Low Power Wide Area Networks: An Overview

Paper presentation by: David Caruthers, Neel Dutta, Yong Xin Huang, Allanah Matthews, Hanbo Wang

Outline

1. Introduction
2. Design Goals and Techniques
3. Proprietary Techniques
4. Standards
5. Challenges and Open Research Directions
6. Business Considerations
7. Conclusion

Introduction

Internet of Things!

- Could solve global challenges
- Interest in IoT is growing
    - $4.3T industry*
- Some research goals
    - Power
    - Scalability
    - Area
- Existing networks
    - Bluetooth
    - Wi-Fi
    - Cellular

Low Power Wide Area Networks (LPWAN)

- Low power => high battery life
  - Ideal for devices that need to be left alone for years
- Wide area
- Trade offs
  - Latency
  - Low data rate

LPWAN Now*

- Very fragmented market
- Need for standardization (SDOs and SIGs)

Design Goals and Techniques

Long Range

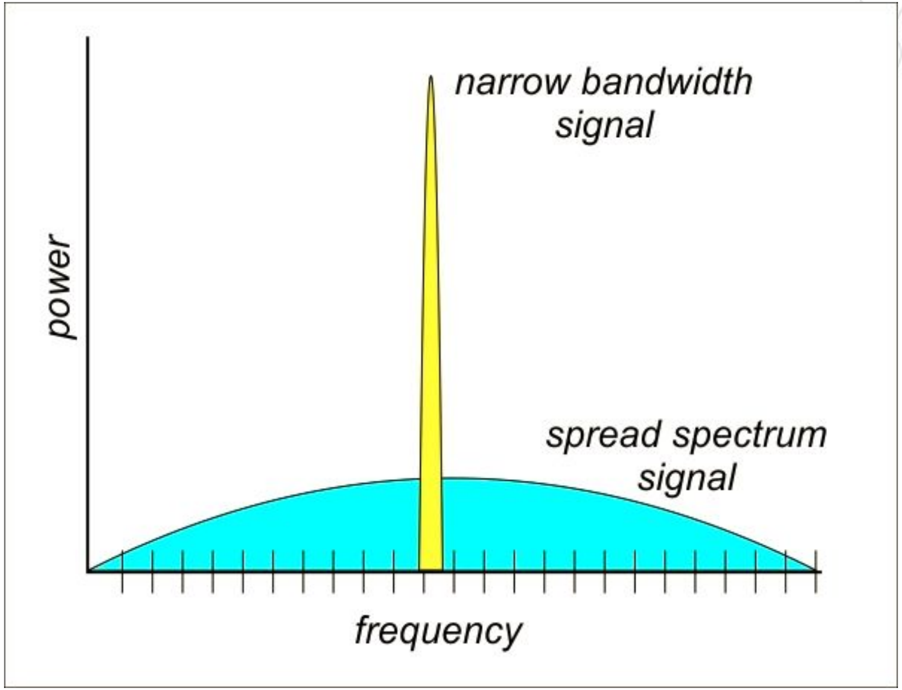
- +20 dB gain compared to cellular
  - That's **100x** more powerful
- Use sub-1GHz
  - Less noisy
  - Less frequency attenuation
  - Less multipath fading from obstacles
- Higher reliability enables long range and good signal propagation
- Link budget of 150 ± 10 dB
  - Received power (dBm) = transmitted power (dBm) + gains (dB) - losses (dB)
- Has more energy in each bit → higher rate of decoding correctly
  - Sensitivity minimum of -130dBm

Long Range - Narrowband and Ultra Narrowband

- **Narrowband**
  - High link budget by encoding signal in low bandwidth (<25kHz)
  - Each carrier has narrow band and minimal noise → less work to decode the signal
- **Ultra narrowband width (UNB)**
  - Minimum width 100Hz
  - Further reduced noise
  - Devices on more due to lower data rate

Long Range - Spread Spectrum

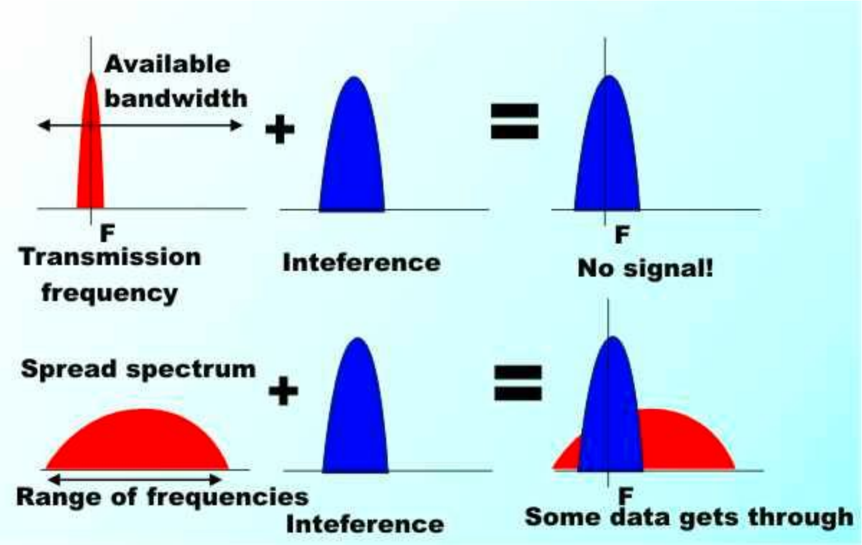
- Spread narrow band signal over more frequencies
  - Less efficient use of spectrum
  - Same power density



https://techimike.com/cwna-chapter-6-dsss-fhss-and-ofdm/ https://www.i-programmer.info/programming/hardware/2767-how-wifi-works.html

Long Range - Spread Spectrum

- Signal is noisy thus making it more resilient to interference, jamming attacks, and harder to detect by eavesdroppers
- Overcome less spectrum efficiency by using multiple orthogonal sequences
  - More work to decode them



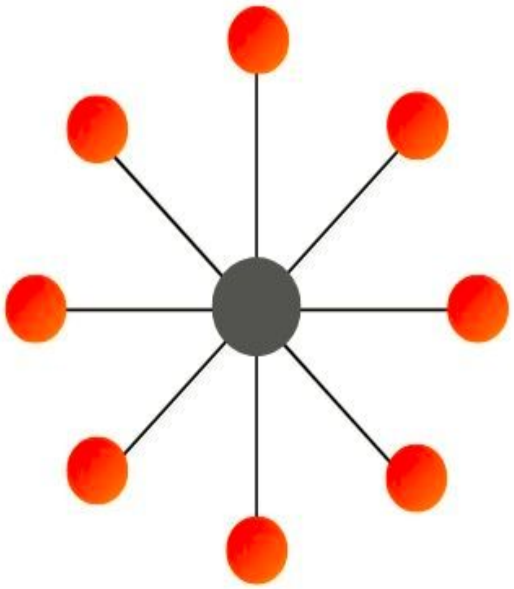
https://techimike.com/cwna-chapter-6-dsss-fhss-and-ofdm/ https://www.i-programmer.info/programming/hardware/2767-how-wifi-works.html

Ultra Low Power Operation

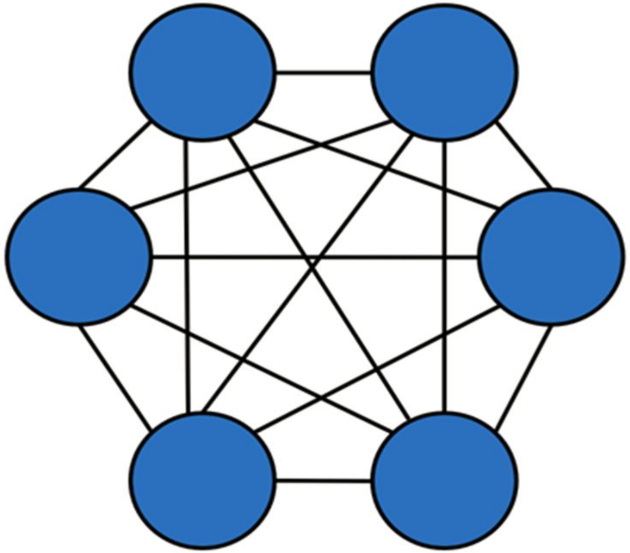
- Longer lasting batteries = less maintenance = more savings
- Duty cycling - turn off power hungry devices when not in use
  - May only turn on to transmit data and wait for a reply
  - Listening is schedule based
  - Can do this to other hardware

Ultra Low Power Operation

- LPWA connect to base (no hops) in a star topology



Star Topology

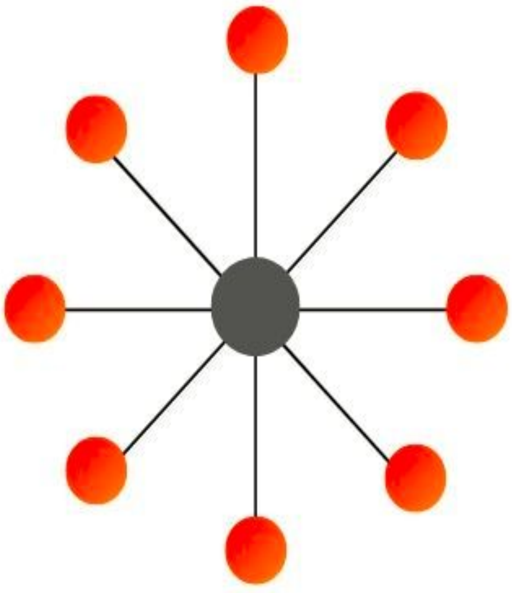


Mesh Topology

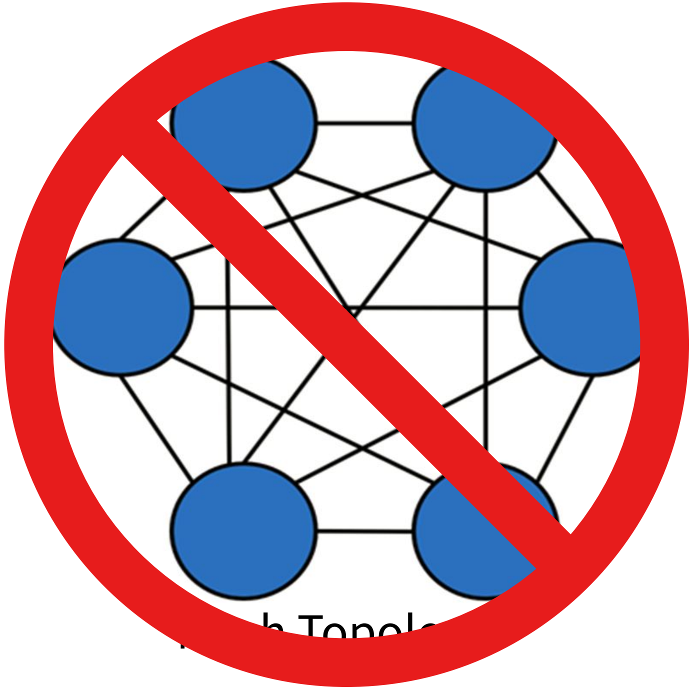
https://boosthigh.com/mesh-network-for-iot-devices/

Ultra Low Power Operation

- LPWA connect to base (no hops) in a star topology



Star Topology



https://boosthigh.com/mesh-network-for-iot-devices/

Ultra Low Power Operation

- Common MAC protocols are too complex
  - LPWA devices drift in time and frequency
  - Too many devices to use CSMA/CA or RTS/CTS
  - Link asymmetry cannot use virtual carrier sensing well
- Most use ALOHA random access without carrier sensing
- Base station is more complex doing more computation, multi-channel listening transmitting
  - Allow end devices to be simpler

Ultra Low Power Operation

- Communication energy > processing operations energy

- Two options:
  - Report all data with more communication need keeps the cost of end device low
  - Process data and return processed result with less communication

Low Cost

- Hardware below $5 and the connectivity subscription per unit as low as $1
- Star topology
  - Offload complexity from end devices
    - Simple MAC protocols
    - Processing less complex waveforms → simpler hardware
- Less infrastructure → lower network cost
- Use license-exempt bands

Scalability

- Efficient exploitation of diversity in channel, time, space, and hardware is vital
- Multiple channels, multiple antenna, and redundant transmission → resilient to interference
- If base station can communicate with end devices can use adaptive channel selection and adaptive data rate
    - Improve reliability and energy efficiency
- If not, end devices send across random channels
- Dense population of devices may cause an interference problems and needs more investigation
- Scalability can be improved (spoken more in depth in an upcoming section)

Quality of Service (QoS)

- No or limited quality of service guarantee

Proprietary Techniques

SigFox

- Proprietary base stations with cognitive SDRs
- UNB supported
  - Low noise levels and low power consumption
- Evolved to support bidirectional communication with significant link asymmetry
- Uplink reliability through redundant transmissions

LoRa

- Uses proprietary Chirp Spread Spectrum (CSS) modulation technique
- Supports spreading factors for adaptive data rates

https://www.techplayon.com/lora-link-budget-sensitivity-calculations-example-explained/

LoRa CSS Spreading Factors (125kHz BW)

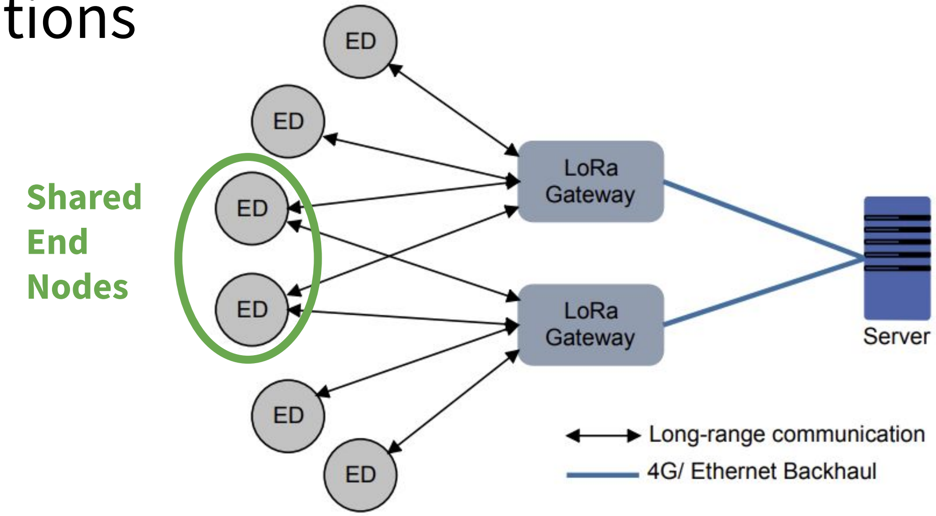
Spreading Factor	Chips/symbol	SNR limit	Time-on-air (10 byte packet)	Bitrate
7	128	-7.5	56 ms	5469 bps
8	256	-10	103 ms	3125 bps
9	512	-12.5	205 ms	1758 bps
10	1024	-15	371 ms	977 bps
11	2048	-17.5	741 ms	537 bps
12	4096	-20	1483 ms	293 bps

Higher Bitrate

Higher TX Time

LoRa

- Star of stars topology for increased reliability
- End device localization via TDOA from synchronized base stations



Piyare, Rajeev & Murphy, Amy & Magno, Michele & Benini, Luca. (2018). On-Demand LoRa: Asynchronous TDMA for Energy Efficient and Low Latency Communication in IoT. Sensors. 18. 3718. 10.3390/s18113718.

Ingenu

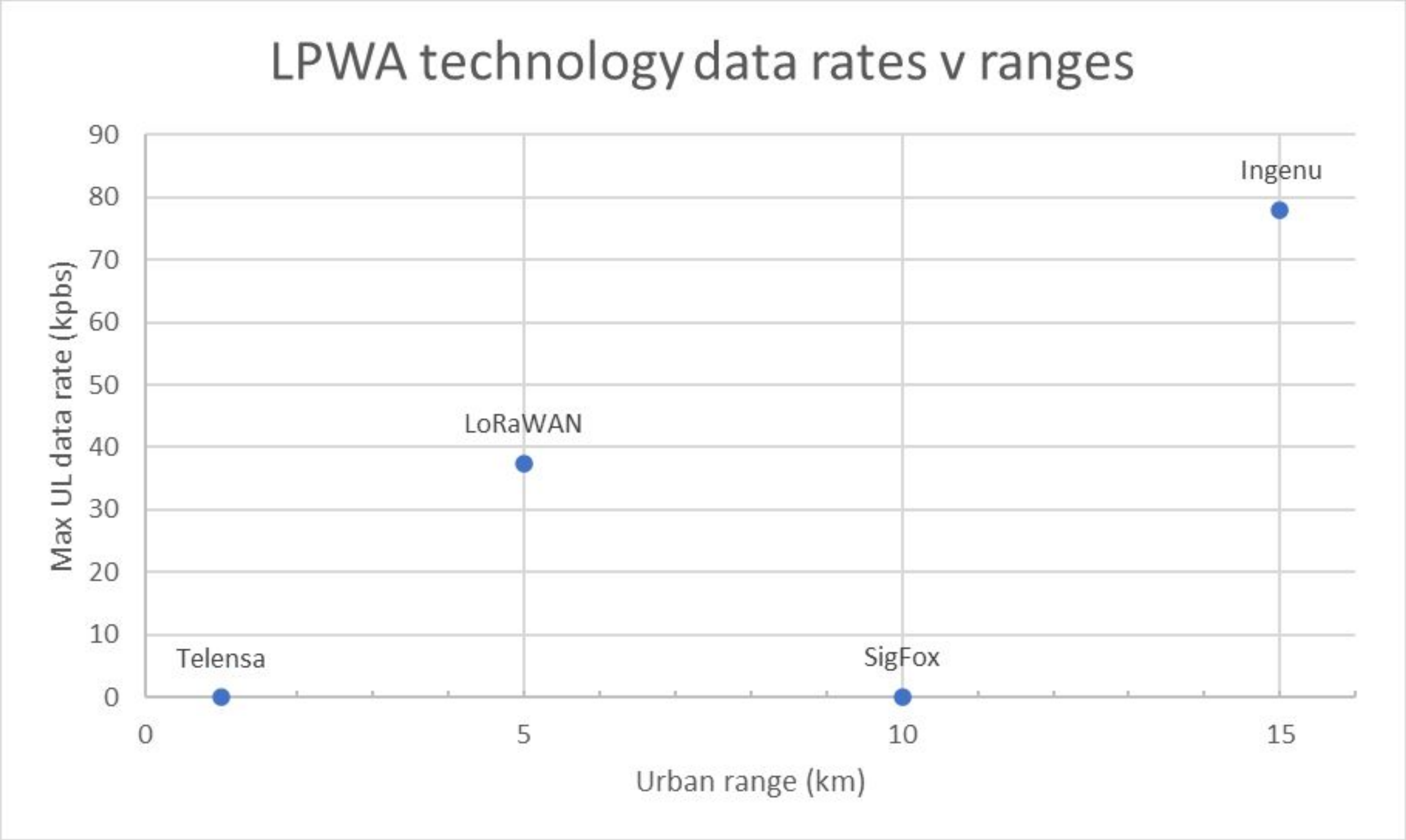
- Patented Random Phase Multiple Access (RPMA) DSSS
    - Increases signal to interference ratio
    - Yields up to -142 dBm receiver sensitivity and 168 dB link budget
- 2.4GHz ISM band
    - Relaxed regulations on max duty cycle yields higher throughput
    - High interference potential

Telensa

- Proprietary UNB modulation technique in sub-1GHz ISM band
- Provides end-to-end solutions with full vertical network stack
- Standardize using ETSI Low Throughput Networks specification for ease of integration
- Smart city application focus

Qowisio

- Combines UNB with LoRa for a dual-mode LPWAN
- Provides LPWA as a service to end users
- Little is known about the technical specifications of the UNB technology

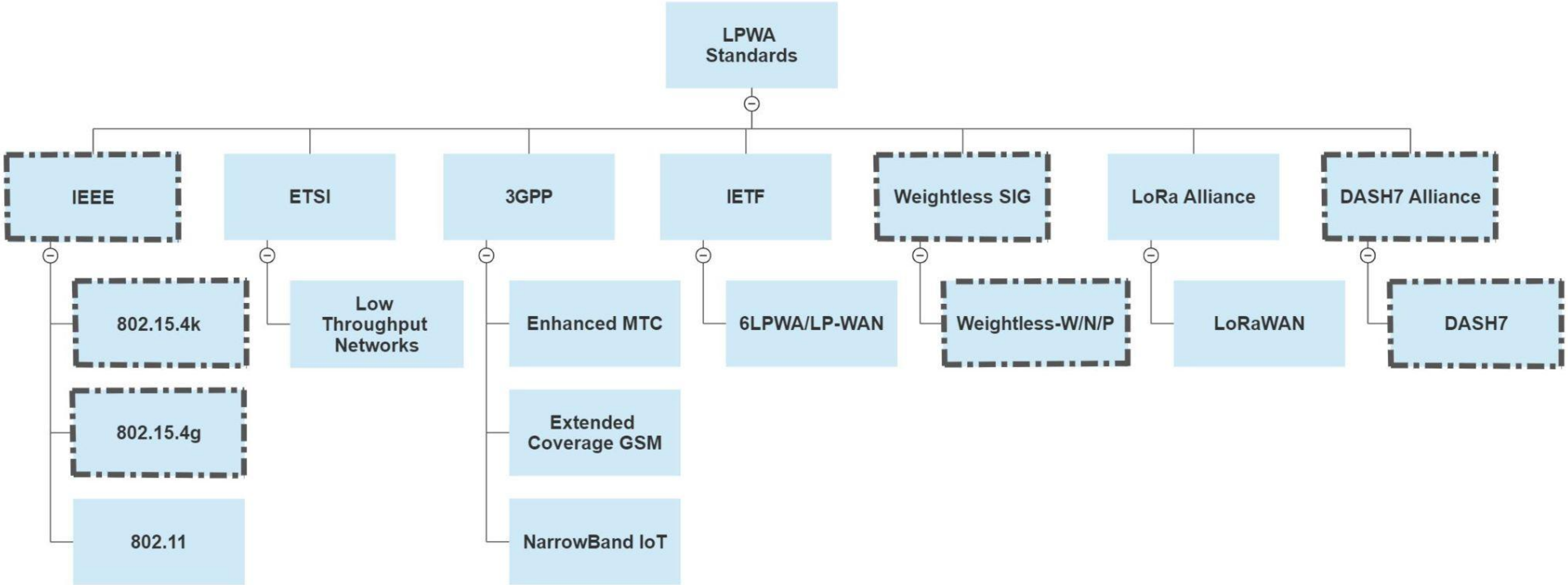

LPWA technology data rates v ranges
Max UL data rate (kpbs)
90
80
70
60
50
40
30
20
10
0
Ingenu
LoRaWAN
Telensa
SigFox
0
5
10
15
Urban range (km)

LPWA technology specifications

	SigFox	LoRaWAN	Ingenu	Telensa
Forward Error Correction	✗	✔	✔	✔
Adaptive Data Rate	✗	✔	✔	✗
Authentication and Encryption	Encryption unsupported	AES 128b	16B hash, AES 256b	?
Over the air updates	✗	✔	✔	✔

Standards

LPWA standards and their developing organizations



IEEE

- IEEE 802.15.4k (Low Energy, Critical Infrastructure Monitoring Networks)
    - Amended to adopt DSSS modulation in the PHY and MAC layers
    - Provides a QoS guarantee by prioritizing traffic
    - Star topology
- IEEE 802.15.4g (Low-Data-Rate, Wireless, Smart Metering Utility Networks)
    - The standard defines three PHY layers: Frequency-Shift Keying, Orthogonal Frequency-Division Multiple Access, and Offset Quaternary Phase Shift Keying
    - Supports multiple data rates ranging from 40 Kbps to 1 Mbps
    - Supports mesh topology

WEIGHTLESS-SIG

- WEIGHTLESS-W
  - Leverages excellent signal propagation properties of TV white-spaces
  - But the shared access of the TV white spaces is permitted only in few regions
- WEIGHTLESS-N
  - A UNB standard for only one-way communication from end devices to a base station
  - Improve the energy efficiency and lower the cost
- WEIGHTLESS-P
  - Blends two-way connectivity with two non-proprietary physical layers
  - The end devices do not require a proprietary chipset.

DASH7 Alliance

- DASH7 Alliance Protocol is an open-source wireless sensor and actuator network protocol, which operates in the 433 MHz, 868 MHz and 915 MHz unlicensed ISM band
- Three major differences
  - DASH7 uses a tree topology by default with an option to choose star layout as well
  - DASH7 MAC protocol forces the end devices to check the channel periodically for possible downlink transmissions, adding significant idle listening cost
  - DASH7 defines a complete network stack. Applications and end devices communicate with each other without having to deal with intricacies of the underlying physical or MAC layers.

Standard	IEEE 802.15.4k	IEEE 802.15.4g	Weightless-SIG Weightless-W	Weightless-SIG Weightless-N	Weightless-SIG Weightless-P	Dash7 Alliance Dash7
Modulation	DSSS, FSK	MR-(FSK, OFDMA, OQPSK)	16-QAM, BPSK, QPSK, DBPSK	UNB DBPSK	GMSK, offset-QPSK	GFSK
Band	ISM Sub-GHz & 2.4GHz	ISM Sub-GHz & 2.4GHz	TV white spaces 470-790MHz	ISM Sub-GHz EU (868MHz), US (915MHz)	Sub-GHz ISM or licensed	Sub-GHz 433MHz, 868MHz, 915MHz
Data rate	1.5 bps-128 kbps	4.8 kbps-800 kbps	1 kbps-10 Mbps	30 kbps-100 kbps	200 bps-100kbps	9.6,55.6,166.7 kbps
Range	5 km (urban)	up to several kms	5 km (urban)	3 km (urban)	2 km (urban)	0-5 km (urban)
Num. of channels / orthogonal signals	multiple channels. Number depends on channel & modulation		16 or 24 channels(UL)	multiple 200 Hz channels	multiple 12.5 kHz channels	3 different channel types (number depends on type & region)
Forward error correction	✓	✓	✓	✗	✓	✓
MAC	CSMA/CA, CSMA/CA or Aloha with PCA	CSMA/CA	TDMA/FDMA	slotted Aloha	TDMA/FDMA	CSMA/CA
Topology	star	star, mesh, peer-to-peer (depends on upper layers)	star	star	star	tree, star
Payload length	2047B	2047B	>10B	20B	>10B	256B
Authentication & encryption	AES 128b	AES 128b	AES 128b	AES 128b	AES 128/256b	AES 128b

Challenges and Open Research Directions

A. Scaling Networks to Massive Number of Devices

- Resource Allocation
  - Hot-spot problem
  - Capacity issues
    - Channel diversity
    - Cross-layer solutions

https://doi.org/10.1016/B978-0-12-374715-0.00008-3

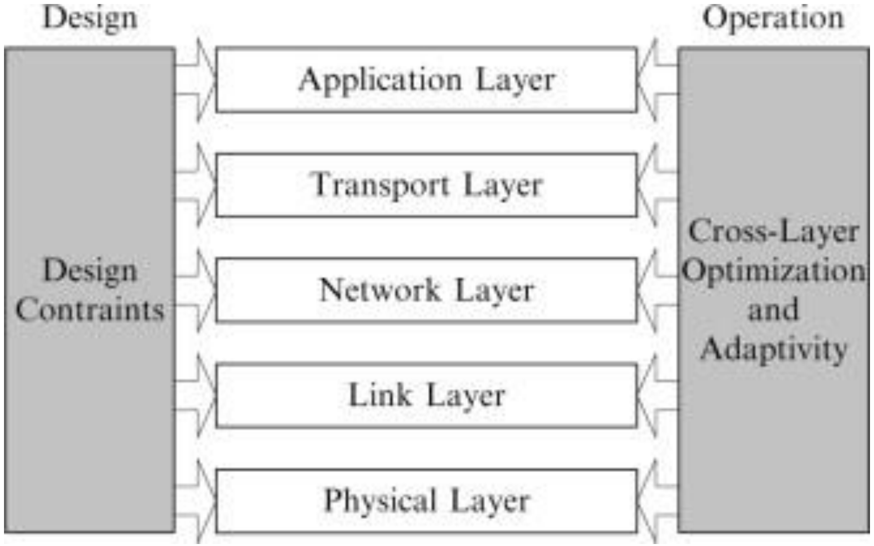
Channel Hopping

- Challenge: synchronize the transmitter and receiver
- Solution
  - Fixed tables of frequency-hopping patterns
  - Guarantee that the transmitter will use all the channels in a fixed period of time

Cross-layer solutions

Why do we need this?

- Significant performance advantages
- Forces designers to consider other layers



Cross-layer solutions

Challenge:

- Tradeoff between energy and delay
- Lack of insight into design
- Requires near brute-force simulation

B. Interference Control and Mitigation

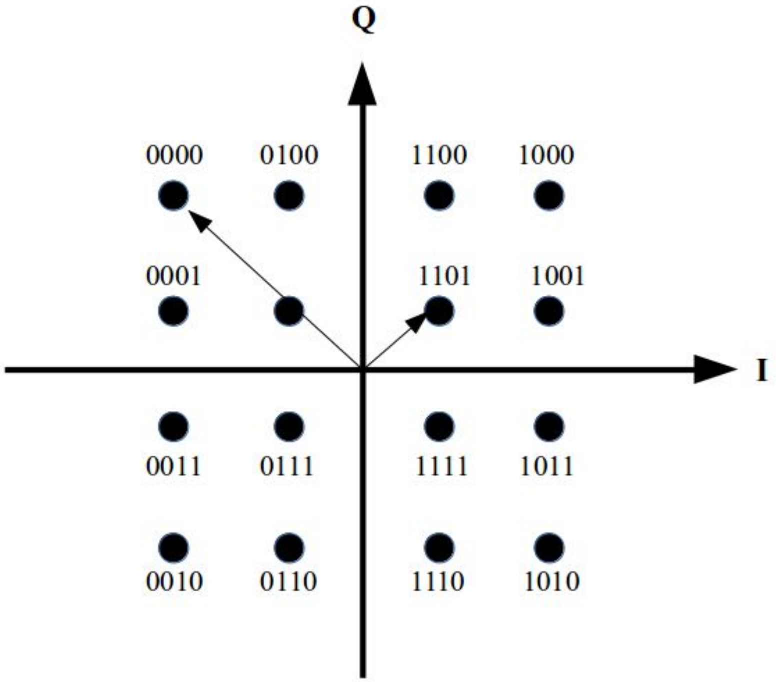
- Adapt transmission schedules: least interference and the best reliability
- Propose rules for unlicensed spectrum

C. High Data-Rate Modulation Techniques

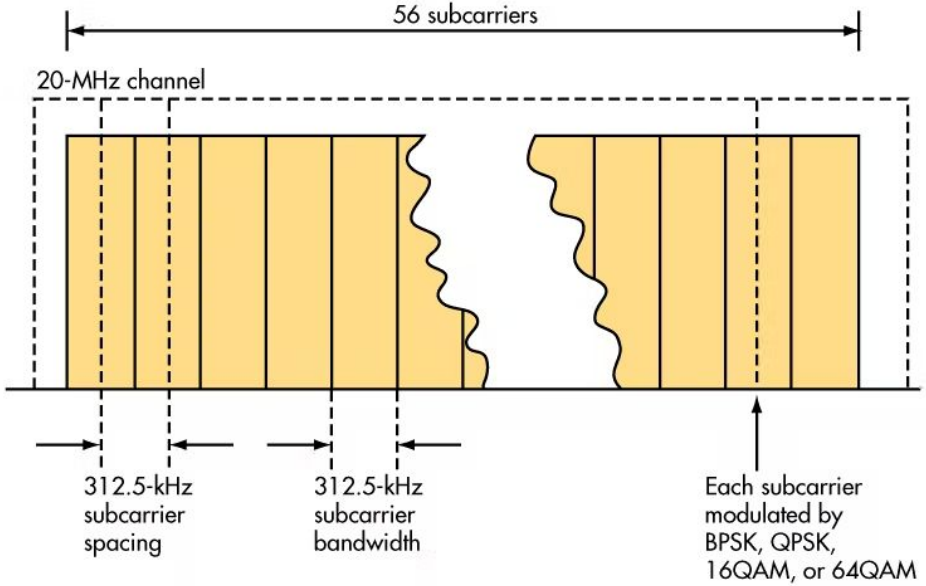
<u>Data rate vs. distances</u>

- Need: Flexible and inexpensive hardware design to support multiple physical layers
- Goal: Multiple modulation schemes

Quadrature Amplitude Modulation



Orthogonal Frequency Division Multiplexing

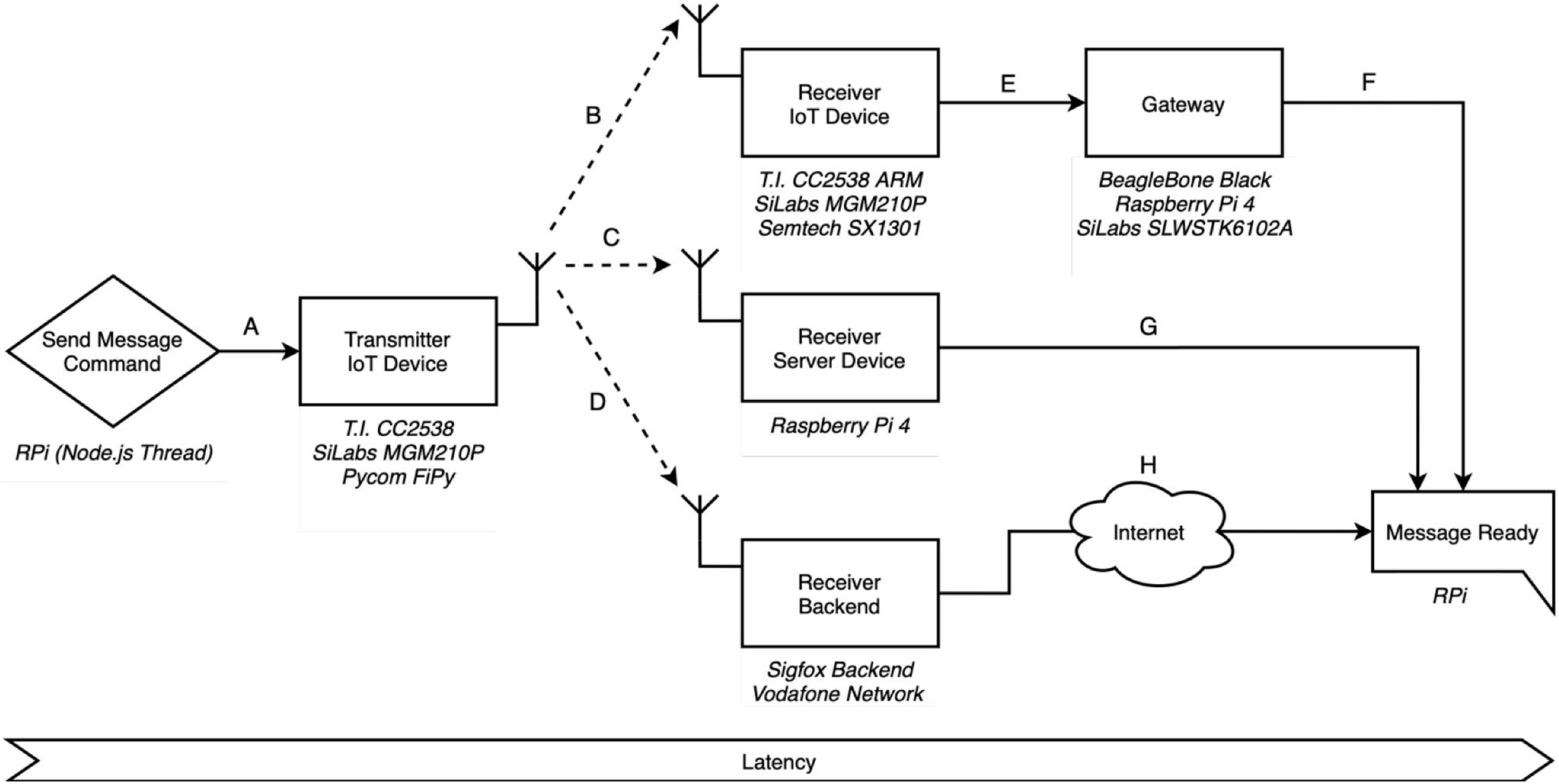


https://wiki.pathfinderdigital.com/wiki/qam

https://www.electronicdesign.com/technologies/communications/article

D. Interoperability Between Different LPWA Technologies/Testbeds and Tools

- Gateways or backend based solutions
  - Problem: Degrading performance
- Middleware or virtualization techniques
- No open testbeds to widely design LPWA systems


Send Message Command
RPi (Node.js Thread)
A
Transmitter IoT Device
T.I. CC2538
SiLabs MGM210P
Pycom FiPy
B
C
D
Receiver IoT Device
T.I. CC2538 ARM
SiLabs MGM210P
Semtech SX1301
E
Gateway
BeagleBone Black
Raspberry Pi 4
SiLabs SLWSTK6102A
F
Receiver Server Device
Raspberry Pi 4
G
Receiver Backend
Sigfox Backend
Vodafone Network
H
Internet
Message Ready
RPi
Latency

E. Localization

- Challenge for LPWA
  - Limited channel bandwidth
  - Often absence of a direct path between end devices and base stations

F. Link Optimizations and Adaptability

- Multiple link level configurations introduce tradeoff between different performance metrics
  - Monitor each link quality and adjust parameters
- Link asymmetry

G. Authentication, Security, and Privacy

- Deal with over-the-air (OTA) updates
- End devices and the networks share a same secret key

H. Mobility and Roaming

- Roaming without compromising the lifetime of the devices
- International roaming

I. Support for Service Level Agreements

- QoS guarantees
- For license-exempt spectrum, service level agreements are likely to be violated

J. Co-Existence of LPWA Technologies With Other Wireless Networks

- Assist route formation
- Combine LPWA and cellular connection to send large traffic volumes

K. Support for Data Analytics

- Single connected device has small revenue
- Higher profitability: selling knowledge to end users

Business Considerations

M2M Problem

- Market gap
- Betting on the market
  - NB-IoT (3GPP)
- Longevity

Conclusion

LPWAN

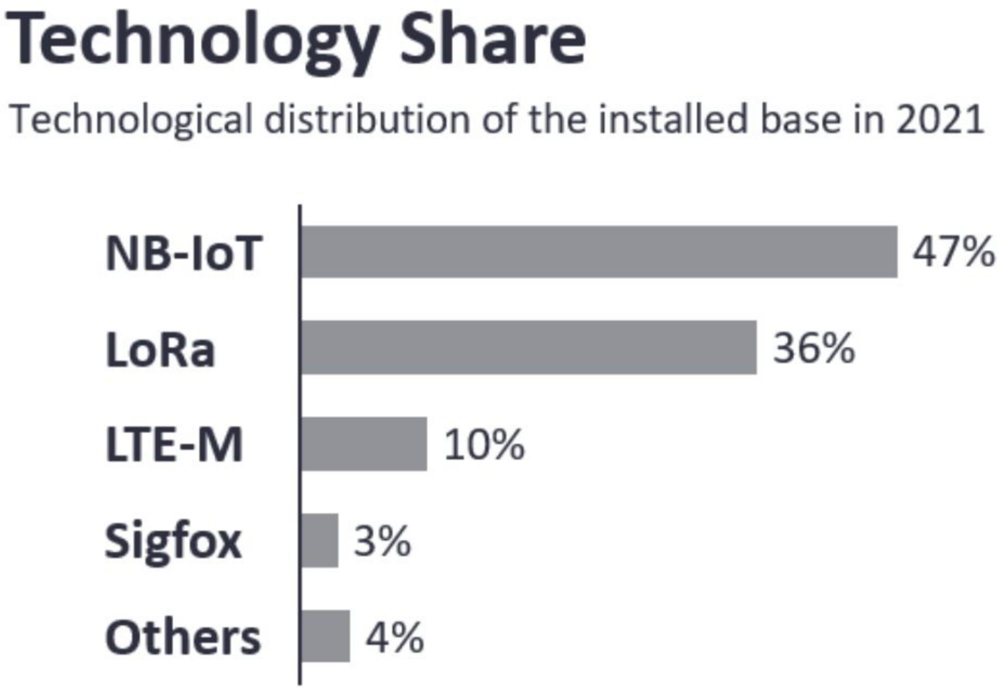
- Area, Power, Scalability, Price
- These goals are often in conflict
- Differences in physical and MAC layer techniques
- Fragmented market => Standards!
- Gaps present still at upper OSI layers

Open Questions

- What new developments in LPWA standards have occurred since this article was published?
- What are the approximate deployment costs of each network type?
- Is QoS still relatively absent in this space?
- What is the energy per transmission for each of these proprietary technologies?

New developments and technology share

- mioty (2018)
  - ISM band
  - Telegram splitting
- Wize (2017)
  - 169 MHz
  - Indoor penetration



https://iot-analytics.com/wp/wp-content/uploads/2021/10/LPWAN-Market-2021-v2-min.png

Network deployment costs

	Spectrum cost	Deployment cost	End-device cost
Sigfox	Free	>4000€/base station	<2€
LoRaWAN	Free	>100€/gateway >1000€/base station	3-5€
NB-IoT	>500 M€ /MHz	>15000€/base station	>20€

K. Mekki, E. Bajic, F. Chaxel and F. Meyer, "Overview of Cellular LPWAN Technologies for IoT Deployment: Sigfox, LoRaWAN, and NB-IoT," 2018 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops), 2018, pp. 197-202, doi: 10.1109/PERCOMW.2018.8480255.