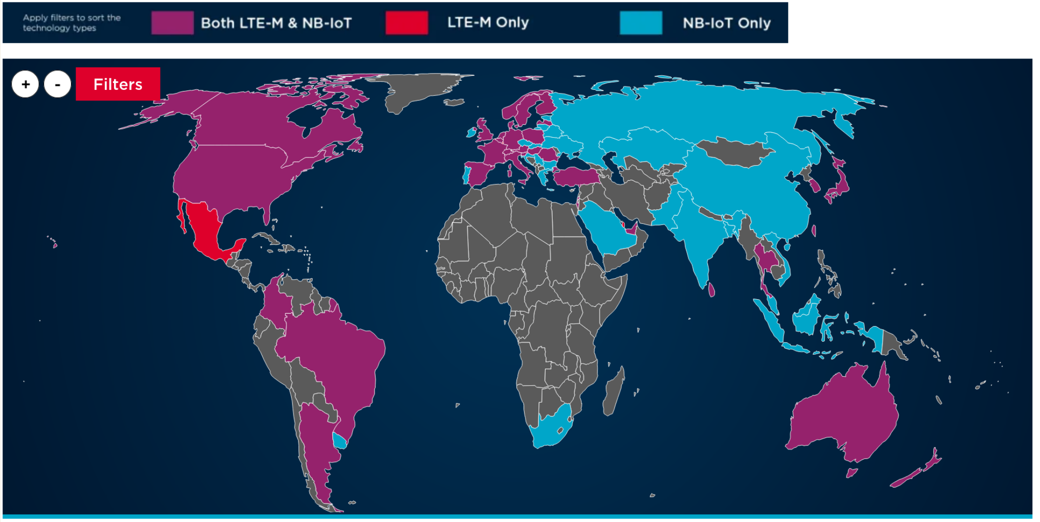
LPWA technologies



LPWA technologies – cellular



NB-IoT vs LTE-M

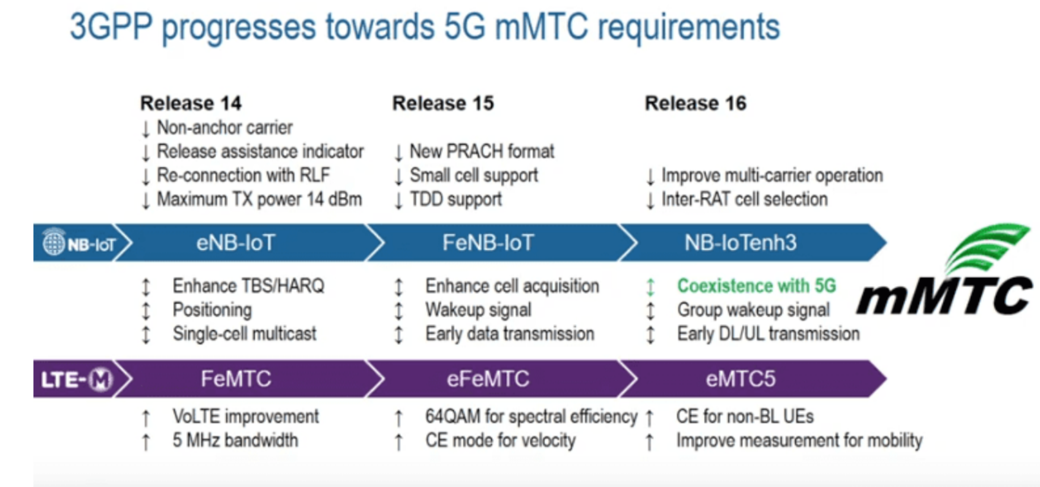


https://www.gsma.com/iot/deployment-map/, 2022

NB-IoT vs LTE-M – 3GPP progresses

	LTE Cat 1	LTE Cat 1 bis	LTE-M				NB-IoT		EC-GSM-IoT
			LC-LTE/MTCe	eMTC					
			LTE Cat 0	LTE Cat M1	LTE Cat M2	non-BL	LTE Cat NB1	LTE Cat NB2	
3GPP Release	Release 8	Release 13	Release 12	Release 13	Release 14	Release 14	Release 13	Release 14	Release 13
Downlink Peak Rate	10 Mbit/s	10 Mbit/s	1 Mbit/s	1 Mbit/s	∼4 Mbit/s	∼4 Mbit/s	26 kbit/s	127 kbit/s	474 kbit/s (EDGE) 2 Mbit/s (EGPRS2B)
Uplink Peak Rate	5 Mbit/s	5 Mbit/s	1 Mbit/s	1 Mbit/s	∼7 Mbit/s	∼7 Mbit/s	66 kbit/s (multi-tone) 16.9 kbit/s (single-tone)	159 kbit/s	474 kbit/s (EDGE) 2 Mbit/s (EGPRS2B)
Latency	50–100 ms		not deployed	10–15 ms			1.6–10 s		700 ms – 2 s
Number of Antennas	2	1	1	1	1	1	1	1	1–2
Duplex Mode	Full Duplex		Full or Half Duplex	Full or Half Duplex	Full or Half Duplex	Full or Half Duplex	Half Duplex	Half Duplex	Half Duplex
Device Receive Bandwidth	1.4–20 MHz		1.4–20 MHz	1.4 MHz	5 MHz	5 MHz	180 kHz	180 kHz	200 kHz
Receiver Chains	2 (MIMO)		1 (SISO)	1 (SISO)	1 (SISO)	1 (SISO)	1 (SISO)	1 (SISO)	1–2
Device Transmit Power	23 dBm	23 dBm	23 dBm	20 / 23 dBm	20 / 23 dBm	20 / 23 dBm	20 / 23 dBm	14 / 20 / 23 dBm	23 / 33 dBm

NB-IoT vs LTE-M – 3GPP progresses



https://enterpriseiotinsights.com, 2022

„Massive Machine-Type Communications (mMTC) is one of three core 5G service areas. It has been created specifically to enable a huge volume of small data packets to be collected from large numbers of devices, simultaneously. mMTC supports applications using Internet of Things (IoT) sensors, meaning that data can be used to reduce energy consumption, make work more efficient, or improve our lives in other way – ***gsma.com***“

EC GSM IoT (formerly EC-EGPRS)

Extended Coverage GSM for Internet of Things – EC GSM IoT

- standardized and published in 3GPP Release 13
- it uses 2 G bands, licensed spectrum like GSM, 850 to 900 MHz, 1800 to 1900 MHz
- network infrastructure is backwards-compatible to previous releases to allow the technology to be introduced into existing GSM networks
- There are four coverage classes supported by EC-GSM – CC1 - CC4 – 7 times increase in Cell coverage
- **Advantages** – ∼10 years of operation with 5 Wh battery, variable data rates with GMSK: 350 bps to 70 kbps, with 8PSK up to 240 kbps, low cost market, 50.000 devices per cell, improved security
- Smart cities & homes, Industrial automation, Wearables, Smart energy (meters with strong coverage requirements and low power use), Intelligent transport systems

Cellular IoT – eMTC/Cat-M1/Cat-M/LTE-M

- LTE-M is the industry term for the Long-Term Evolution (LTE) machine-type communications (MTC) LPWA technology standard. LTE-M follows 3GPP specifications similar to LTE technology. Second generation of LTE chips build for IoT. Compatible with existing LTE network
- Using conventional LTE cellular bands like 700 MHz, 800 MHz and 900 MHz
- **Advantages** – Low power consumption, full mobility, voice through VoLTE, high reliability and superior data rate carrier-class e2e network security (based on LTE)
- **Limitations** – a support of higher bandwidth limits
- Wereables, telematics, parking, industry environment monitoring, industrial IoT with Emergency Voice call support, healthcare, ...

Cellular IoT – NB-IoT

- Using conventional LTE cellular bands like 700 MHz, 800 MHz and 900 MHz, and 2G bands
- Sensor based applications, with low data rate requirement and long sensors measurements, smart gas meters, parking operators, fire protection, etc.
- ∼1 km in urban area, up to ∼10-15 km range in rural area
- **Advantages** – great indoors, better area coverage (20 dB additional link budget), expanding worldwide, reuse of the LTE design, lower cost than eMTC, long battery life – enables lower processing and less memory on the modules, support of massive number of devices at least 50.000 per cell, maximum message/day is unlimited
- **Limitations** – voice is not supported, low data rate applications with link peak DL = ∼200 kbps & UL=∼144 kbps, limited mobility and mostly designed for stationary devices, expensive software upgrades, interoperability problems (Huawei vs Ericsson), it does not support Adaptive Data Rate (ADR)

5G IoT, 6G

The 5G requirements defined by ITU-R and 3GPP broadly cover three main use cases

- **Mobile IoT/Massive IoT/LPWA**: improved network coverage, long device operational lifetime and a high density of connections. This is also known as mMTC (Massive MTC)
- **Critical communications**: high performance, ultra-reliable, low latency industrial IoT and mission critical applications. This is also known as Critical IoT, URLLC (Ultra Reliable Low Latency Communications)
- **Enhanced Mobile Broadband**: improved performance and a more seamless user experience accessing multimedia content for human-centric communications

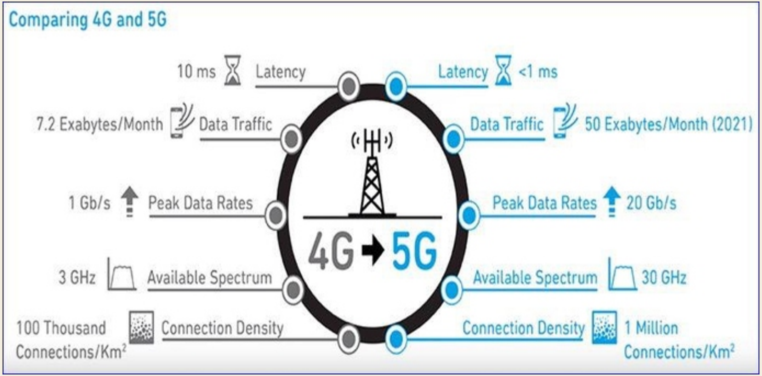
NB-IoT and LTE-M networks are forwards-compatible with 5G technologies, and are specified originally to serve mMTC-banded IoT applications

5G and IoT

To deliver ultra-high speeds with the lowest latencies, 5G networks leverage radio frequencies in two groups:

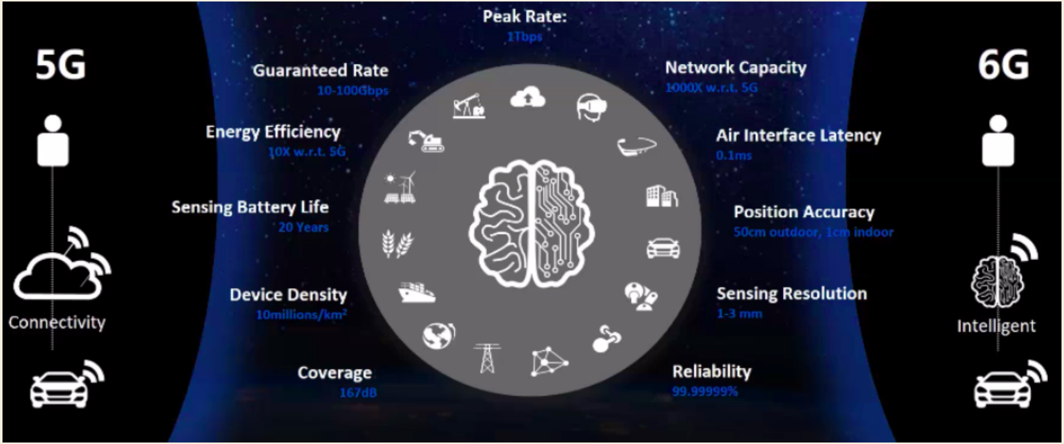
- FR1, also called the sub-6 GHz range,
- FR2 between 24 and 52 GHz and with extends to EHF range also known as millimetre wave (mmWave) frequency. mmWave defined as the band of spectrum between 30 GHz and 300 GHz.

5G since (2020)



1000^6 *EB exabyte*, in other words Mega TB (Giga GB)

6 G is coming



Huawei – white paper `https://www-file.huawei.com/-/media/corp2020/pdf/tech-insights/1/6g-white-paper-en.pdf?la=en`

LoRa

LoRa is a wireless modulation technique derived from Chirp Spread Spectrum (CSS) technology. It encodes information on radio waves using chirp pulses, as the latest addition, it also uses Long Range Frequency Hopping Spread Spectrum (LR-FHSS)

- A proprietary technology of Semtech, is matched to the star topology
- The minimum bandwidth is 125 kHz, which supports a maximum clutch loss of 157 dB
- Proprietary, energy-efficient LoRa-based Chirp Spread Spectrum modulation is used to increase interference immunity. LoRa itself uses SF7 to SF12 spreading factors
- LoRa modulation can be used in a wide range of frequencies from 137 MHz to 1020 MHz. This includes ISM series of license-free bands such as 169 MHz, 433 MHz, 868 MHz, 915 MHz and 2.4 GHz. This is a key tool for cheap, worldwide deployment and interoperability
- **Advantages & limitations** – LoRa is not suitable for example for streaming video, it is suitable for IoT and M2M. LoRa is a physical layer implementation and is agnostic with higher layer implementations. This allows LoRa to co-exist and work with the existing network architectures

LoRaWAN

LoRaWAN is a Media Access Control (MAC) layer protocol built on top of LoRa modulation

- Network architecture, typically deployed in the star topology
- Nodes are not associated with a particular gateway. Instead, data transmitted by the node is typically received by multiple gates
- Gateways here work as a transparent bridge that passes messages between end devices and a central network server
- Gateways are connected to a network server via standard IP (Internet Protocol) connections, while end devices use wireless communication with LoRa radio connections

LoRaWAN is officially approved **as a standard for Low Power Wide Area Networking** (LPWAN) by the International Telecommunication Union (ITU) in 2021

LoRaWAN

- **Advantages** – 10 years on a single coin cell battery, long range, deep indoor coverage, license free spectrum, geolocation, public and private deployments, end-to-end security AES-128 encryption, roaming, low-cost, supports Adaptive Data Rate (ADR), the basic range is ∼5 km in urban, ∼20 km in rural area, maximum message/day is unlimited
- in 2022, Lacuna and Semtech expanded LoRaWAN coverage through IoT to Satellite Connectivity

https://lacuna.space/

Sigfox

- It uses Binary phase-shift keying modulation, UNB, the bandwidth is 100 Hz
- Maximum data rate up to 100 bps, maximum messages/day UL=140, DL=4
- Star topology
- **Advantages** – one of the lowest cost of many ultra-simple designs, global roaming capabilities, enhanced location tracking; in the open countryside, the signal range to the base station is up to 50 km; the network is highly resistant to interference
- **Limitations** – is a service provider without an option for private networks, it does not support the modern encryption technology, other limitations listed on page 46.

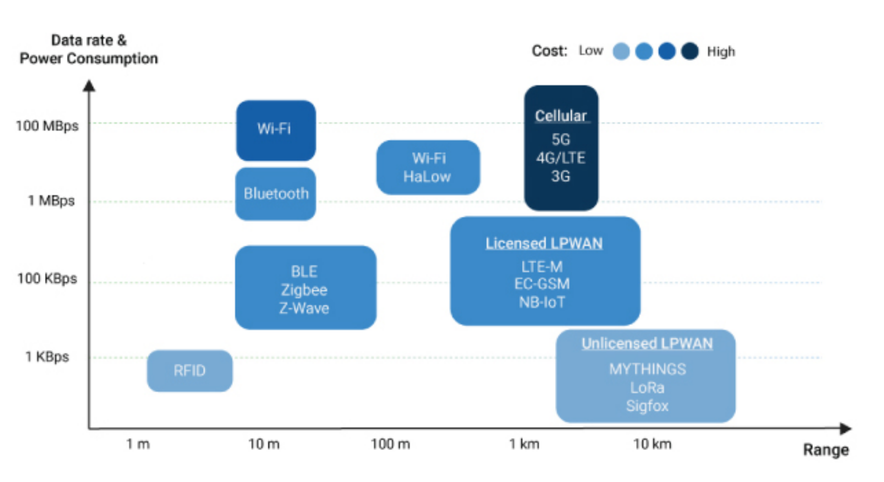
Some LPWA comparison

Cellular LPWAN – best suited for higher data rate IoT and in smart city where telecom infrastructure is mature. Not optimal for applications where ultra-low power is at a high priority. Also not optimal for industrial deployments which often take place at remote locations

Ultra-Narrowband – mitigate noise level, slow data rate, a very long on-air radio time, battery drain, limited mobility support due to long transmission (Doppler effects). All messages have to be rerouted to a centralized cloud platform of the provider (security and privacy question)

Spread Spectrum – improving range without compromising data rate as in UNB. But, low spectrum efficiency and problems with asynchronous communication causes message overlays. Scalability problems – for a best range a highest spreading factor is required. More complicated network management is required to improve capacity by enabling simultaneous demodulation of multiple messages.

Discussion – what is the best for a project?



https://behrtech.com/blog/6-leading-types-of-iot-wireless-tech-and-their-best-use-cases/
https://www.digi.com/blog/post/long-range-vs-short-range-wireless-communications

Thank you for your attention!