IoT connectivity options, their strengths and limitations

Master in TIC
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Goals

- Expose the specific requirements of IoT and why traditional wireless technologies fail to meet them.
- Describe the technologies that can be used to build IoT networks, both for short and long distances.
- Describe LPWAN solutions currently with more traction and those poised to attain it, both proprietary and 3GPP based ones.
- Explain how satellites will play an increasing role on IoT in the near future.

IoT requirements and tolerances

Require:

- Low cost
- Energy efficiency
- Massive deployments
- Extended coverage
- Security
- Confidentiality
- Positioning capability

May tolerate:

- Low throughput
- Very sparse datagrams
- Delays
- Long sleeping times
- Packet losses
- Lack of mobility
- Planned retransmissions

Some specific IoT issues

- Traffic pattern, payload size, periodicity, latency
- Identity and level of security required
- Reliability
- Sector specific regulations (for instance, health care)
- Analytics
- Billing and charging
- Service level agreements (SLA)
- QoS for specific equipment
- Capability to address group of devices with a single action, for instance firmware upgrade

Short or long range coverage

Wireless Personal Area Networks (WPAN):

- Very short range, low power and low bit rate.
- Widely deployed in homes.
- Can use mesh topology to extend range.
- Limited packet size, limited node processing power.
- Might not support security.
- Often dependent on gateways for Internet connection.

Low Power Wide Area Networks (LPWAN):

- Low throughput.
- Low power consumption.
- Long range.
- Long sleeping times.

IoT Applications: Critical or Massive?

Massive IoT

- Very cost sensitive.
- Low consumption.
- Small payloads.
- Latency and loss tolerant.
- Unlicensed frequencies acceptable.
- Cloud back end.
- Can be served by proprietary or cellular based solutions.

Critical IoT

- Very high availability.
- Very low latency.
- Variable payloads.
- Licensed frequencies required in many cases to guarantee reliability.
- Best served by cellular based solutions.

Wireless Personal Area Networks (WPAN)

Issues for Internet connectivity:

- Internet requires globally unique addresses. Although IPv4 can be used, clearly to cater to the billions of IoT devices to be deployed, IPv6 is the best solution.
- IPv6 uses 128 bit long addresses, and a minimum packet size of 1280 octets. Most devices cannot support these numbers and adaptation is required.
- The IETF 6LowPAN study group has devised mechanism for IPv6 address compression and packet fragmentation to accomplish this adaptation.
- Alternatively, gateways must be deployed.

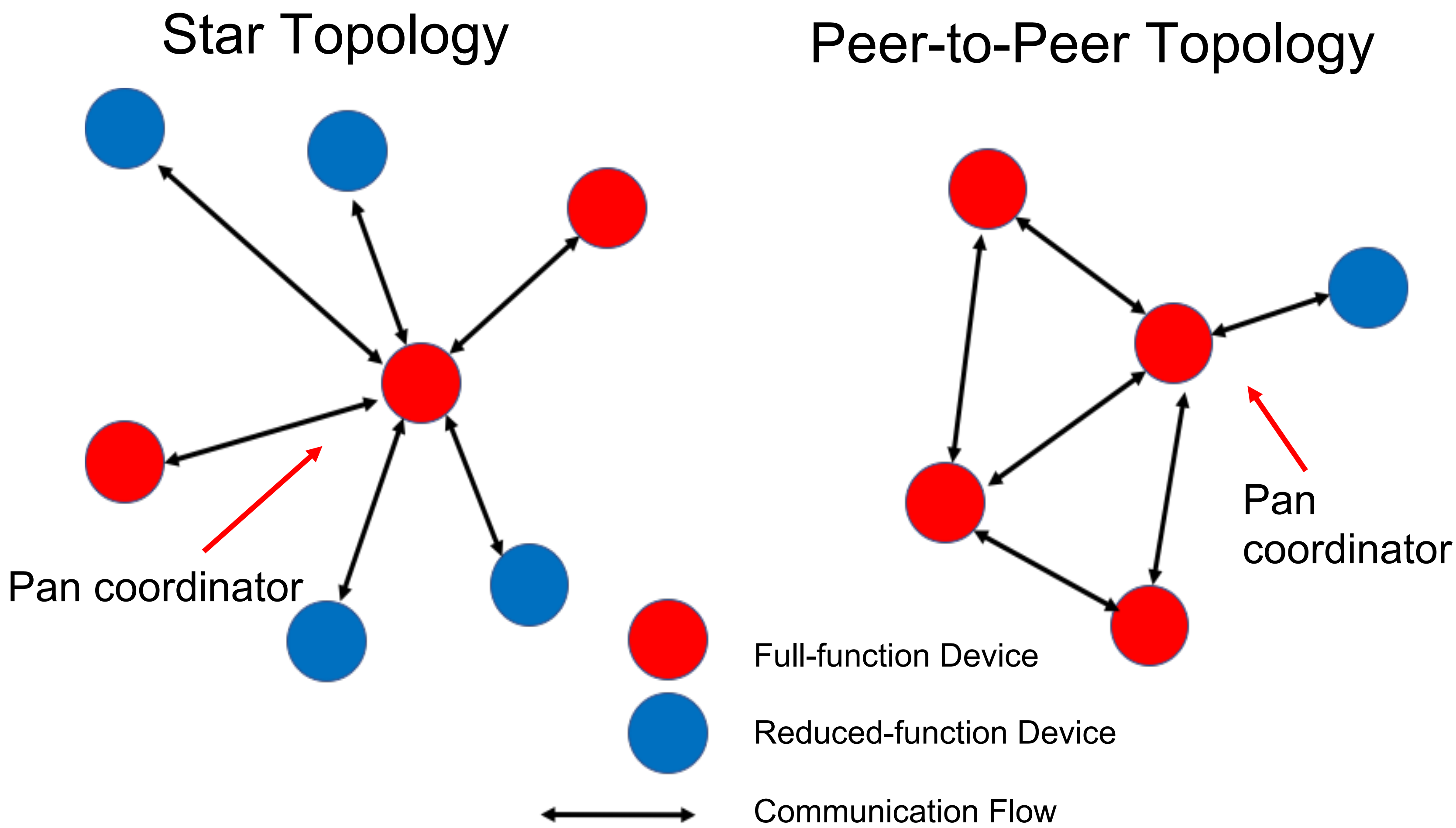
IEEE 802.15.4

Standard for Low-Rate Wireless Personal Area Networks (LR-WPANs)

- Little or no Infrastructure, low power.
- Defines the Physical (PHY) and the Medium Access control (MAC) sublayer.
- Targets small, power-efficient, inexpensive solutions for a variety of devices.
- It is used by many upper layer protocols like Zigbee, Thread, Wireless HART, DASH-7.
- Last amendment: IEEE 802.15.4-2020, approved June 2020.

http://ieeexplore.ieee.org/browse/standards/get-program/page/series?id=68

IEEE 802.15.4 Topology



IEEE 802.15.4 Security

- Wireless networks are vulnerable to passive eavesdropping attacks.
- Devices constraints in terms of computing power, storage and power consumption, limit the choice of cryptographic algorithms and protocols.
- High quality random number generators might not be available on-board.
- Security is based on symmetric-key cryptography and uses keys provided by higher layers processes which must offer secure and authentic storage of keying material.

http://ieeexplore.ieee.org/browse/standards/get-program/page/series?id=68

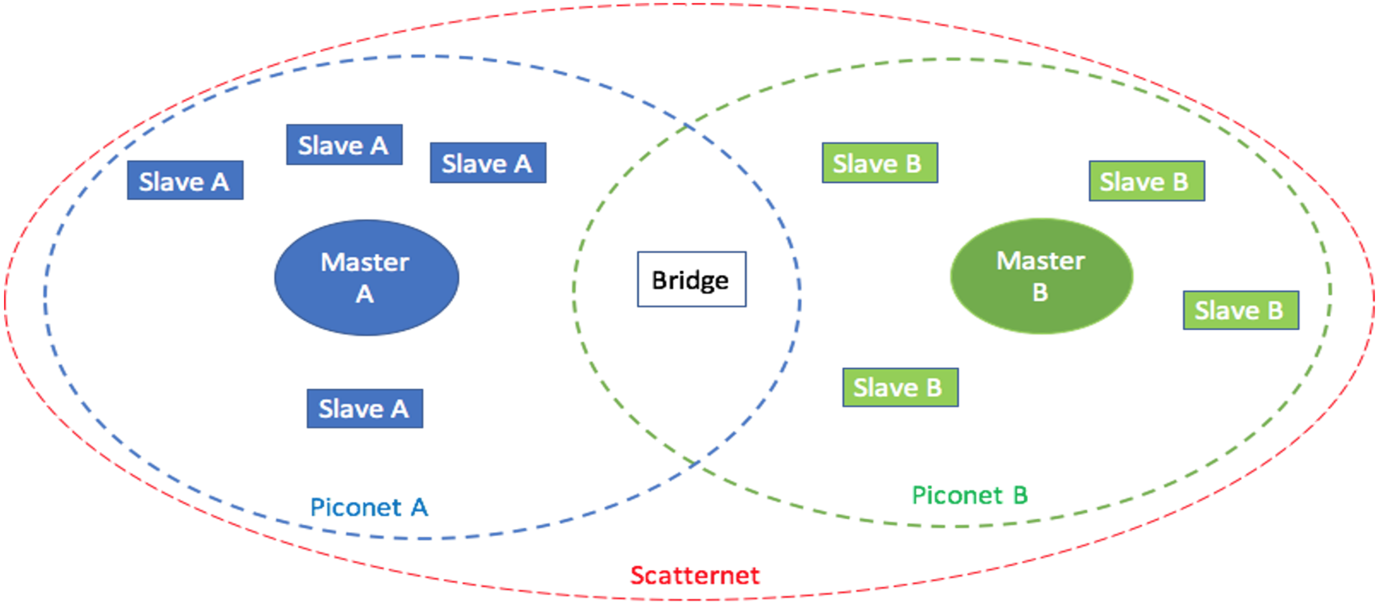
Bluetooth

- Based on IEEE 802.15.1
- Smart Mesh.
- 79 channels 1 MHz wide and frequency hopping to combat interference in the crowded 2.4 GHz band.
- Used mainly for speakers, health monitors and other short range applications.

Bluetooth architecture

Master node controls up to 7 active slave nodes and up 255 inactive nodes,forming a *piconet*.

- Several piconets can form a *scatternet* by leveraging bridging nodes associated to more than one *master.*
- *Slaves* must communicate through the master node.



Bluetooth Low Energy (BLE) or Smart Bluetooth

- Based on IEEE 802.15.1
- 40 channels 2 MHz wide and frequency hopping to combat interference
- Data channels used for bidirectional traffic.
- Beacon mode, where low power, transmit-only sensors periodically transmit in one of three dedicated "advertising channels".
- BLE compatible receiving devices must periodically listen in each of the three advertising channels
- Consumption: Transmitter 2.9 mW, receiver 2.3 mW.

802.11ah (WiFi HaLow)

- Sub 1 GHz, most commonly 900 MHz
- Low power, long range WiFi, less attenuated by walls and vegetation.
- Up to 1 km range.
- Lower power consumption thanks to sleep mode capabilities.
- 1, 2, 4, 8 and 16 MHz channels.
- Competes with Bluetooth, speed from 100 kb/s to 40 Mb/s.
- Support of Relay AP to further extend coverage.

Zigbee

- Based on IEEE 802.15.4, provides the higher functions up to the application layer for WPAN.
- Mesh topology.
- Short range, 20 to 250 kbps.
- 2.4 GHz, 915 MHz or 868 MHz.
- Channels 2 MHz wide with Direct Sequence Spread Spectrum media access.
- Zigbee alliance supported by many vendors.

Zigbee

Three specifications targeting different applications

- Zigbee Pro for reliable device to device communication supporting thousands of devices. Green Power feature for energy saving.
- Zigbee RF4CE for simpler, two-way control applications, lower memory requirements, lower cost.
- Zigbee IP for Internet Protocol v6 wireless mesh connecting dozens of different devices.

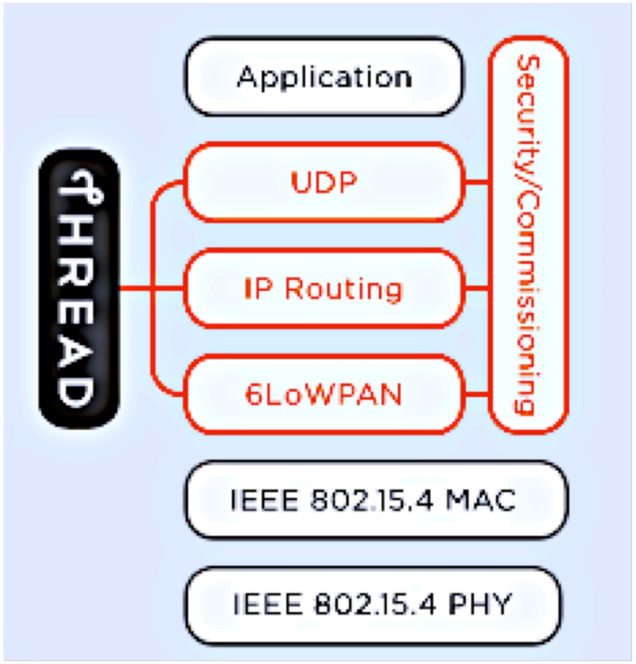
6LoWPAN

IPv6 over low power wireless personal area networks, concluded working group of IETF

- Defines encapsulation and header compression to send and receive IPv6 packets over IEEE 802.15.4 networks.
- Defines mechanisms for fragmentation and reassembly of IPv6 packets to meet constraints of IoT networks.
- Thread is a royalty-free protocol using 6LoWPAN for IoT.

Thread

- Thread is an open IPv6 based mesh technology for home IoT
- Uses 6LoWPAN and AES encryption.
- Supports up to 250 devices.
- Self healing network for the home.
- Low consumption: Sleepy nodes, short messages.



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Z-Wave

- Low-power wireless communication protocol for Home Automation Networks (HAN)
- Mesh operating in the 800-900 MHz range
- Up to 100 m range and 40 kb/s, 1 mW
- Supports IP transport and routing protocols
- Controller and slave nodes
- Source routing managed by controller
- Wide range of device and command classes

DASH 7

- Full OSI stack protocol for sensors and actuators (layers 1-7)
- Unlicensed bands at 433 MHz, 868 MHz and 915 MHz
- Asynchronous MAC, command-response
- Highly structured presentation layer
- Up to 2 km range and 167 kb/s data rate
- Low latency, low consumption, mobility support
- AES encryption support
- Open Standard based on ISO/IEC 18000-7

QUIZ

What are the main trade-offs that have been made in IoT networks in order to improve battery lifetime?

What are the main trade-offs that have been made in wireless personal area networks in order to allow for a great number of devices?

Two categories of LPWAN

Cellular IoT

(3GPP standardized)

- LTE-M
- NB-IoT

Proprietary

•SigFox

•LoRa

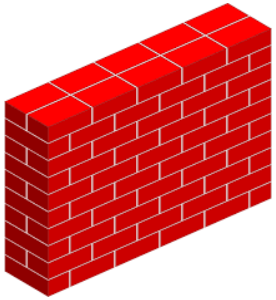
•RPM (Ingenu)

LoRa and Sigfox account for the majority of current LPWAN connections but Cellular IoT is gaining ground.

Cellular success

- Cellular technologies promoted by 3GPP have had an enormous success.
- They have focused on providing ever greater speeds to meet the demand of the booming data consumption, but had to reduce the range as a compromise.
- 4 G user devices have complex and power hungry circuitry that does not meet the needs of IoT.
- A cellular device must keep frequent communication with the base station, thus consuming energy even when there is no traffic.

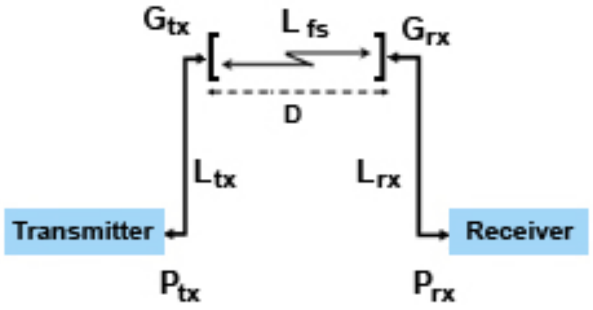
Proprietary LPWAN



Limitations of cellular were addressed by proprietary LPWANs:

- IoT connectivity requires low cost devices that consume little power to allow their deployment in large numbers and possibly in places that make battery changing impractical.
- Most of these devices do not need a high throughput.
- Many do not have stringent latency requirements.
- Some might be in basements or beyond several walls that absorb significant amount of RF signals, requiring a high power budget (Maximum Coupling Loss).

Proprietary LPWAN



- Many enterprises have rushed to fill the mobile cellular market gap with different approaches.
- In general, they trade throughput for power budget.
- The amount of spectrum required is much lower.
- They also let the end device to "hibernate" for long periods and only "wake up" when they actually have data to transmit. This is the most effective strategy to save power.
- All started as proprietary single vendor solutions, but some of them have spawned alliances and fora in which other manufacturers can participate.

Battery duration

Devices sleep most of the time, employing low data rate and limited number of messages per day

- LoRa, SigFox: up to 10 years
- NB-IoT, up to 10 years
- LTE-M, up to 5 years
- 802.15.4, months
- WiFi, a few days

Energy scavenging schemes are being pursued: Photovoltaic, piezoelectric, thermoelectric, vibration, air or water flow, inductive powering, radio frequency energy.

Sigfox

- Ultra narrowband technology designed for low throughput.
- Maximum of 140 uplink messages/day with 12 octets payload, 26 octets total with overhead.
- Maximum of 4 downlink messages/day with 8 octets payload.
- Each message transmitted 3 times in 3 different frequencies offering resilience to interference.
- Unlicensed frequencies: 868 MHz in Africa and Europe, 915 MHz in US.
- Mobility restricted to 6 km/h.
- One hop star topology.
- Low consumption, low cost.

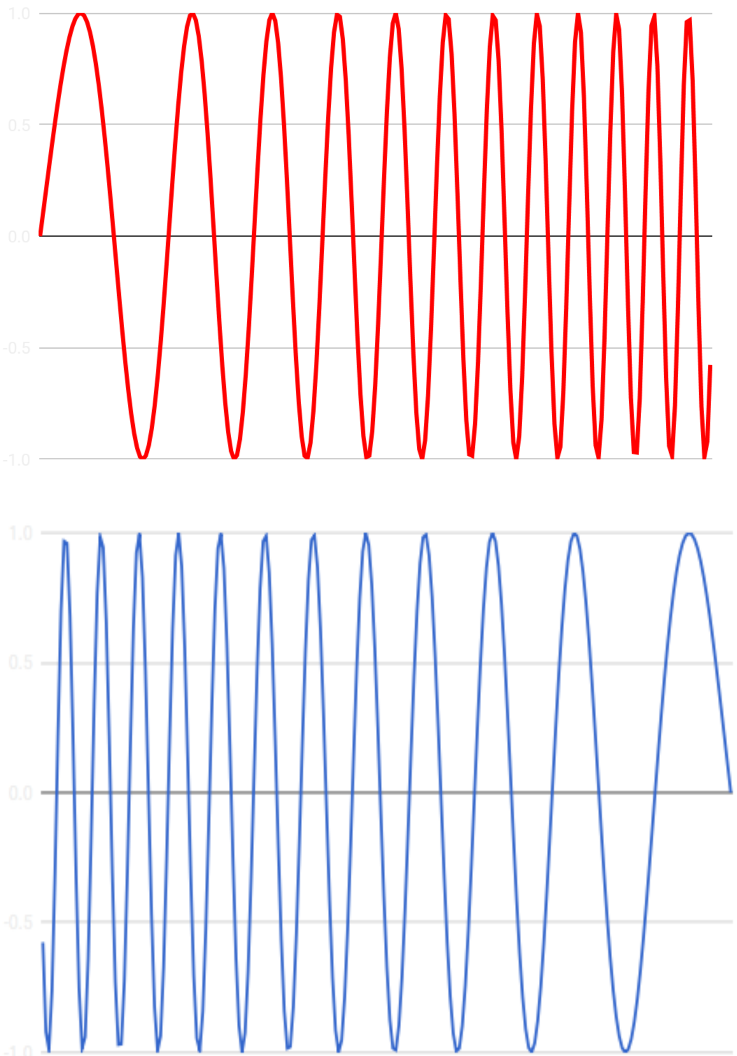
Sigfox

- Partnerships with cellular providers with an aim to worldwide penetration.
- Many network operators worldwide offer Sigfox services on a subscription basis.
- Cloud managed, leveraging SDR to offer many services.
- Coarse positioning capability without GPS.
- Roaming capability.
- Sensitivity up to -142 dBm, 162 dB MCL.

LoRa and LoRaWAN

- LoRa is a proprietary modulation based on spread spectrum, trading bandwidth for S/N.
- It achieves long range and deep indoor penetration.
- Uses linearly varying frequency pulses called “chirps” inspired in radar signals.
- Several vendors offer devices built on the chip owned by Semtech.
- LoRaWAN is an open standard promoted by the LoRa Alliance that adds the MAC, networking and application layers providing the required functionalities for a complete networking solution.

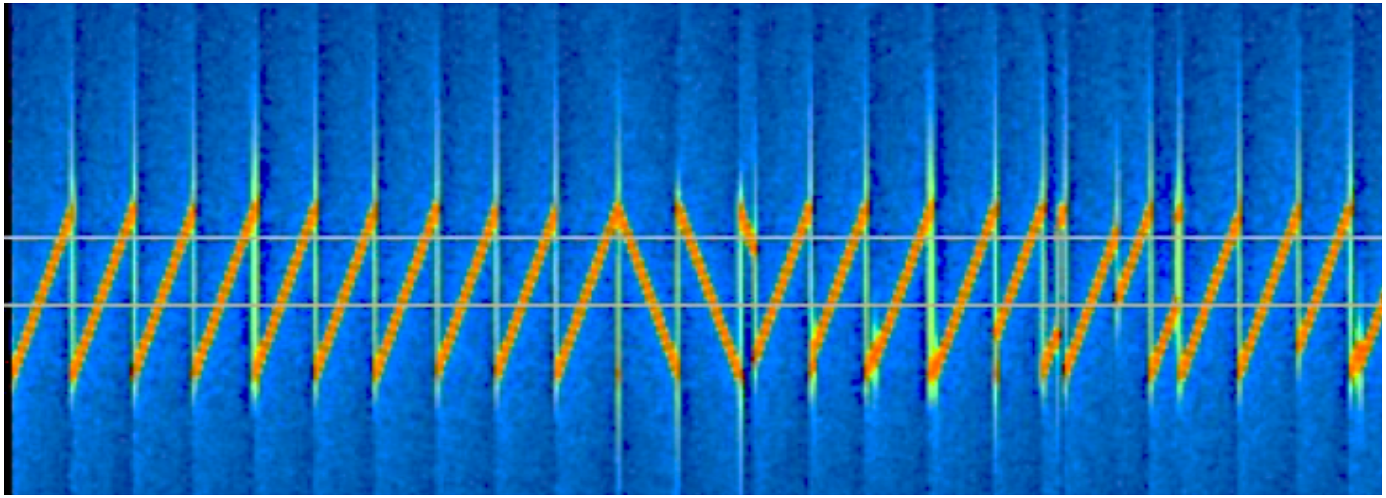
LoRa modulation



Up-chirp:
sinusoidal signal of linearly
increasing frequency

Down-chirp:
sinusoidal of linearly
decreasing frequency

LoRa physical layer

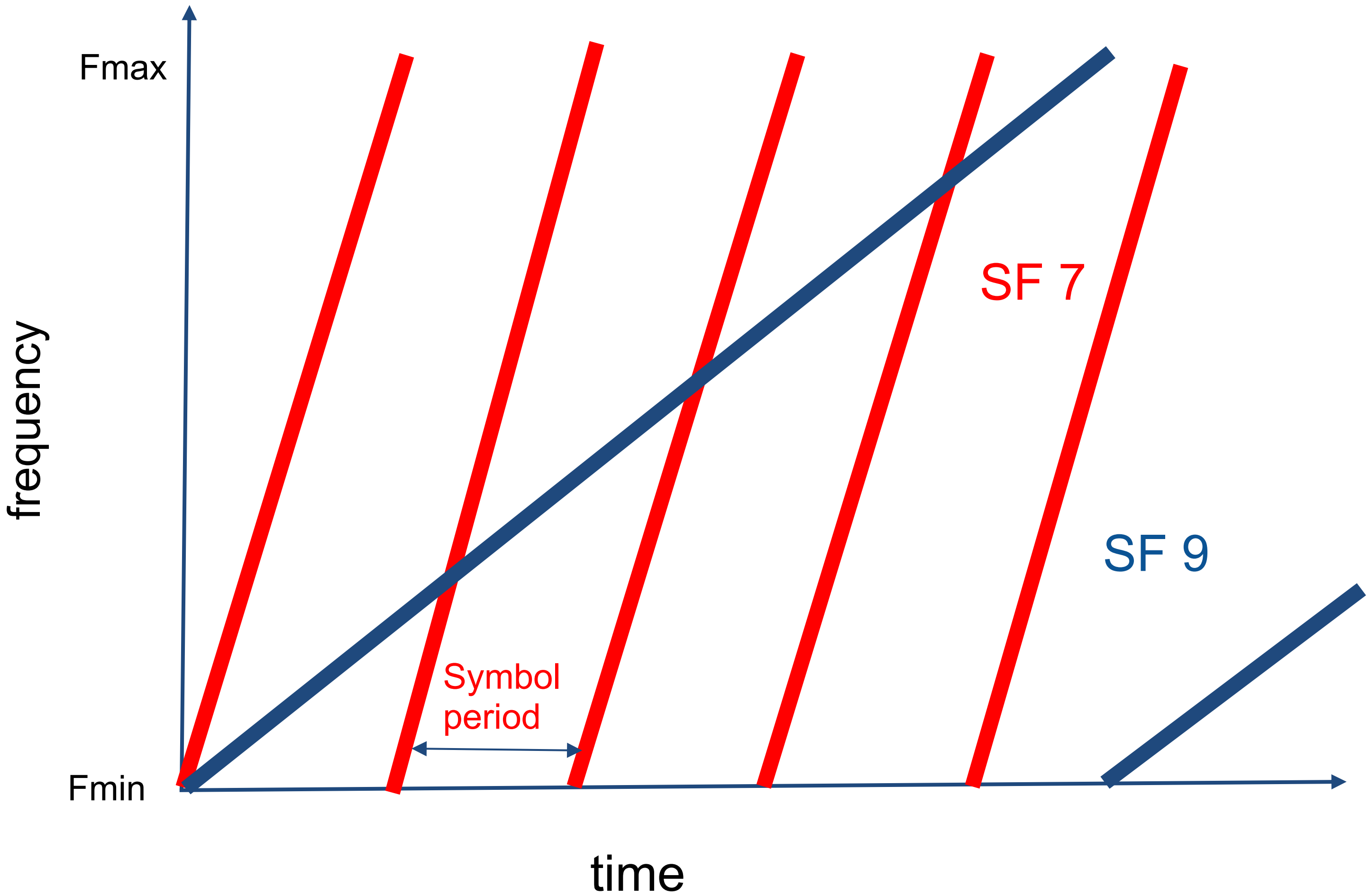


Preamble: at least 10 up-chirps followed by 2.25 down-chirps

Data: Information transmitted by the Instantaneous frequency transitions

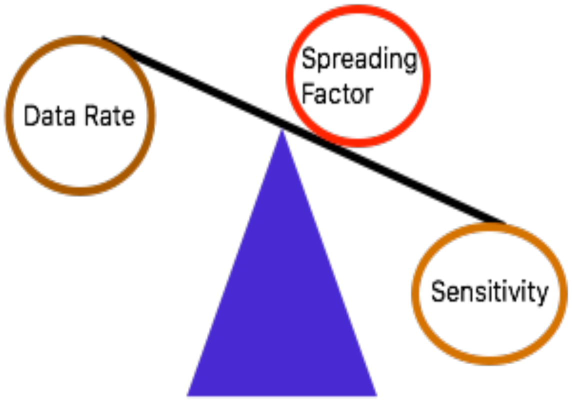
Beginning of data

Spreading Factors and duration

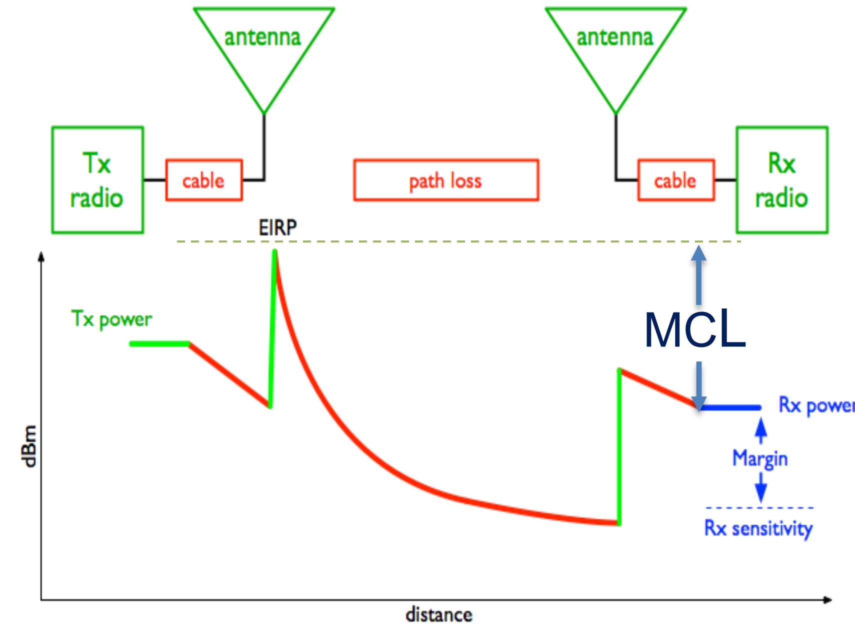


Adaptive Data Rate (ADR)
at 125 kHz BW

Sprd. Factor	S/N dB	bit rate bit/s	ms per ten byte packet
7	-7.5	5469	56
8	-10	3125	103
9	-12.5	1758	205
10	-15	977	371
11	-17.5	537	741
12	-20	292	1483



LoRa link budget



N= KTB K=1.38 exp-23 T=290
logN= log(KT) +log(B)

Tx Power=14 dBm

BW = 125 kHz, S/N = -20 (for SF 12)

Assume Noise Figure = 7 dB

Sensitivity = -174 +10 $\log_{10}$ (BW) +NF + S/N =

-174+51+7-20= -136 dBm

Link budget for ITU Region 1: 14+136 = 150 dB

In ITU Region 2, up to -157 dB in the 900 MHz band

RPMA

Random Phase Multiple Access, backed by Ingenu

- Spread Spectrum technology based on CDMA.
- 172 dB link budget offers the longest range.
- 2.4 GHz band, 1 MHz channel bandwidth.
- Up to 624 kbps UL and 156 kbps DL, slower in mobile applications.
- Reliable message through ack and 128 bit AES.
- Robust to interference and Doppler effects.
- Supports background firmware updates.

Cellular IoT (CIoT)

The 3GPP response to the threat of LPWAN was addressed starting from Release 13 on of the 3GPP standard, with 2 variants:

- LTE-M
- NB-IoT

They are both officially 5G technologies and differentiate in terms of bandwidth, data rate, latency and power consumption to cover different needs thus presenting a strong competition to the proprietary LPWAN vendors.

3GPP can benefit of existing direct ties with consumers and a well known, mature ecosystem.

LTE-M (eMTC)

- High System capacity and reliability
- Low Latency
- Full or half duplex
- Supports both TDD and FDD
- Supports Voice/IP and positioning
- Limited or full mobility
- Power saving mode (PSM)
- Extended discontinuous reception (eDRx) up to 44 minutes (amount of sleeping between paging cycles)

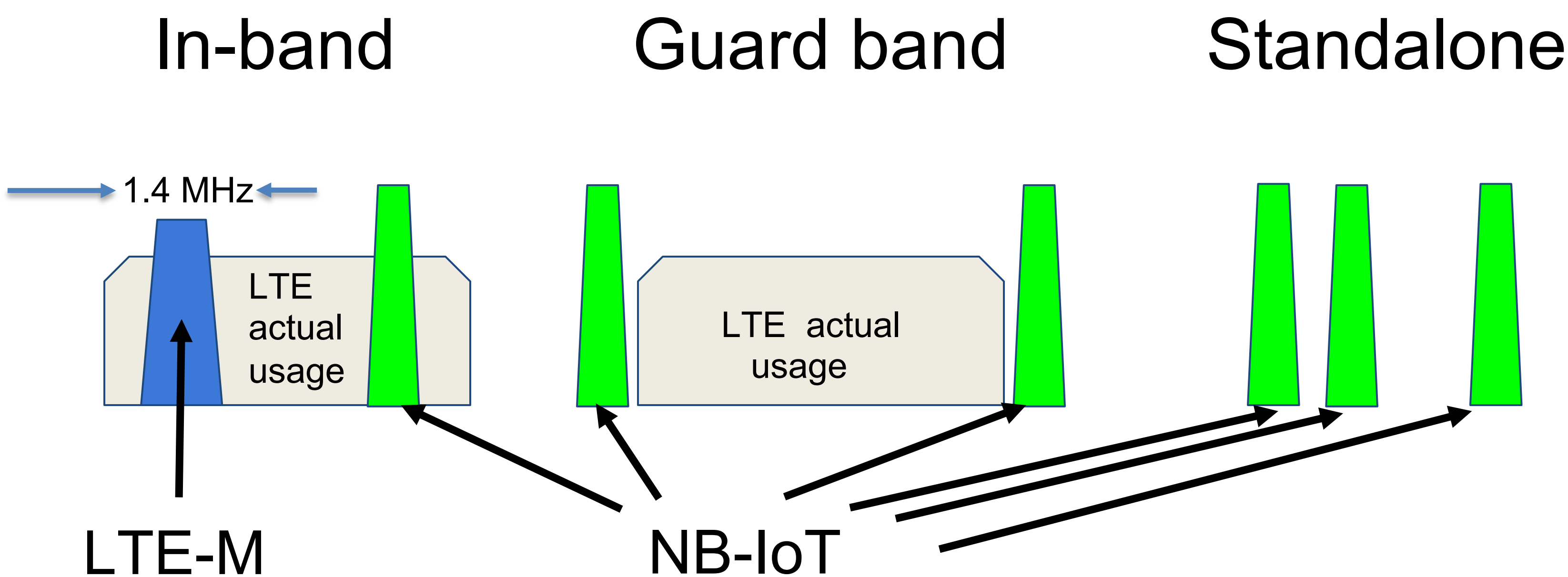
Narrowband for IoT (NB-IoT)

- Messages can be repeated up to 128 times in UL and 2048 in DL, to provide processing gain at the receiver, at the expense of additional latency.
- Bandwidth is 180 kHz, half duplex, does not support voice or mobility.
- Support for time-division duplexing (TDD), over-the-air (OTA) firmware updates, unlicensed frequencies, small cells and Wake-up Signal (WUS) for groups.
- 164 dB power budget, improved wall penetration and range.
- Long battery life and lower device complexity and cost.

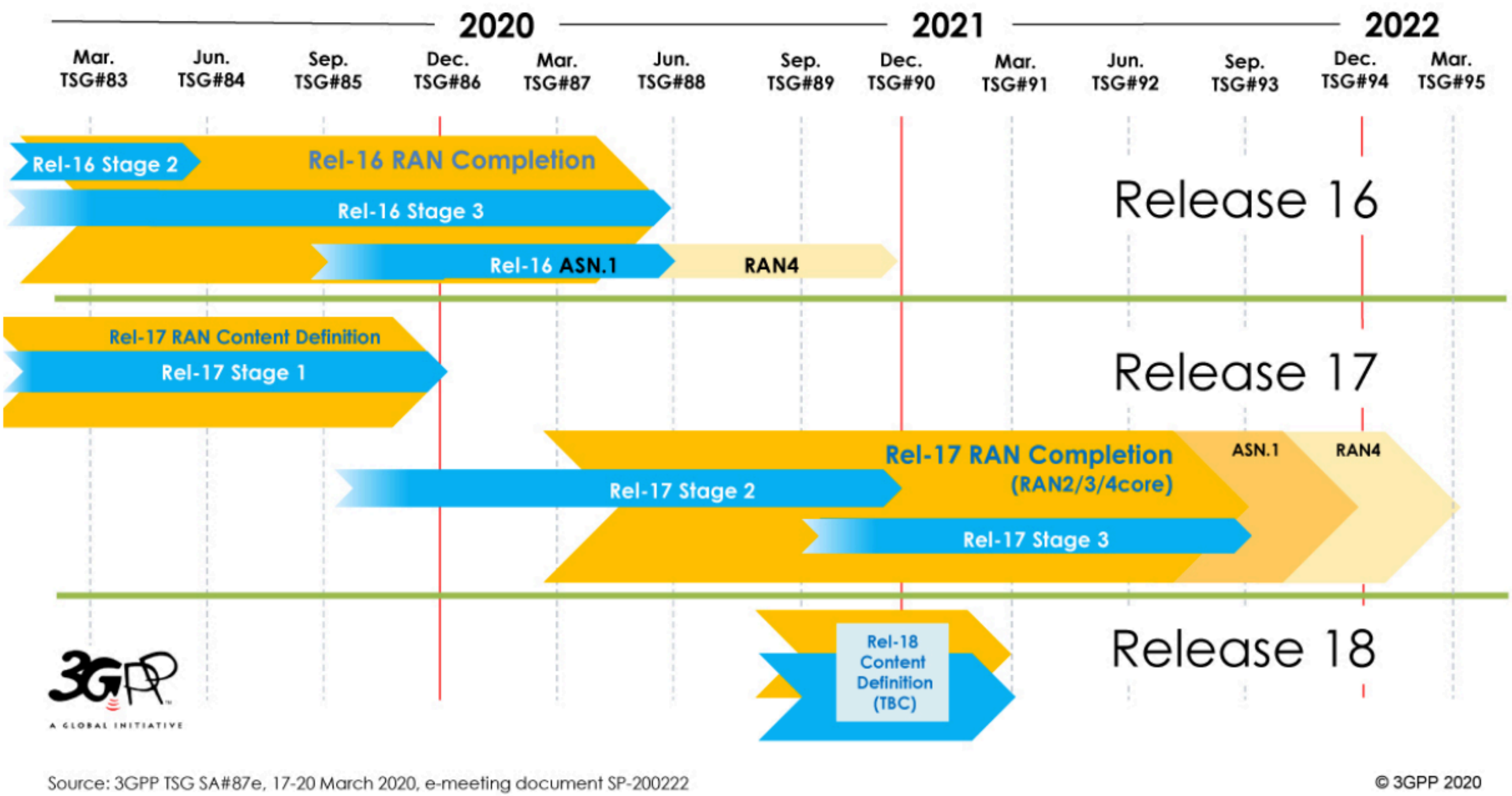
Narrowband for IoT (NB-IoT)

- 20 dB higher power budget as compared with GPRS.
- 10 years battery life.
- Lower cost than LTE-M.
- Positioning capabilities.
- Support of up to 52 500 users per cell.
- Early Data transmission.
- 23 dBm/ 20 dBm or 14 dBm power output.
- Single or multi-tone transmission.
- Up to 3 hours extended discontinuous reception (eDRx).

Spectrum flexibility for LTE-M and NB-IoT

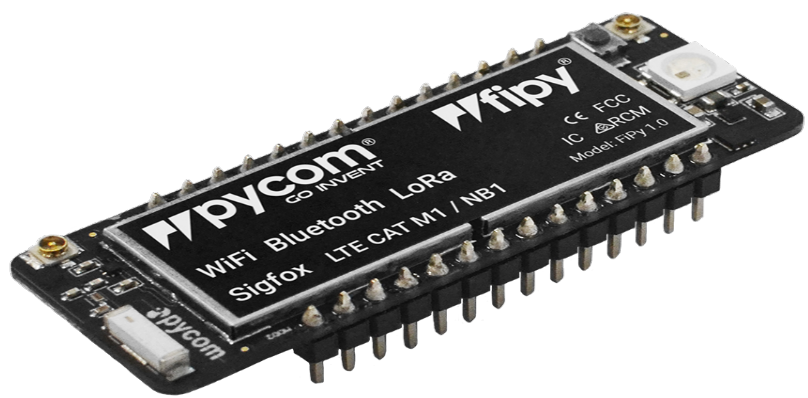


3GPP Releases



Hybrid Solutions

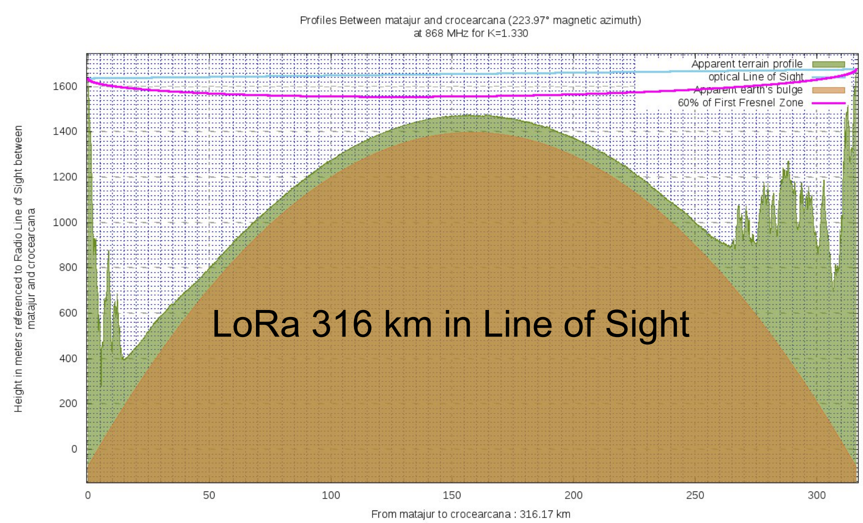
- Some vendors are offering modules that support cellular IoT solutions as well as LPWAN ones.
- This opens up the possibility of building a LPWAN network now, with the prospect of migrating to an LTE-M or NB-IoT one in the future or even building from scratch a hybrid network in which devices can connect to several networks, depending for instance in coverage or cost.



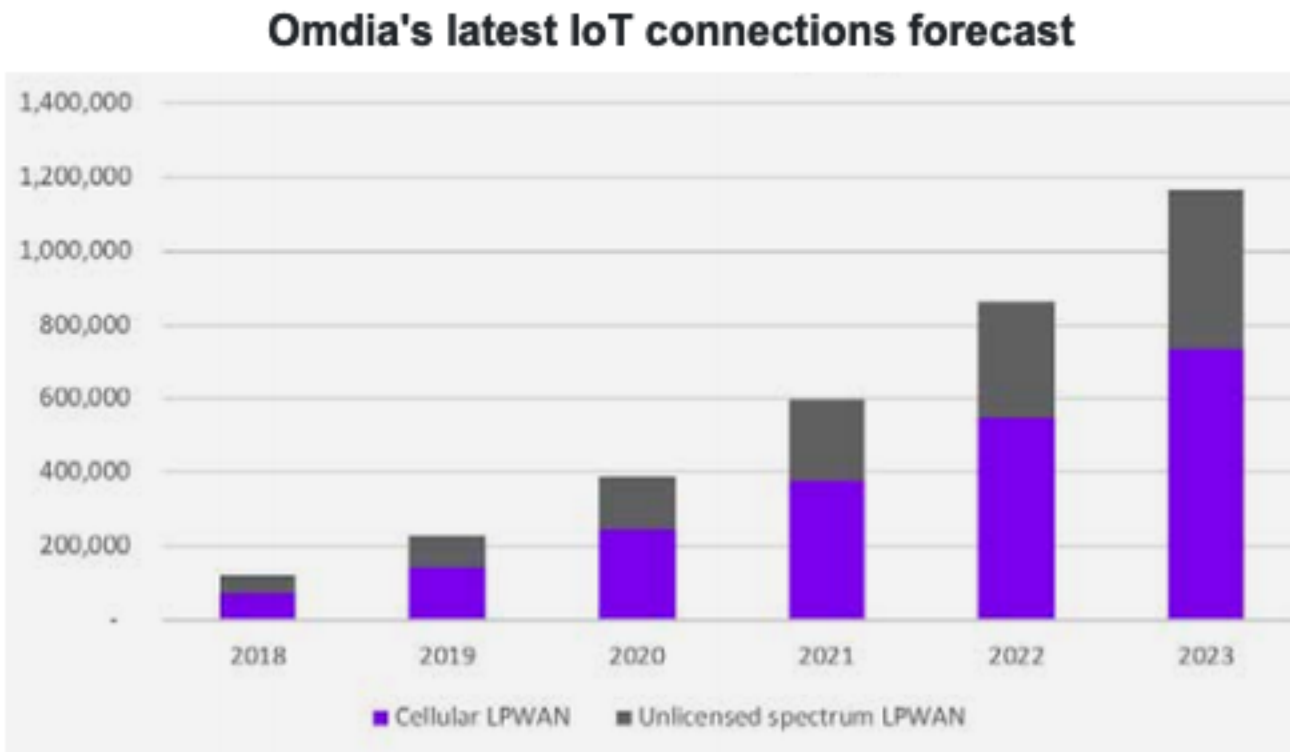
Technology	Sensitivity	Data rate	Spectrum
WiFi (802.11 b,g,h)	-95 dBm	1-54 Mb/s	Wide Band
Bluetooth	-97 dBm	1-2 Mb/s	Wide Band
BLE	-95 dBm	1 Mb/s	Wide Band
SigFox	-142 dBm	100 b/s	Ultra Narrow Band
LoRa	-137 dBm	18 b/s - 37.5 kb/s	Narrow Band
LTE-M	- 140 dBm	Up to 1.4 Mb/s	Narrow Band
NB-IoT	- 141 dBm	up to 250 kb/s	Narrow band

Range

- 802.15.4 less than 100 m
- WiFi, typically 100 m
- 2G, typically 3 km, maximum 30 km
- LTE-M, few kilometers
- NB-IOT, many kilometers
- LoRa and SigFox: many kilometers



LPWAN market share forecast



Cellular IoT includes legacy 2G, 3G, NB-IoT and LTE-M
Unlicensed spectrum LPWAN are mostly LoRa and SigFox

Lacuna Satellites for LoRa

from:
https://www.semtech.com/company/press/semtech-and-lacuna-receiving-messages-from-space

- Lacuna Space uses a constellation of polar low-earth orbiting satellites to receive messages from sensors integrated with LoRa radios.
- At about 500 km above the ground, the satellites circle over the poles every 100 minutes and as the earth revolves below them, they cover the globe.
- The satellites store the messages for a short period of time until they pass over the network of ground stations.

Concluding remarks

- IoT requires specific standards.
- WiFi , Zigbee and BLE have limited range.
- Legacy cellular technologies not efficient.
- Cellular IoT based on Releases 13, 14, 15 and 16 address most of the shortcomings but availability is still limited.
- Several vendors offer proprietary alternatives.
- LoRa and SigFox are widely used worldwide for long distance at limited data rates.
- LoRaWAN has been leveraged to build customer's private LPWAN infrastructure and also a crowdfunded global initiative called "The Things Network".
- Satellites will play an increasing role in communications given their global coverage capabilities.

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