# IoT Networking, part I

## Wireless networks for the Internet of Things

**Sebastian Büttrich 2024**

# Agenda: Networking, part 1

- Scope
- **Criteria for IoT Networks**
- Properties of the Physical Layer
- Wireless basics
- Link budgets, dBms, etc
- **Overview of relevant IoT Network Options in 2024**

# Layer Models

Both models try to describe how information is transmitted between two devices across a network, providing an abstract framework with (somewhat) independent encapsulated layers.

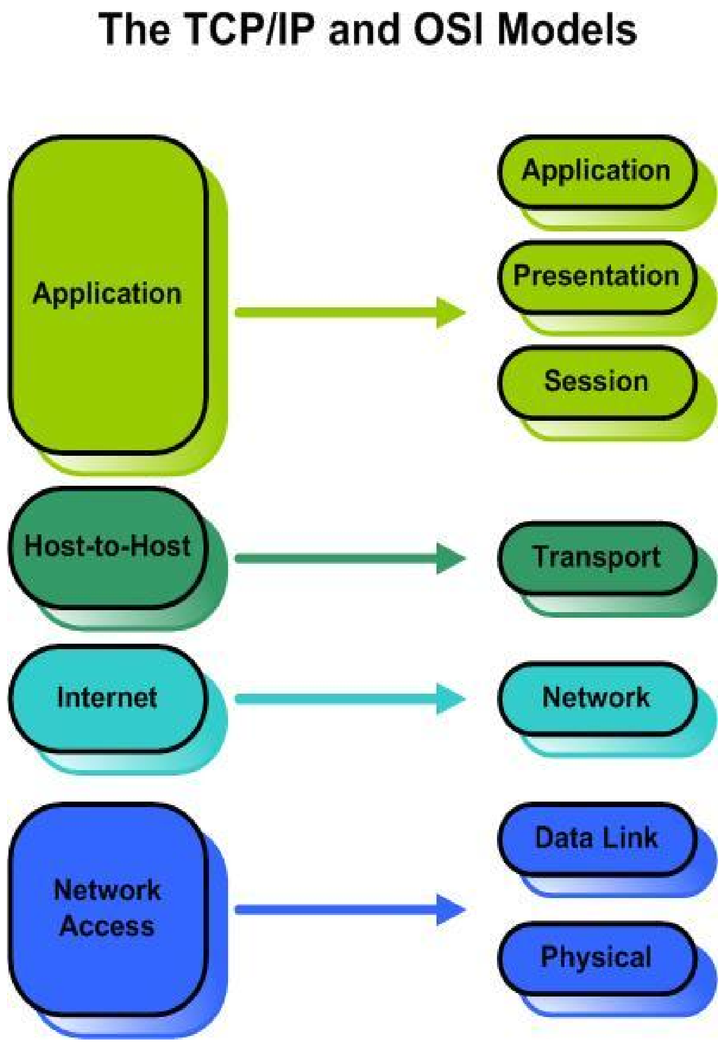
**OSI/ISO**
7 layer model
developed in 1984 by the International Organization for Standardization (ISO).

**TCP/IP model**
4 layer model
designed by Vint Cerf and Bob Kahn in the 1970s.

Applying these models 100% stringent and correct to real life technologies can be difficult or impossible, however

they are useful for an understanding of communications, design and troubleshooting.

Each layer has a specific function. This makes it easier to pinpoint where issues are occurring in the event of a failure.



# Layer Models / Discussion

Examples for Discussion:

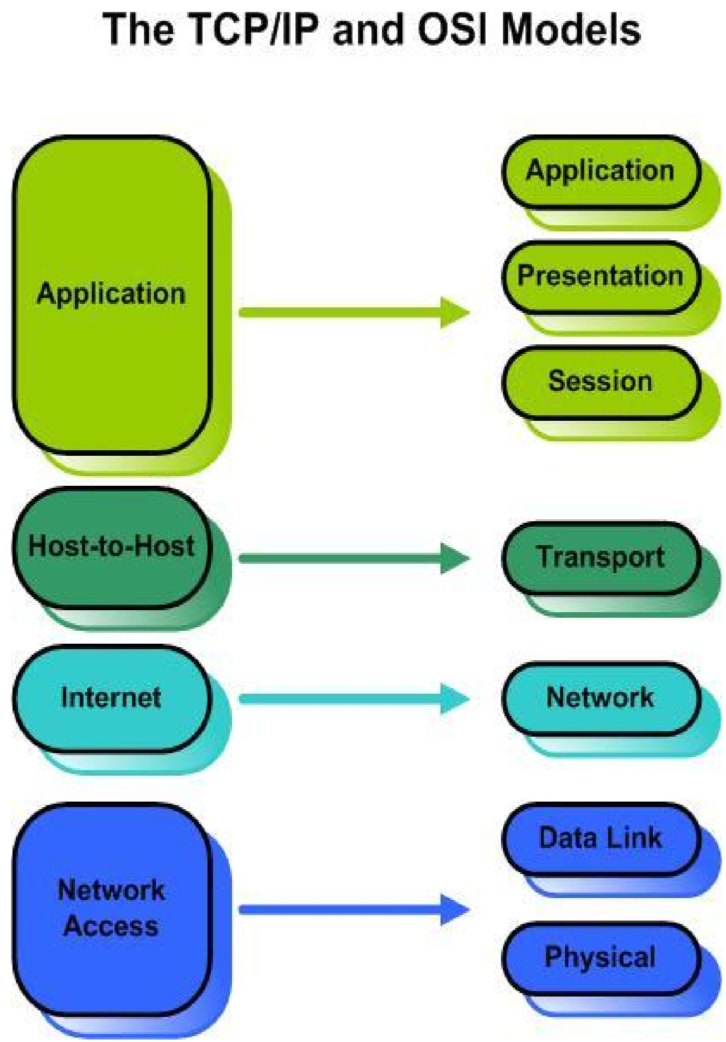
Where do the following belong?

… a web browser?
… 923 MHz?
… a copper cable?
… Wi-Fi?

Can we do IP over Bluetooth?

Can we have MQTT without IP?

Can you do LoRa on 2.4 GHz?



# Layer Models / Discussion

Case:

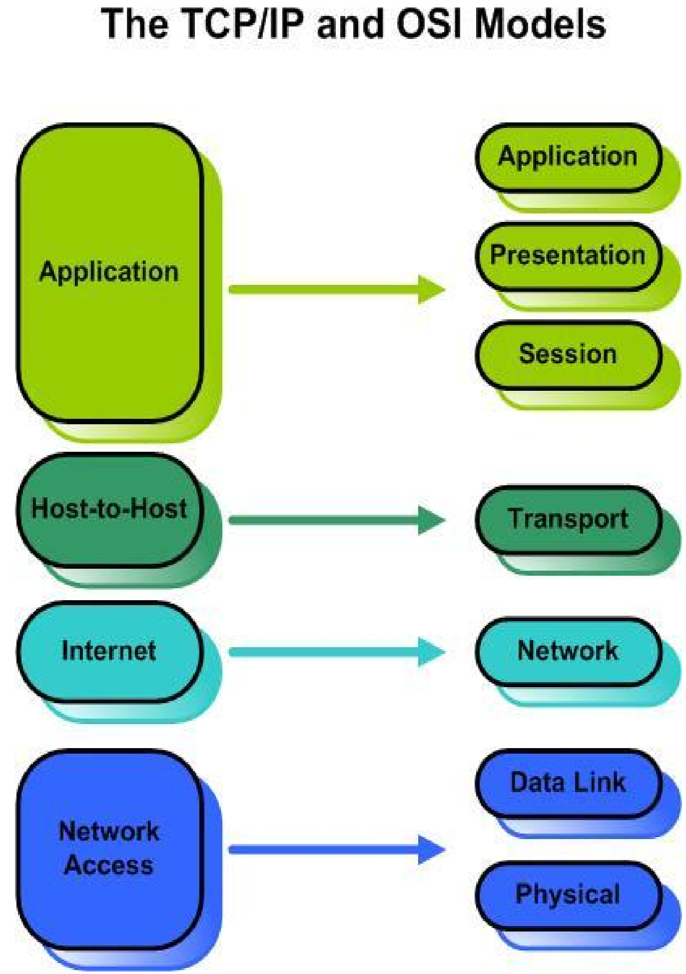
You are working at the helpdesk of IT.

A student or staff member reports that

**“the internet does not work”.**

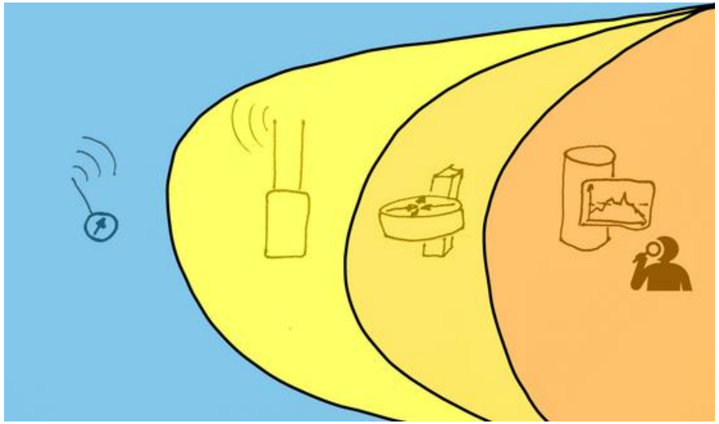
Discuss!

What might they be saying?
What questions should you ask,
And what layer are those addressing?



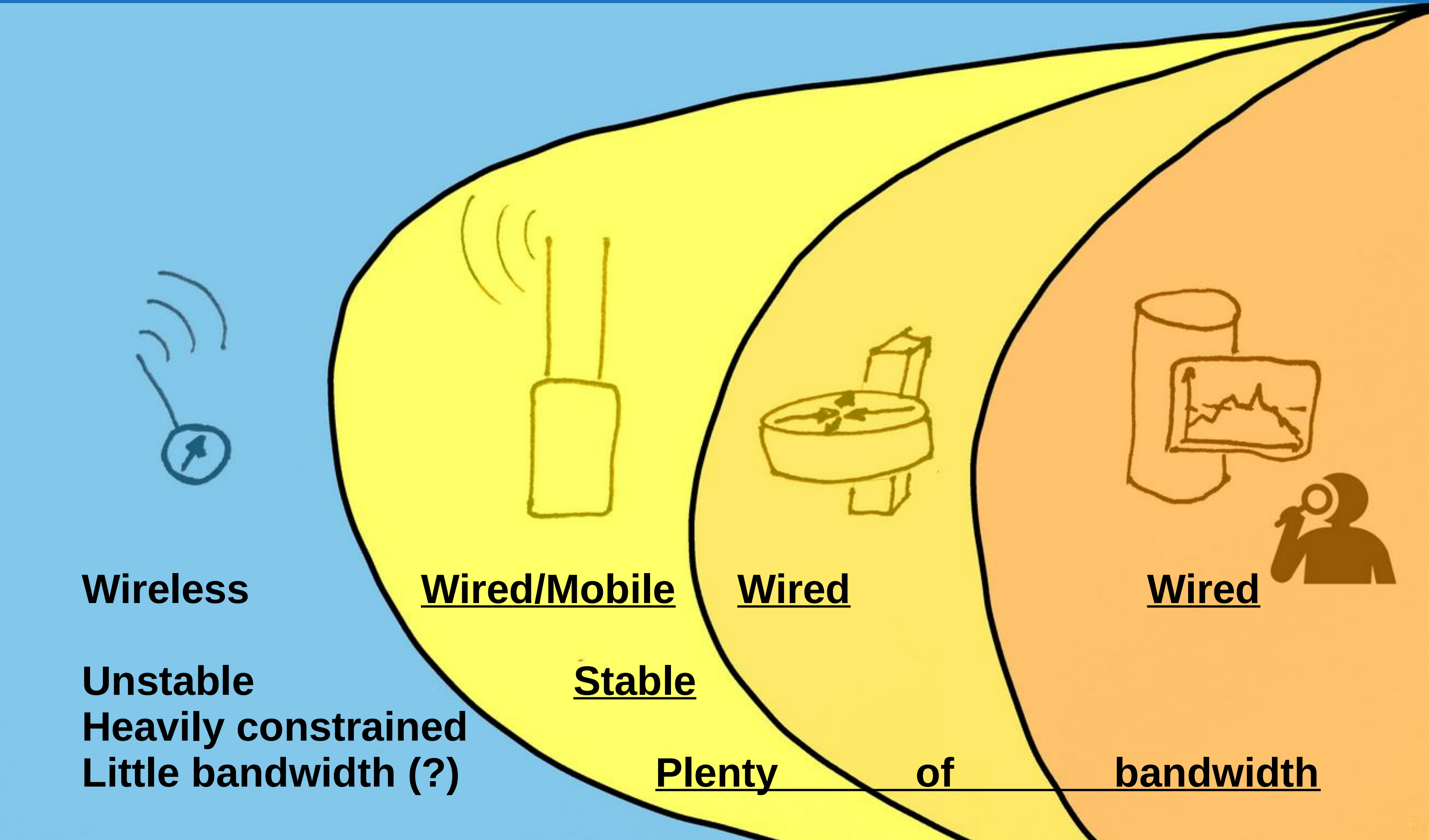
# Scope

- Between the four (or more) stages/tiers in IoT systems: **networks**
- While connectivity in the
  **backend is mostly of conventional type**
  (internet infrastructure – fiber, cables, etc –
  tcp/ip, https, … ),
  connectivity on the first meters,
  for the actual “things”
  (from sensors, nodes, motes to gateways, APs, base stations)
  is still an **emerging landscape with many competing options**



- This lecture is mostly about **networking of “things”**,
  not about the backend, which is sufficiently addressed
  by general networking lectures.

# Network centric view



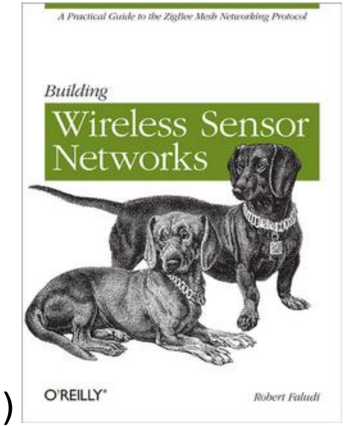
# Recap

We call it the **Internet of Things** – why?

What about it is “Internet”, and in what way?

IoT devices are typically **not on TCP/IP** and if they are, typically **not routed**, i.e. not reachable from the public internet.

# Scope




**Options for networking things:**

- **Wireless**
  - *Human connectivity* networks (WiFi, Bluetooth)
  - Low-rate wireless personal area networks (LR-WPANs) (zigbee, 802.15.4)
  - Cellular (GSM, LTE 4G, 5G, …. 6G, 7G under development)
  - Low Power Wide Area Networks (LPWAN, cellular and non-cellular)
- Wires & cables & fiber
- Other (“exotic”): e.g. acoustic modems for underwater

**We could also distinguish by :**

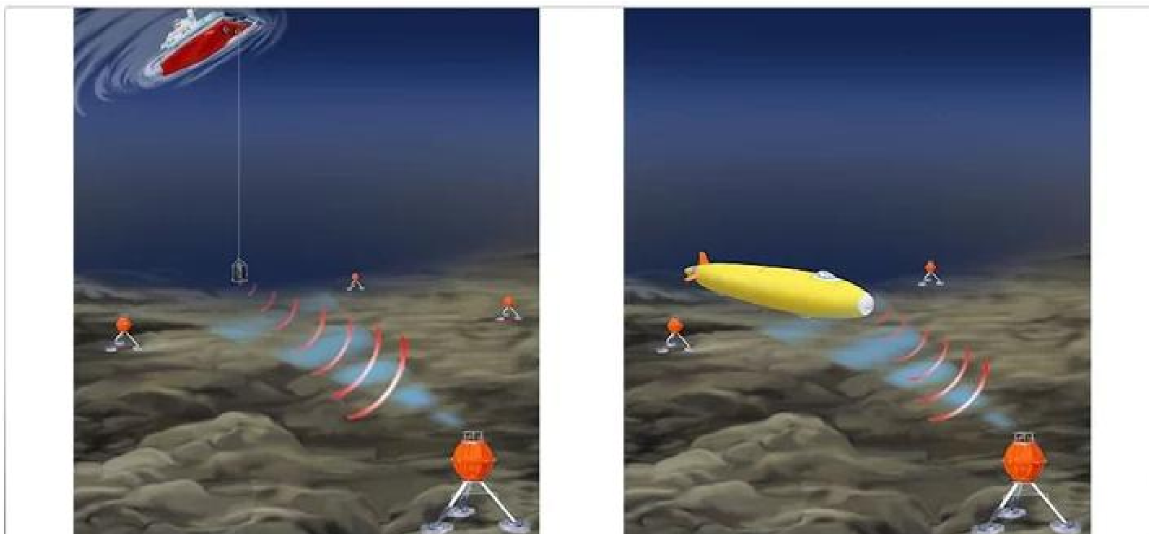
- Terrestrial (with all of the above)
- Satellites, Aerostats, HAPs (High Altitude Platforms) -

*with a variety of frequency bands and technologies*

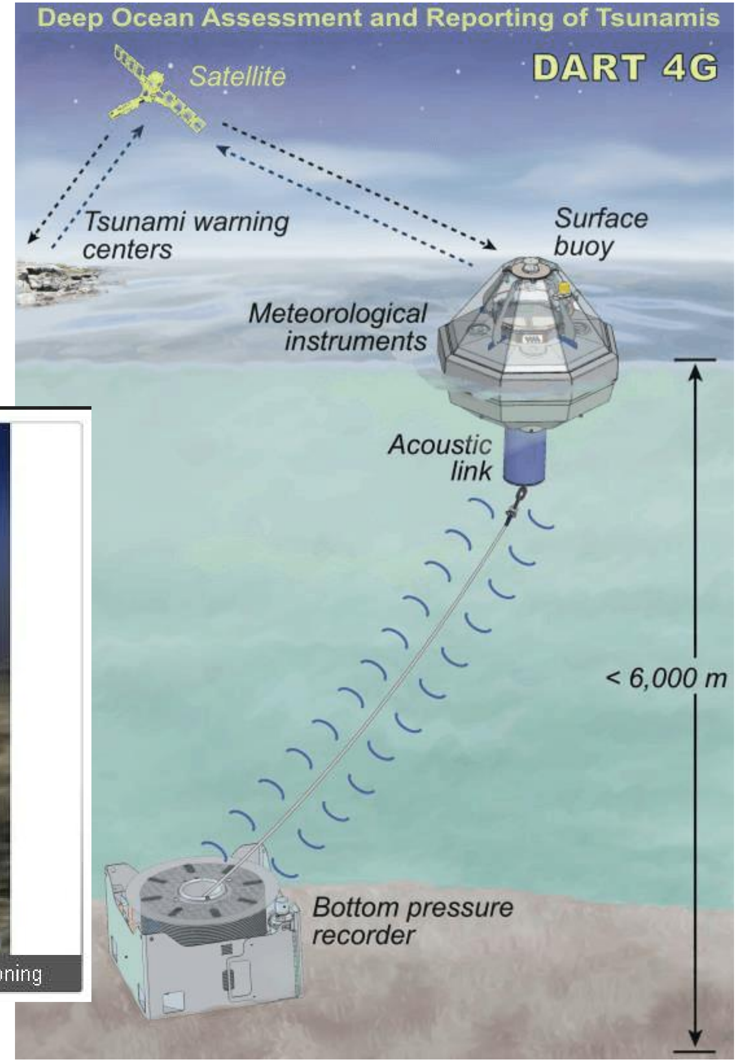
# Scope

**Exotic (non-EM) options:**

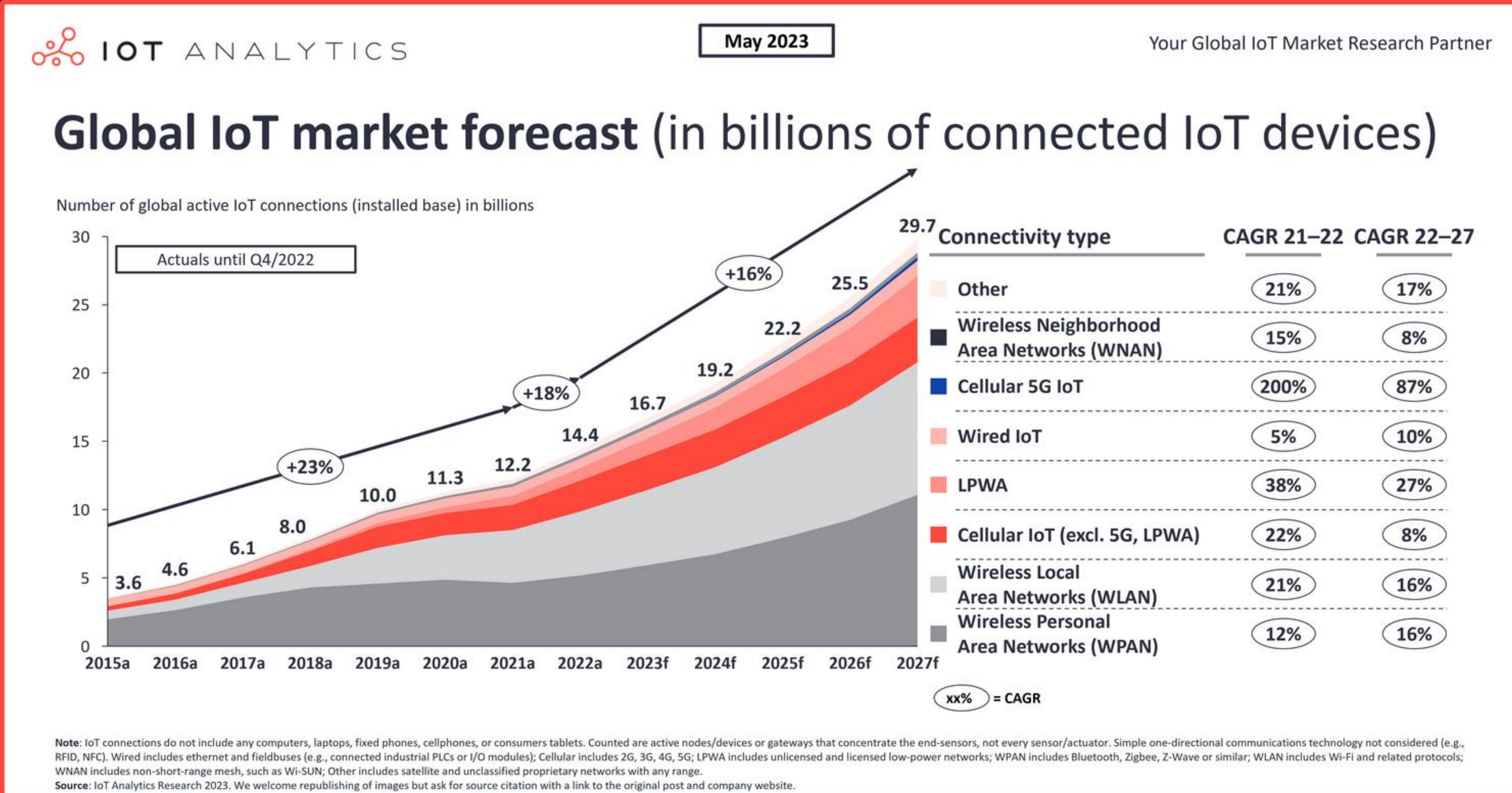
- Acoustic Communication



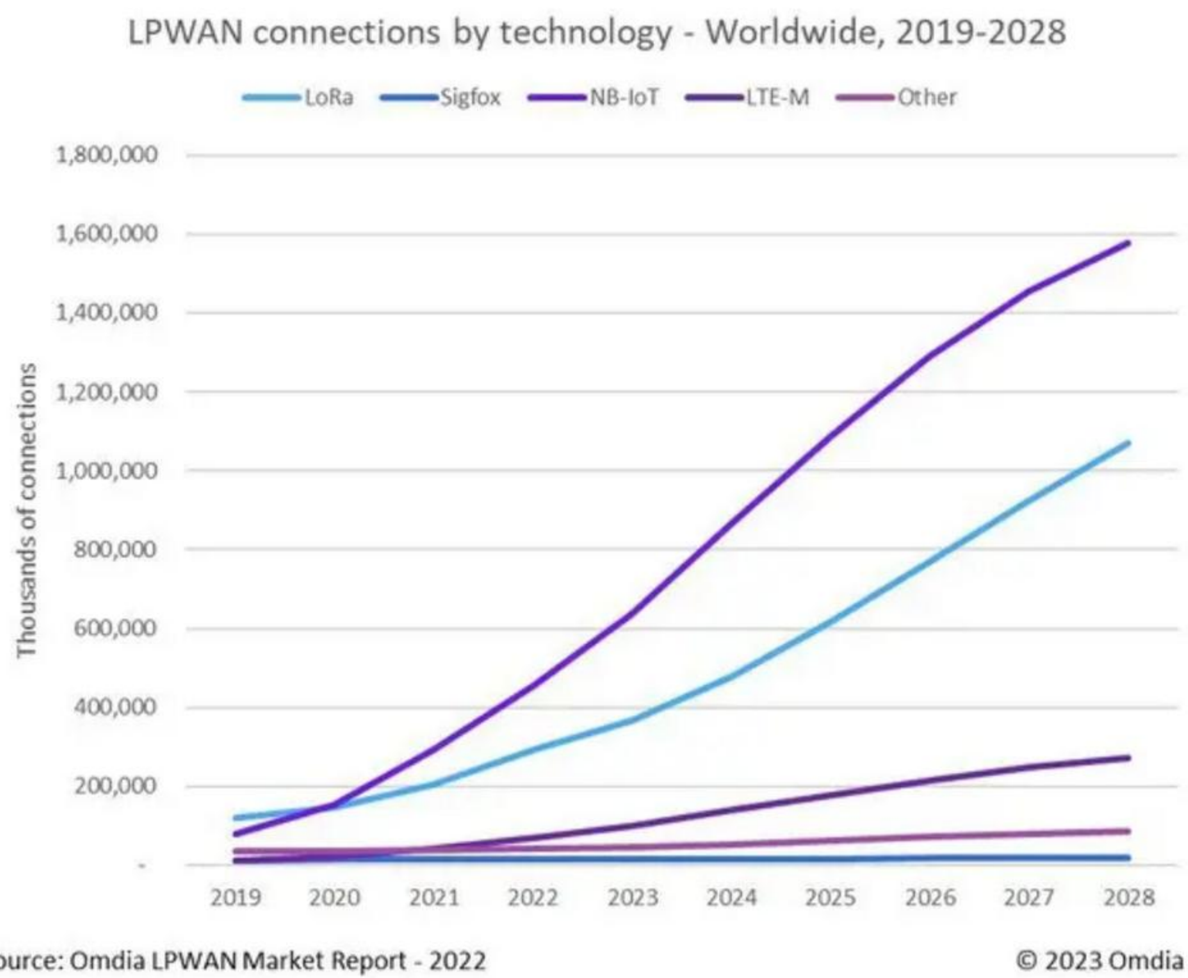
BlueComm optical modems can be used in conjunction with Sonardyne 6G acoustics for navigation and positioning



# IoT Options – first overview – statistics & forecasts



# IoT Options – first overview – statistics & forecasts



# IoT Options – first overview – more useful (?) stats

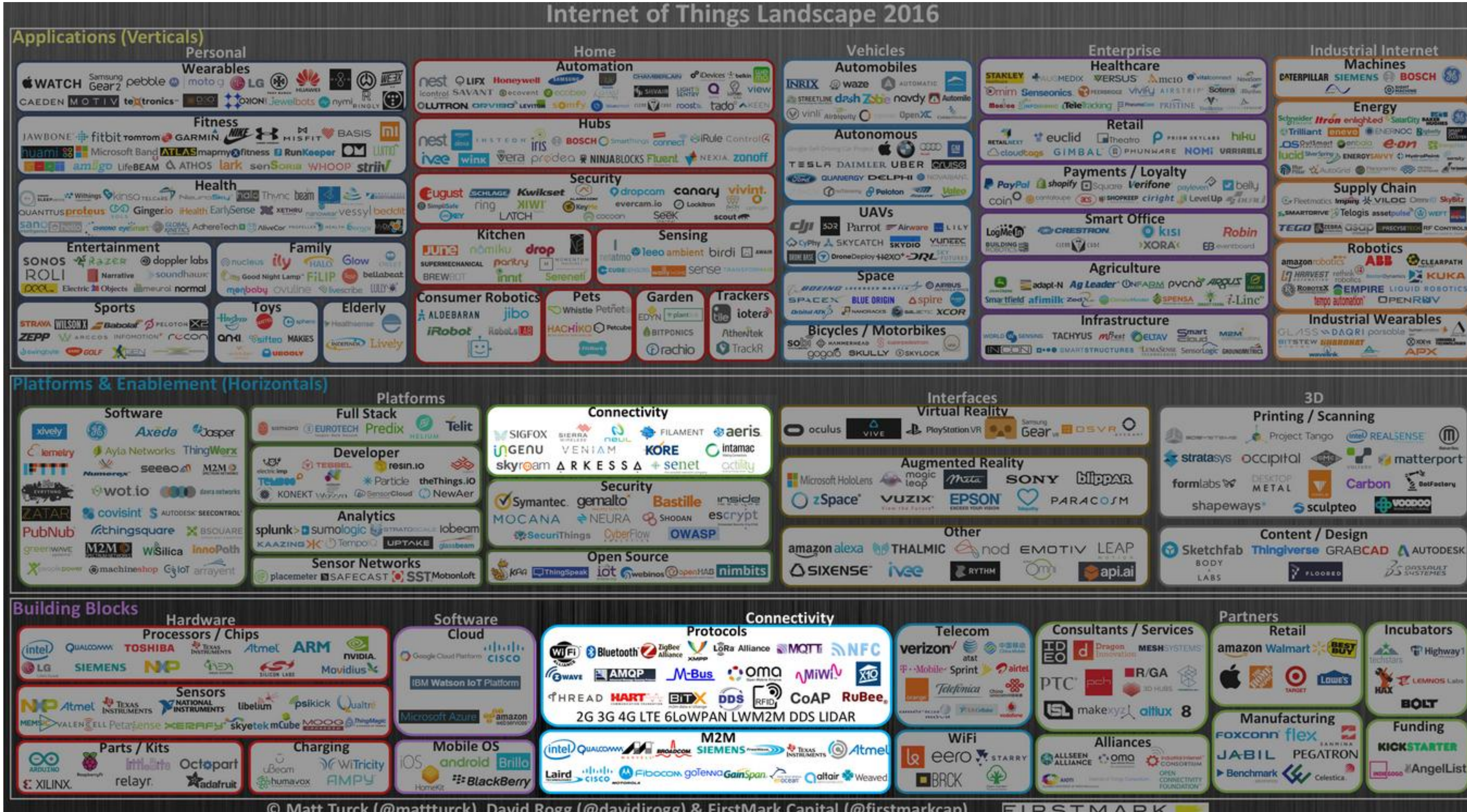
The overall 5G IoT installed base has been forecast to grow to around 49 million in 2023 (Statista).

IoT spending surpassed an estimated $1 trillion in 2023 (FinleyUSA)

The Asia Pacific region had the largest regional market share with 37% (over a third of total global IoT spending.)
This was followed by North America (29%) and EMEA (Europe, Middle East, and Africa) (23%). (European Commission)

IoT developers are primarily concerned with connectivity (52 percent), while security sits at 33 percent. Deployment and Data Collection are tied for third place, with 25 percent each. (Source: Eclipse Foundation)

# Scope



Internet of Things Landscape 2016
Applications (Verticals)
Personal
Wearables
Fitness
Health
Entertainment
Family
Sports
Toys
Elderly
Home
Automation
Hubs
Security
Kitchen
Sensing
Consumer Robotics
Pets
Garden
Trackers
Vehicles
Automobiles
Autonomous
UAVs
Space
Bicycles / Motorbikes
Enterprise
Healthcare
Retail
Payments / Loyalty
Smart Office
Agriculture
Infrastructure
Industrial Internet
Machines
Energy
Supply Chain
Robotics
Industrial Wearables
Platforms & Enablement (Horizontals)
Platforms
Software
Full Stack
Developer
Analytics
Sensor Networks
Connectivity
Security
Open Source
Interfaces
Virtual Reality
Augmented Reality
Other
3D
Printing / Scanning
Content / Design
Building Blocks
Hardware
Processors / Chips
Sensors
Parts / Kits
Charging
Software
Cloud
Mobile OS
Connectivity
Protocols
2G 3G 4G LTE 6LoWPAN LWM2M DDS LIDAR
M2M
Telecom
WiFi
Consultants / Services
Alliances
Partners
Retail
Manufacturing
Incubators
Funding
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# Criteria

In order to navigate the confusing landscape, we need a clear understanding of our **criteria** – how do we choose the right option (or one of them) for a given case?

**Central criteria:**

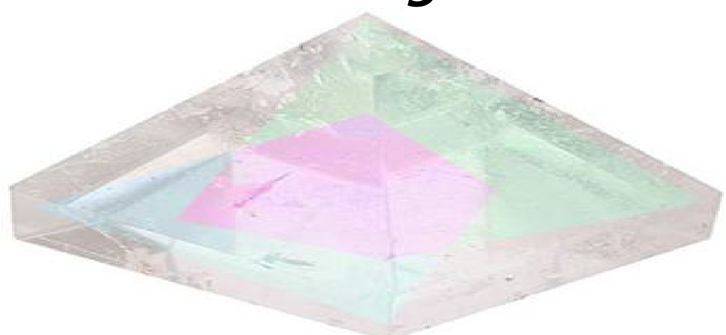
- **range** … reach, coverage
- **data** rates … throughput
- **power** … autonomy
- **cost**
- **business model**
- **regulations** / legalities

# Criteria

In reality, we will not be able to have all of it, at the same time – luckily, we typically do not need all of it either.

***range***

***data***



***power***

***cost***

# Criteria

IoT Networks often (! not always) are characterized by

- very low bandwidth – often just a few bytes
- low power – long autonomous lifetime – which translates into ..
- low cost per node – essential!
- range/reach may vary – from meters to 1000s of kms

***range***

***data***

***power***

***cost***

# Criteria - details

**range**

LOS (line of sight) / NLOS (non line of sight)

Coverage: local / regional / global? One/many locations? Mobility?

**data rates**

packet sizes – how much do I need to send?

flexibility of packets – does size vary?

latency – sync/async – do I need my in data real-time? how close to real time?

capacity/scale - how many nodes?

up/downlink – do I need to push updates etc to nodes?

**power** (is its own chapter) – *some comments next slide*

**cost ($)**

cost of hardware, networks, infrastructure

**business model** provider, self-driven, public, ...?

**regulations** laws/legalities/regulations – in all locations

# Criteria - Power

**Some comments on power & networking**

The **main power cost is transmission/networking**

(no rule without exception though – need to verify!)

**Processor:** typically < 1 nJ per Instruction

Acquiring a digital data sample from a sensor: order of 1 nJ

**Networking:** Example: WiFi

100 mW (pure radio power, no periphery) gives you in the range of 10 Mb/s ==> 10 nJ/bit ==> 100 nJ / 10bit sample

Power uptake of radio chips is typically several times the radio output power

(scales quadratically with distance)

**==> Sending the sample requires 100x more power than sampling it!**

# Criteria – Business & Regulations

**Some comments on business & regulatory aspects.**

Both are dependent on national/ regional conditions.

**Business:**

Mentalities, e.g. CAPEX vs OPEX,

ownership vs subscriptions models, etc

Capital market structures, availability of capital, etc

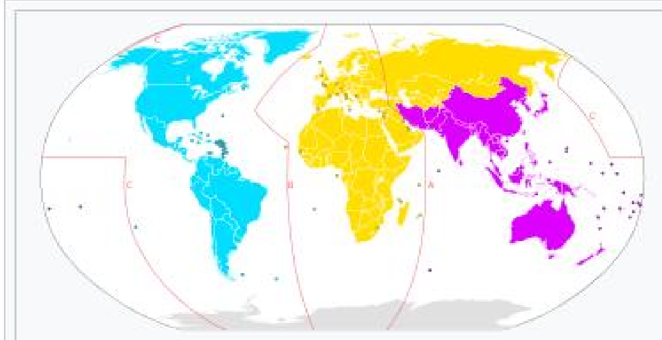
**Regulations:**

ITU regions

SRD (short range device (…)) regulations

ISM (industrial – scientific – medical)

vs licensed/proprietary bands



ITU regions and the dividing lines between them.

Region 1

Region 2

Region 3

# Criteria - ....

**Have we not forgotten something?**

**Yes.**

**The “S” in IoT stands for Security.**

# Criteria - Security

**The "S" in IoT stands for Security.**

Security deserves its own chapter.
While it is obviously one of our criteria,
it is very **dangerous to assume that security can be achieved on network level,**
i.e. choose a networking option based on security,
and then assume that the system is "secure".
Vulnerabilities on the physical network layers are just some of many more.

Obviously, we will demand certain minimal
**security features on the networking level – device authentication, session encryption**, etc
Some of these may be additional, not supplied by the networking choice as such.

# Criteria - Other

In any real life project,

there will be **a variety of other criteria**,

some of which might be neither technical, functional nor rational.

**Examples:**

- independence of location's existing network –

why does your electricity utility's powermeter not use your Wi-Fi?

Why can you as an external provider not use a public institution's network?

- existing partnerships, business constellations

- in our (ITU) case: research or study interest, openness of standards/protocols

(we might force you to try LoRaWAN, even if Wi-Fi does the job!)

# Properties of the physical layer

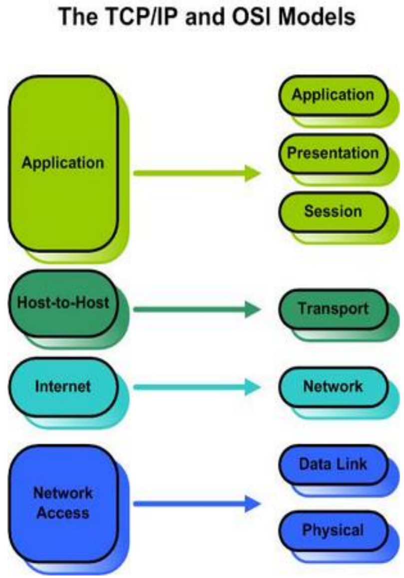
**A quick view on the physical layer (Layer 1)**

The first, raw physical layer (PHY) consists of

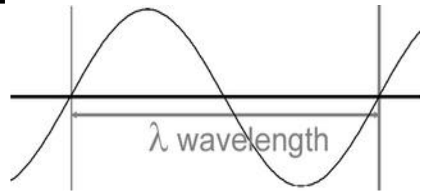
Copper, glass, electromagnetics, optics,
Waves, beams -

before any Layer 2 (MAC)
or protocols of higher layers comes into effect.

https://en.wikipedia.org/wiki/Physical_layer



# Electromagnetic waves




“Wireless” = Electromagnetic waves –

Electromagnetic fields that oscillate and travel in space.

They have a speed, a frequency, a wavelength.

$$c = \lambda * \nu$$

**c** is the speed of light (in vacuum) $3 \times 10^8$ m/s

$\lambda$ Lambda is the wavelength [m]

$\nu$ Nu is the frequency [1/s = Hz] (more often you will find it called **f**)

The reason this is essential knowledge:

**Pretty much everything scales with wavelength / frequency!**

# Electromagnetic waves

Mechanical waves – like sound, waves in water - require a physical medium to transport them.

**Electromagnetic waves do not require a medium -**

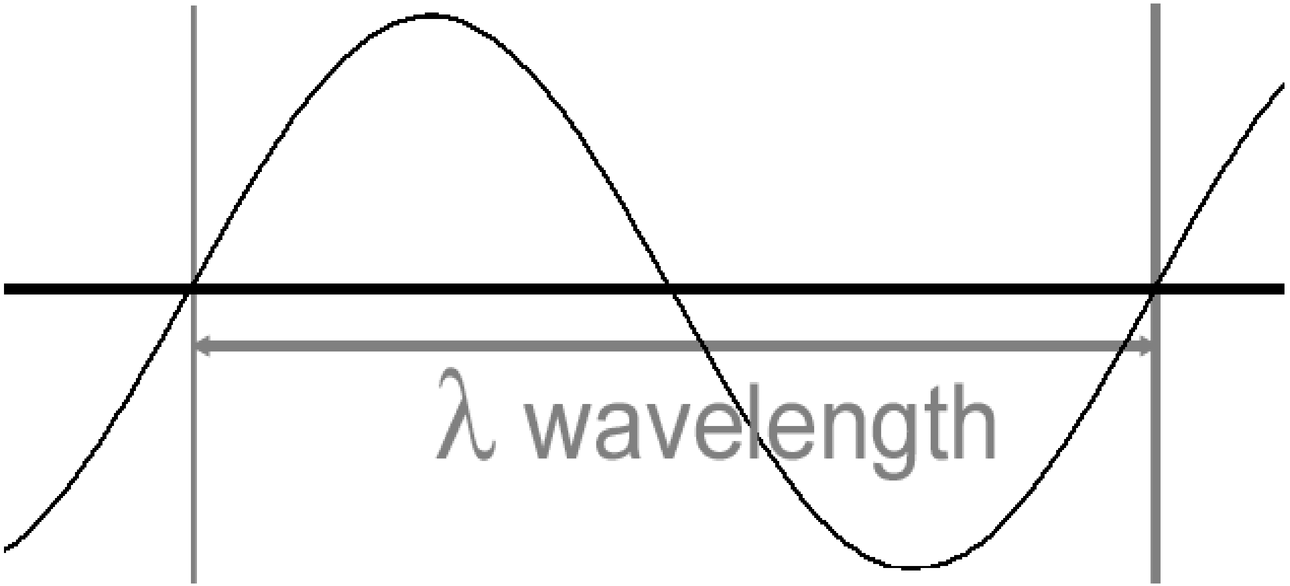
they are the “dance without a dancer”.

They can travel through vacuum and through physical medium (but very dependent on what that medium is!)

Examples: Light, Radio, Infrared, X-Ray, Gamma Ray

# Electromagnetic waves

$c = \lambda * \nu$




Examples:

2.4 GHz – 12 cm
5 GHz – 6 cm
26 GHz – 11 mm … higher frequencies: “mm waves”

# Electromagnetic waves

Electric &
Magnetic
Field

Polarization

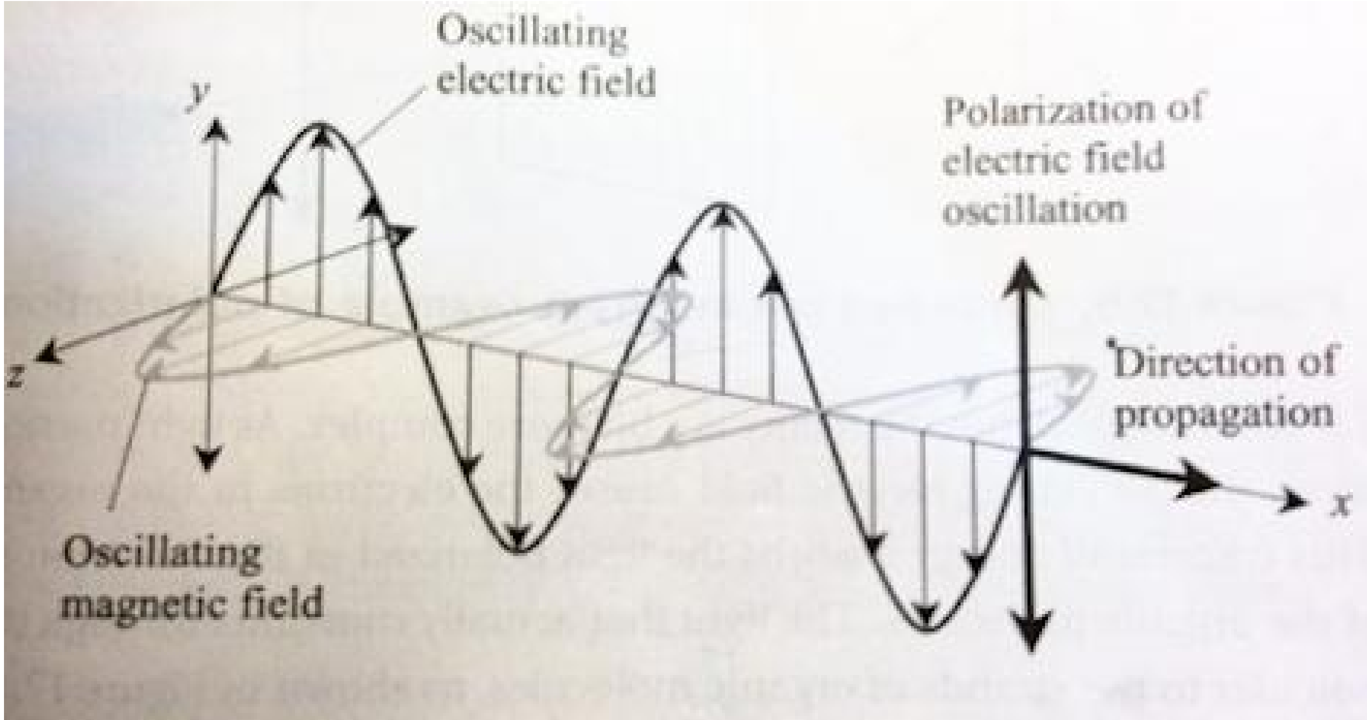



**Figure 17.7.** Electromagnetic wave

# Electromagnetic waves

Waves do not move in straight lines.

Any point in a wavefront

is the origin of a new wave (**Huygens' principle**).

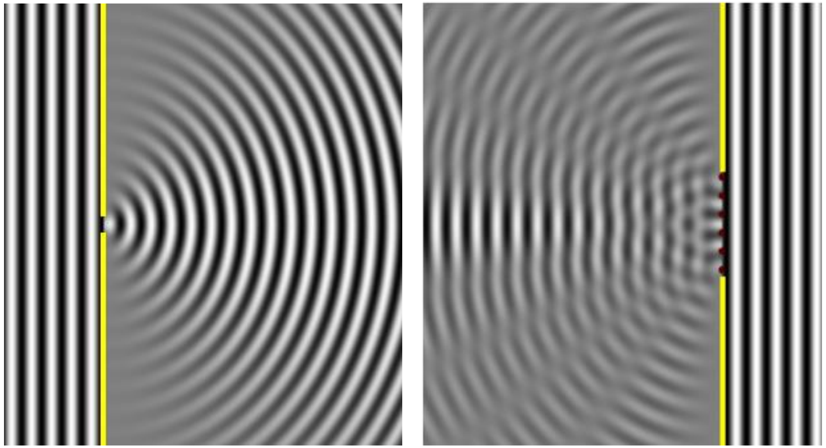
Even light does this – just difficult to see,

as

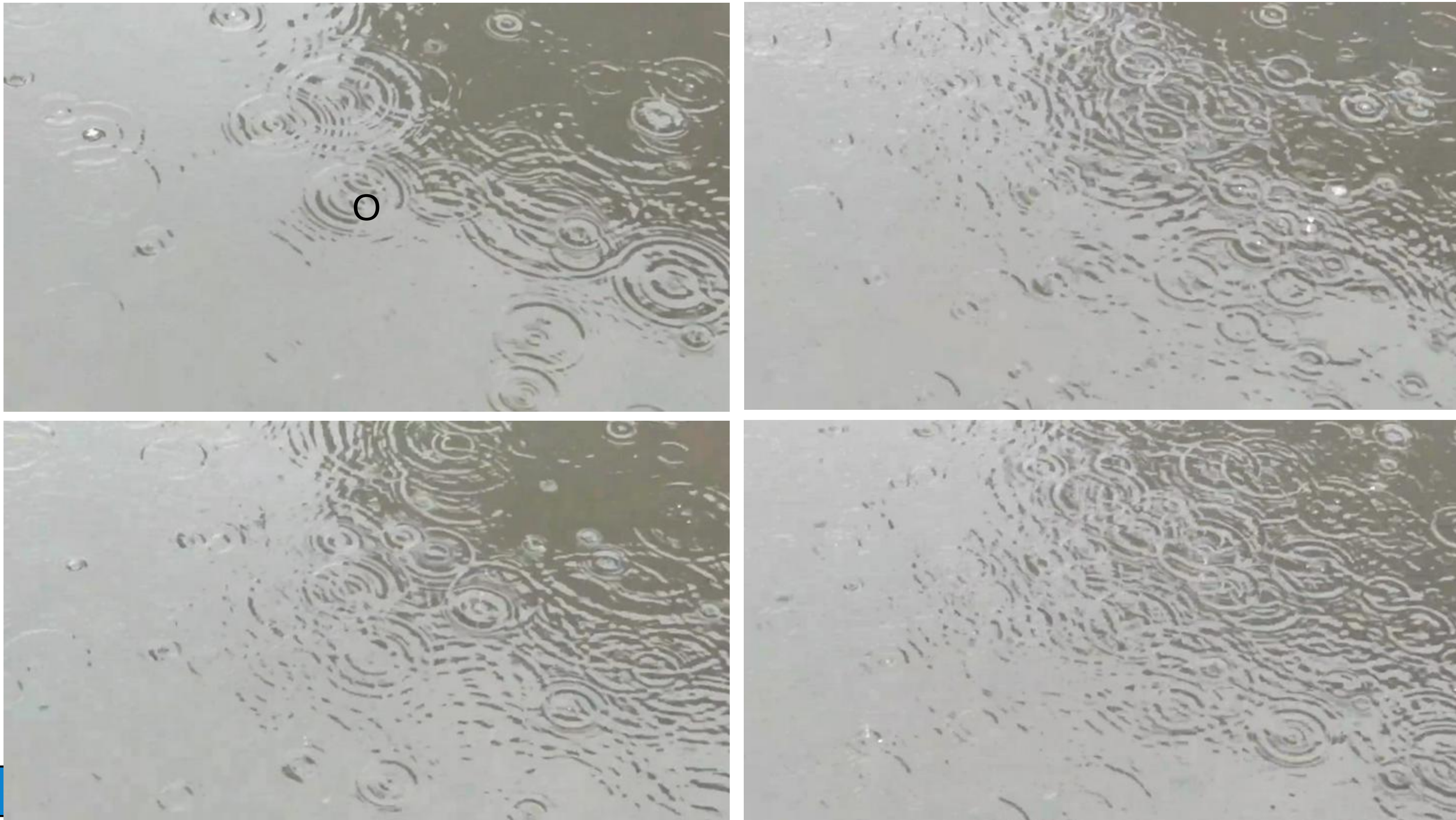
behaviour

scales with

wavelength.



# Electromagnetic waves – an analogy



# Electromagnetic waves – an analogy

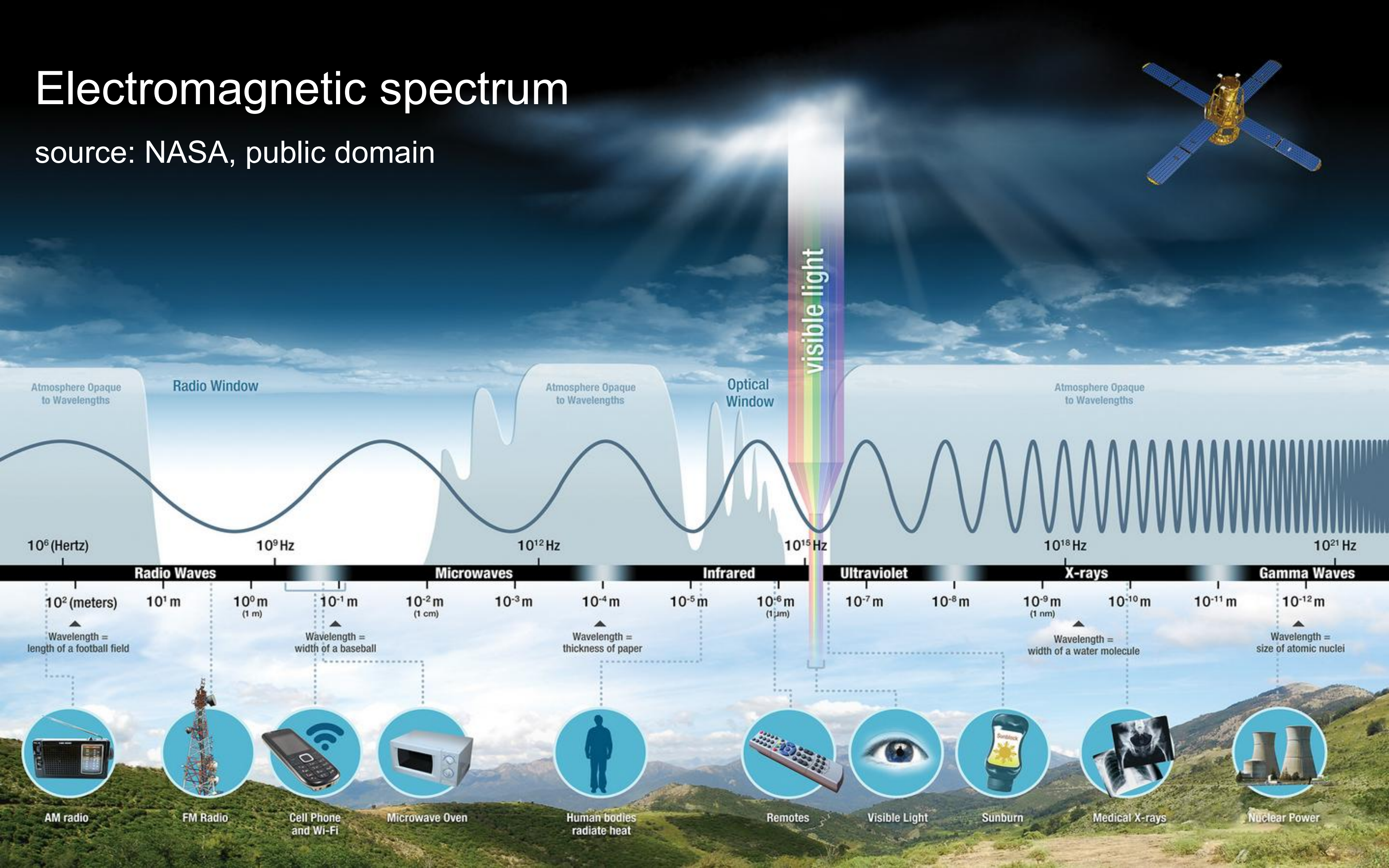
# Electromagnetic waves

| | |
|---|---|
| • **radio** | 30 Hz to 300 GHz |
| • microwave | 300 MHz to 300 GHz |
| • VHF | 30 MHz to 300 MHz |
| • UHF | 300 MHz to 3 GHz |

It’s all wireless … and we can call it all **radio.**

# Electromagnetic spectrum

source: NASA, public domain



# Properties of the physical layer

**For all wireless (electromagnetic, radio) communications, some simplified rules:**

**Low frequency**
**Long wavelength**

***Better penetration***
***Longer range***

***Better NLOS capability***

***Less data ****

**High frequency**
**Short wavelength**

***Easily blocked***
***Shorter range***

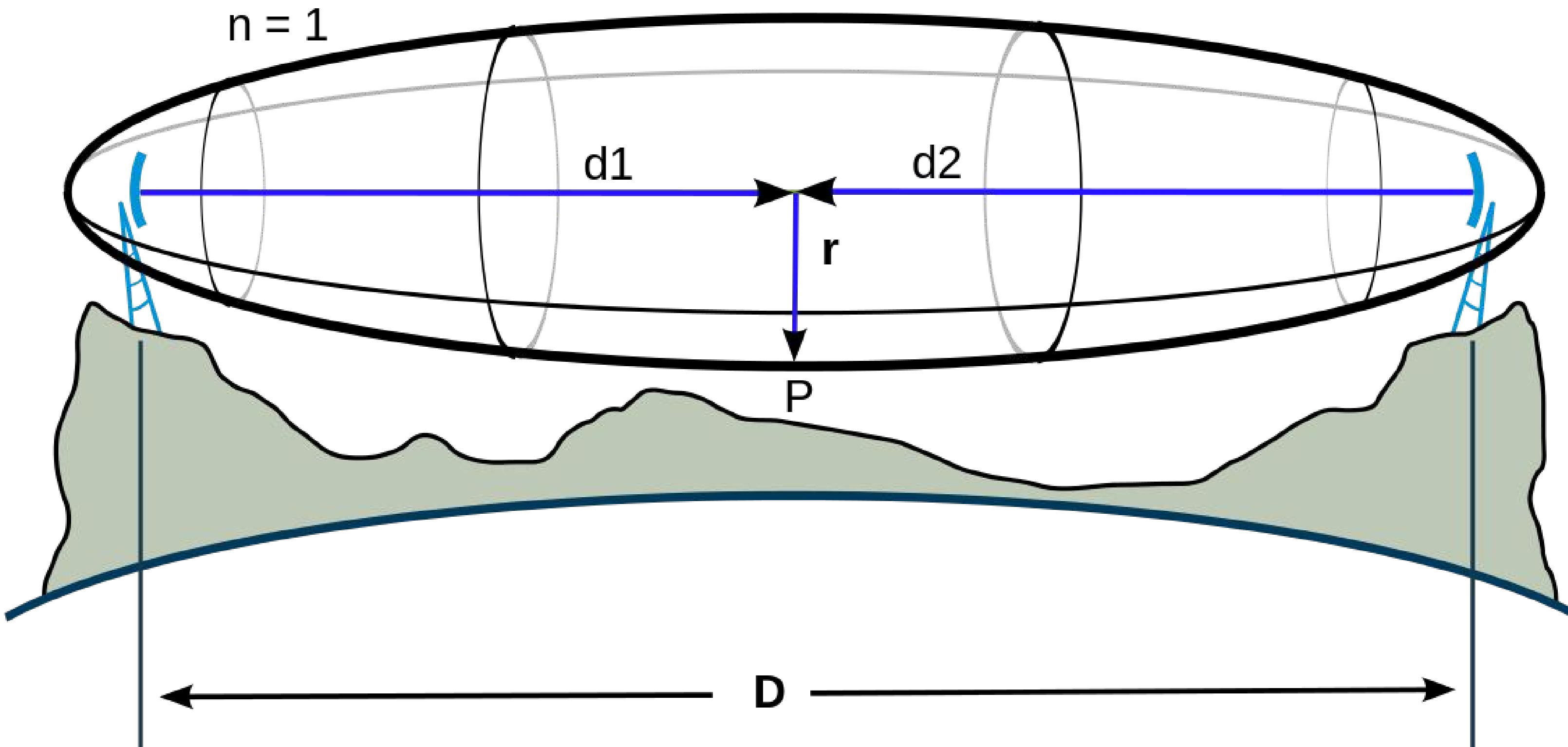
***Strictly needs LOS***

***More data ****

***No strict line between two frequency ranges – it is a continuum***

**** because more bandwidth is available at higher frequencies***

## Line-of-sight (LOS), non-Line-of-sight (NLOS)
## Fresnel zones




source: https://commons.wikimedia.org/wiki/File:FresnelSVG1.svg

# Link budgets and dB

**Link budget**

is the calculation of losses and gains along a full signal path.

(Demonstrate by example)

**Margin**

Is the remaining signal left along the whole link

**dB**

Is the common unit used in radio link budgets

# dB

- **Definition: $\mathbf{10 \times Log_{10} (P_1 / P_0)}$**

- 3 dB = double power
  -3dB = half the power
  10 dB = one order of magnitude up = x 10
  -10 dB = one order of magnitude down = /10

- Why dBs? Nature tends to behave logarithmic (think rabbits or attenuation in materials … & calculating in dBs is easier :)

- Relative dBs
  - dBm = relative to 1 mW
  - dBi = relative to ideal isotropic antenna

# dB

- **Definition: 10 x $\mathbf{Log_{10} (P_1 / P_0)}$**

- 1 mW = 0 dBm
- 100 mW = 20 dBm
- 1 W = 30 dBm

**Examples from wireless networking:**

- An omni antenna with 6 dBi gain
- A parabolic dish with 29dBi gain
- A cable (RG213) with 0.5 dB/m loss
- Maximum power of LoRa: 14 dBm = ….?
- And for Wi-Fi? …..

# Link budgets

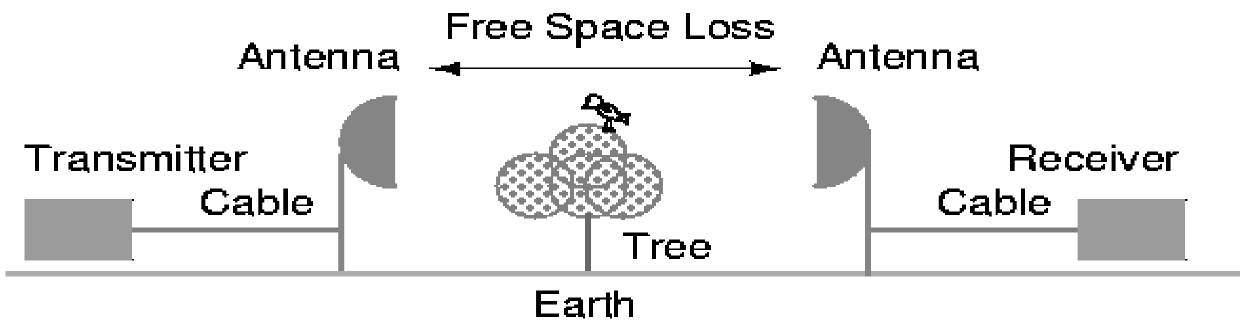
- two kinds of contributions
  - what we can not change: **path loss**
  - what we can change: **antennas, cables, RX, TX**

# Radio link

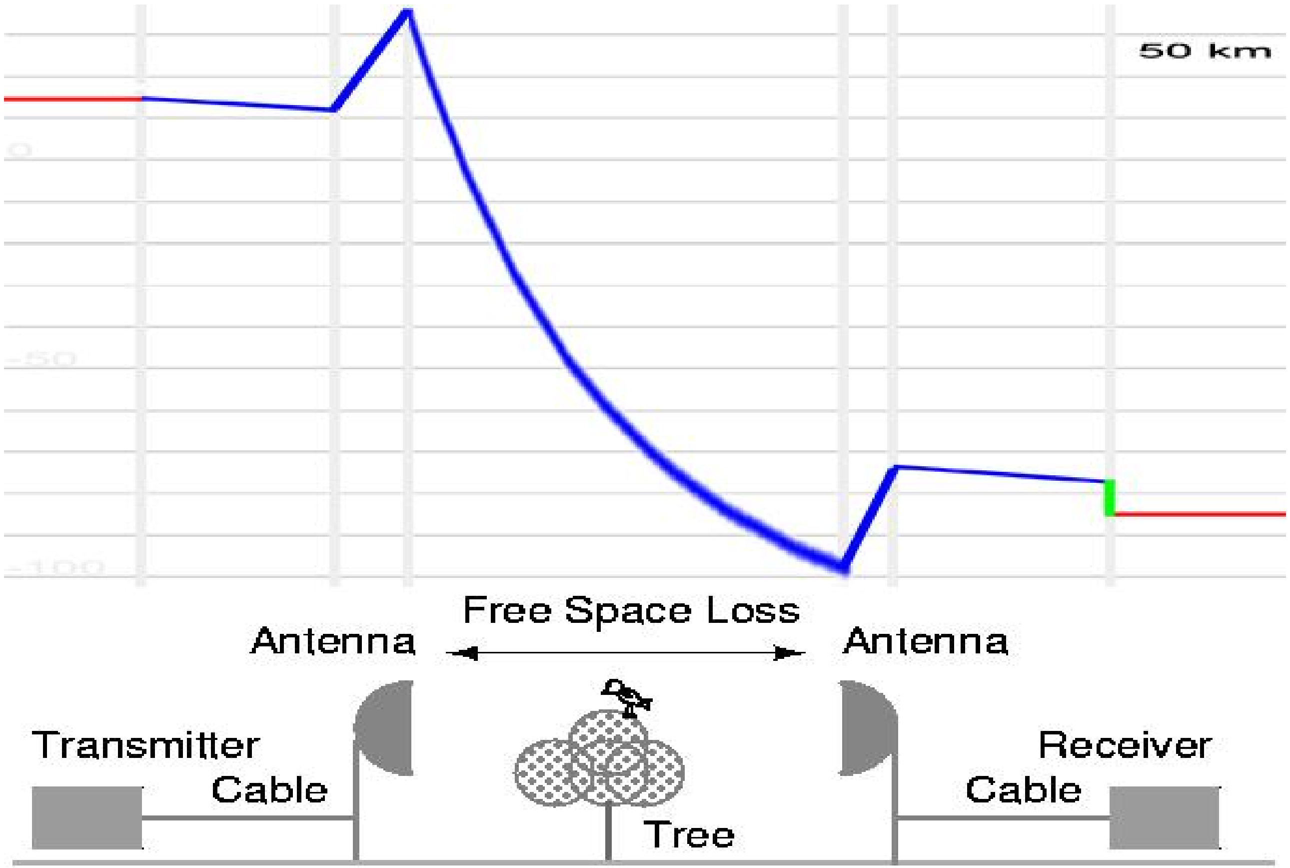
- **Effective transmit power:**
  transmit power [dBm]
  - (cable + connector) loss [dB]
  + amplifier gain [dB]
  + antenna gain [dBi]

- **Propagation loss [dB]:**
  Free space loss [dB]

- **Effective receiving sensibility:**
  antenna gain[dBi]
  + amplifier gain [dB]
  - cable loss [dB]
  - receiver sensitivity [dBm]

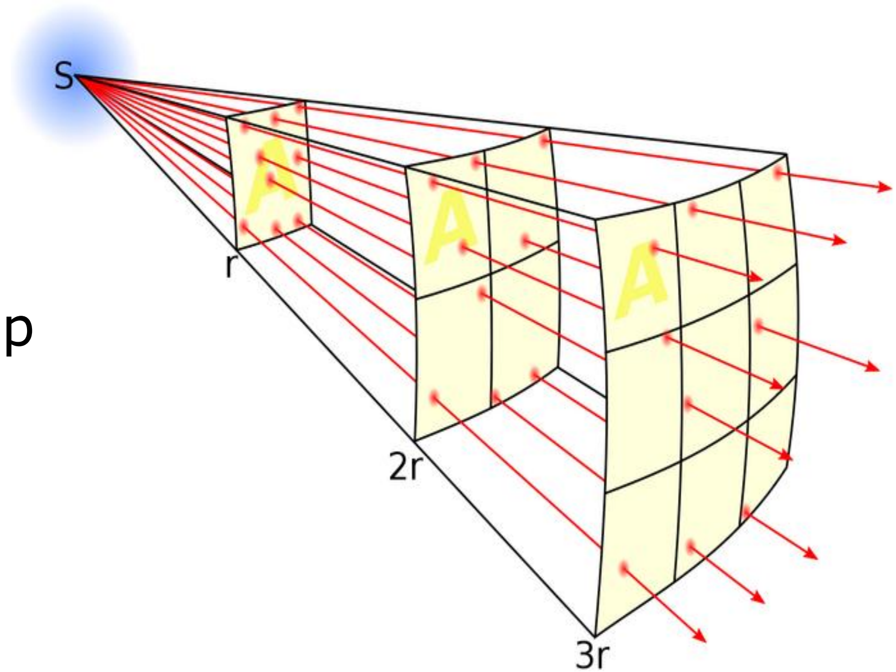


# Link budget


50 km
Free Space Loss
Antenna
Antenna
Transmitter
Cable
Tree
Receiver
Cable

# Path loss / Free space loss

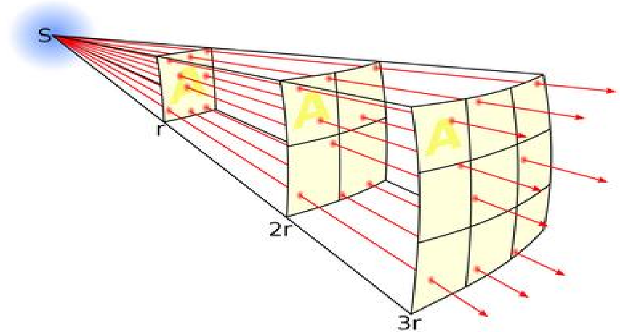
Due to **pure geometry** -
nothing to do with obstacles,
rain, fog, trees, or such -
those contributions come on top




$$\mathrm{FSPL} = \left( \frac{4\pi d f}{c} \right)^2$$

source: By Borb, CC BY-SA 3.0,
https://commons.wikimedia.org/w/index.php?curid=3816716

# Path loss / Free space loss




**in dB, with f in GHz and d in k**

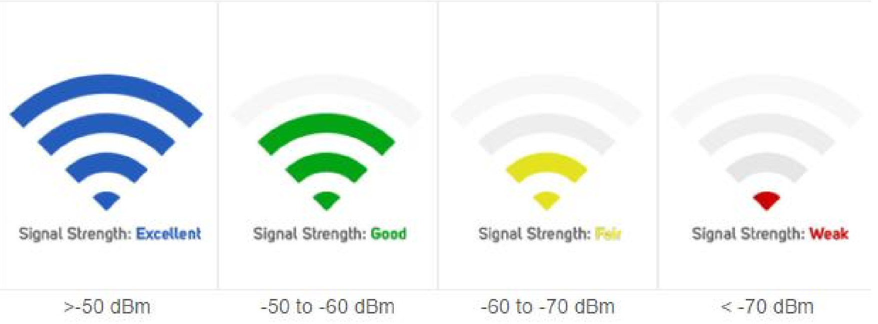
$$\mathrm{FSPL(dB)} = 20\log_{10}(d) + 20\log_{10}(f) + 92.45$$

for 2.4 Ghz, memorize: 1 km = - 100 dB
and then 20 dB for every order of magnitude (for d or f!):

| | |
|---|---|
| 100 m | - 80 dB |
| 1 km | -100 dB |
| 10 km | -120 dB |
| 100 km | -140 dB |

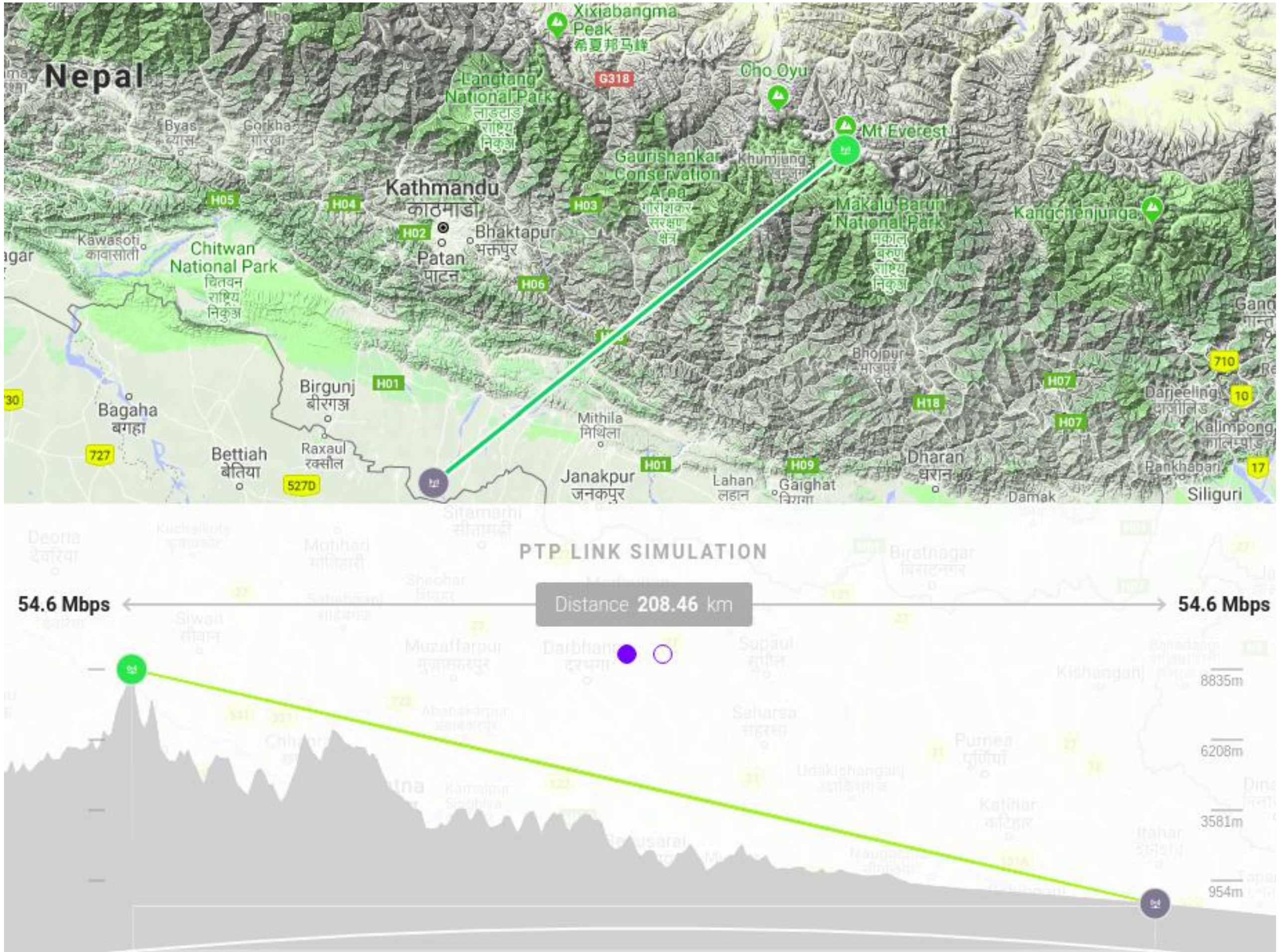
# Link budget

- Output power (TX): limited by regulations, often 20 dBm for Wi-Fi
- Receive sensitivity: depends on quality of radio, e.g. Wi-Fi:
  - Professional AP: -98 dBm
  - Home AP: -95 dBm
  - Mobile phone: -85 dBm




- Receive Sensitivity LoRa: approx -130 dBm (
- Antennas are important (but out of scope for this lecture)

# Modelling long range links




Mountain topologies

help us get around

**Earth Curvature**

Link simulation for a

Nepal project, 2019

# Modelling long range links

Ubiquiti Link: https://link.ui.com

RadioMobile, a ham radio classic:

https://www.ve2dbe.com/rmonline_s.asp

BotRF (a telegram bot):

http://wireless.ictp.it/school_2017/Slides/RfBot.pdf

Zennaro, Marco, Marco Rainone, and Ermanno Pietrosemoli. "Radio link planning made easy with a telegram bot." International Conference on Smart Objects and Technologies for Social Good. Springer, Cham, 2016.

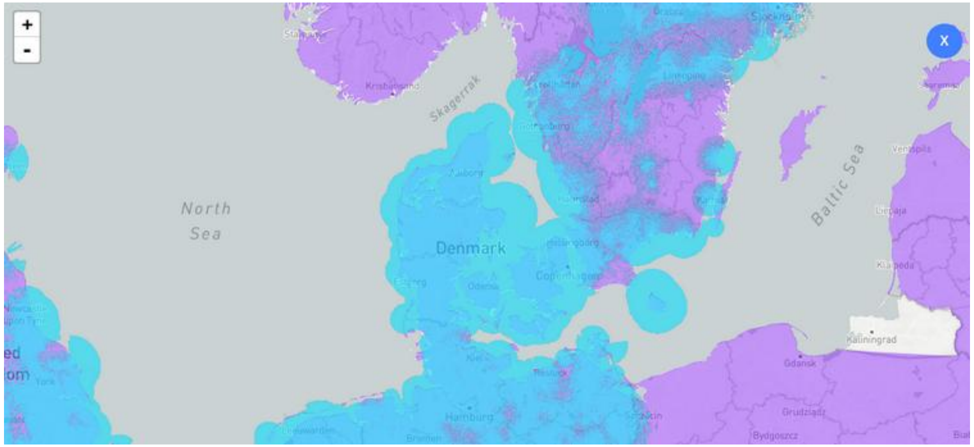
# Indoor & urban

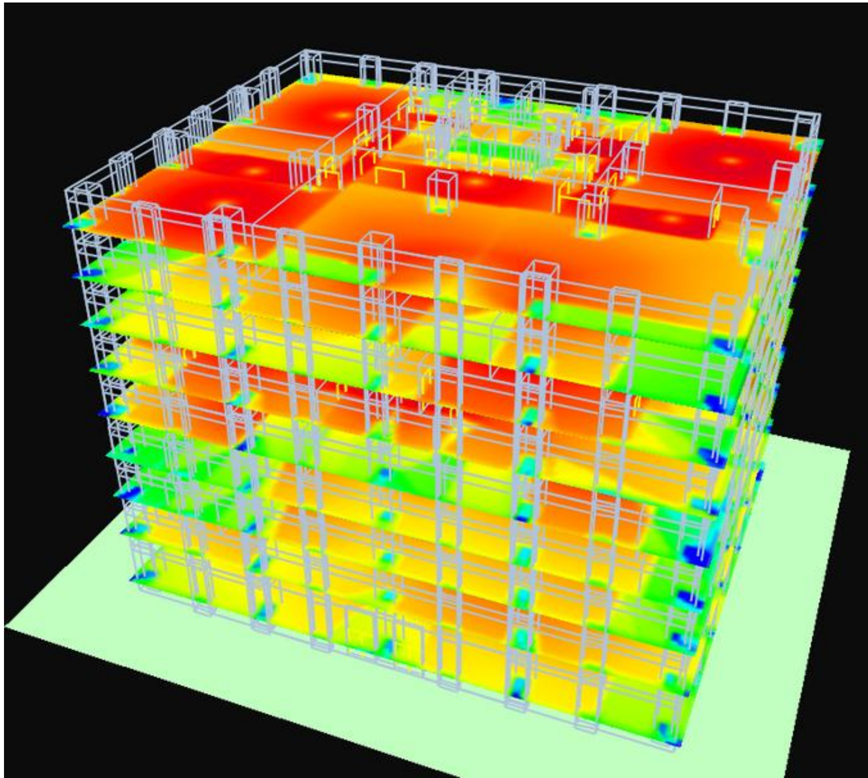
Link budgets are primarily used for long distance, point to point calculations – aggregated they make up coverage maps, “heatmaps”, etc

Methods and objects to model differ:

- walls, ceilings, furniture, …

- buildings, topology, …



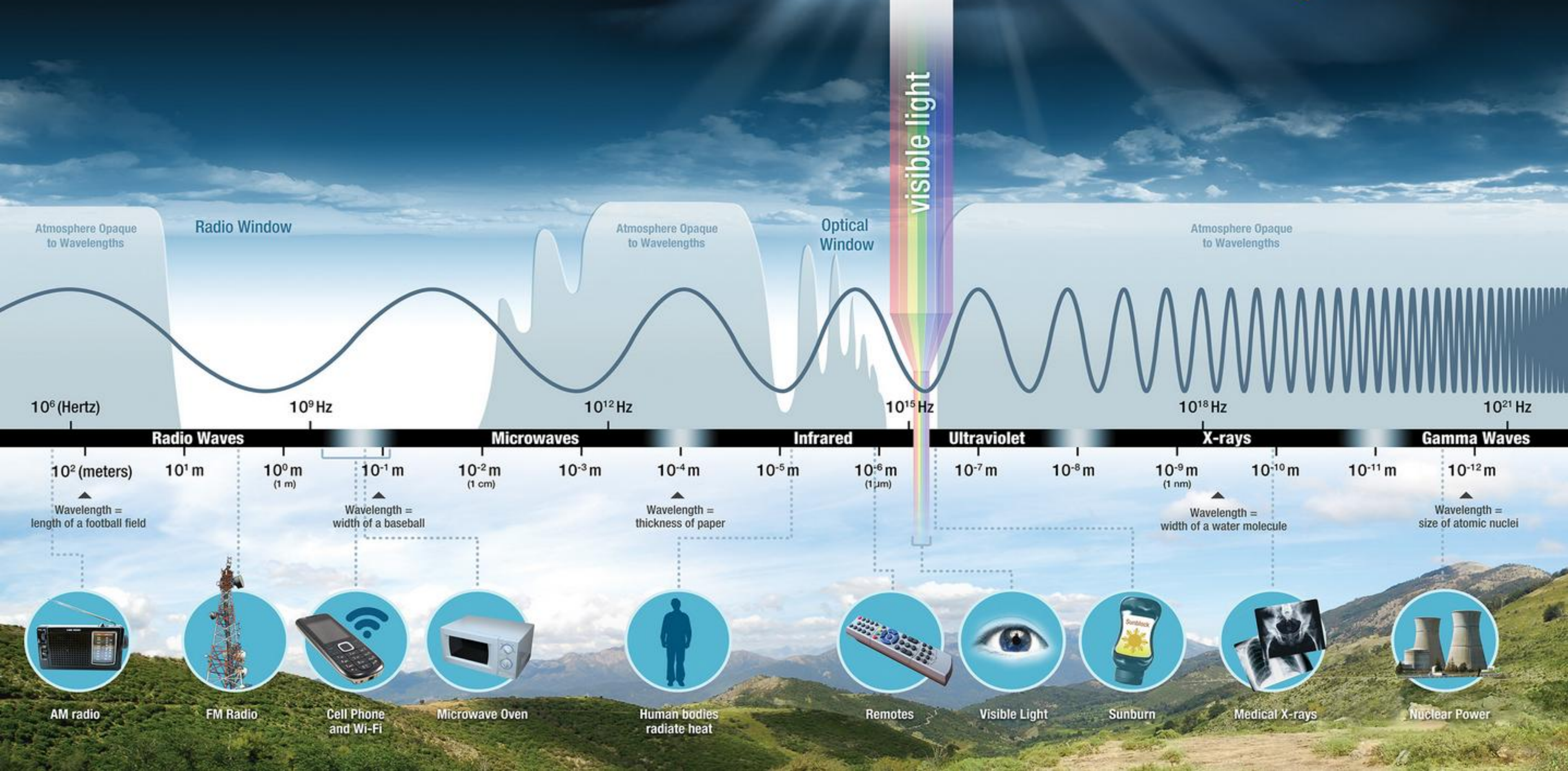


Sigfox

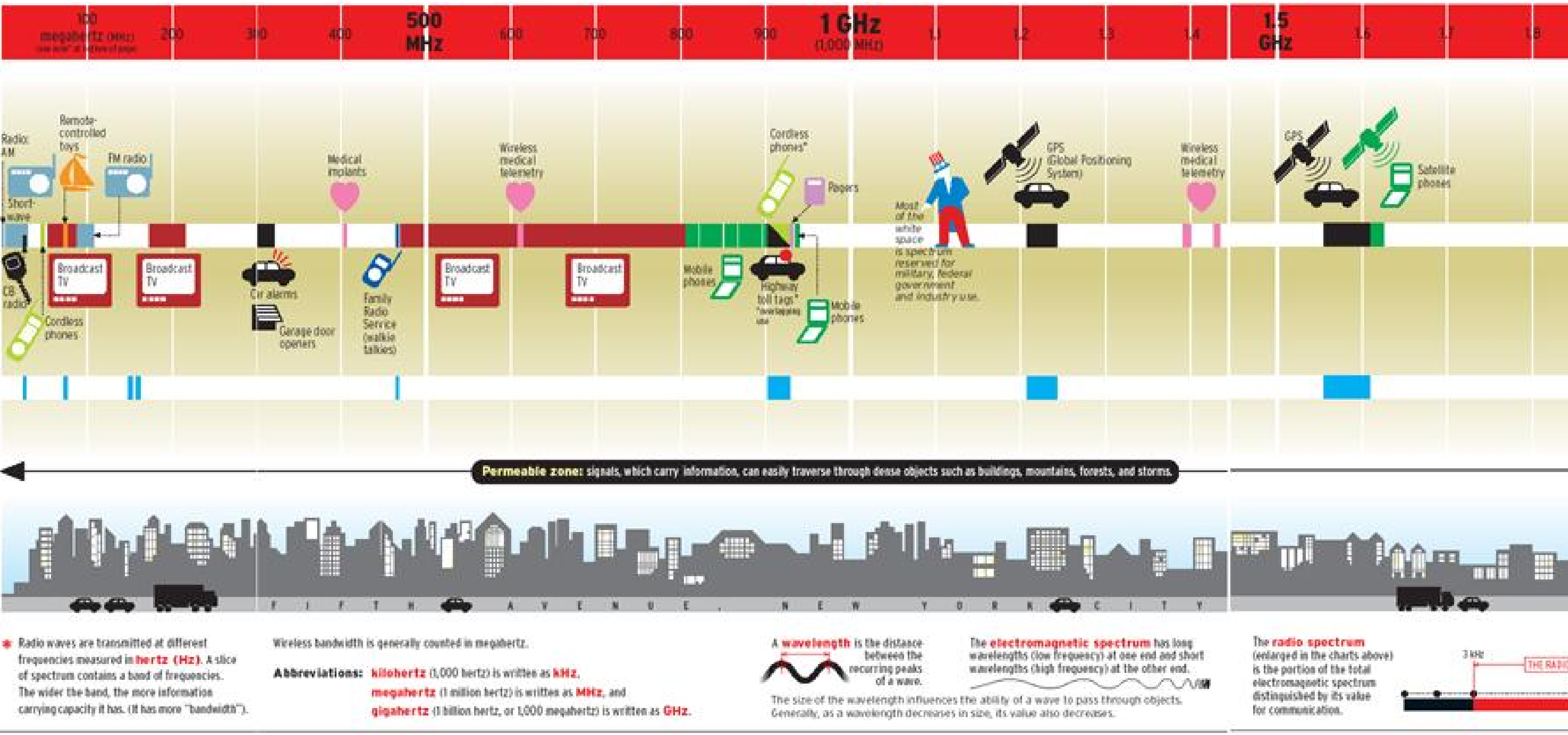
Neondrum/Ranplan

# Electromagnetic spectrum

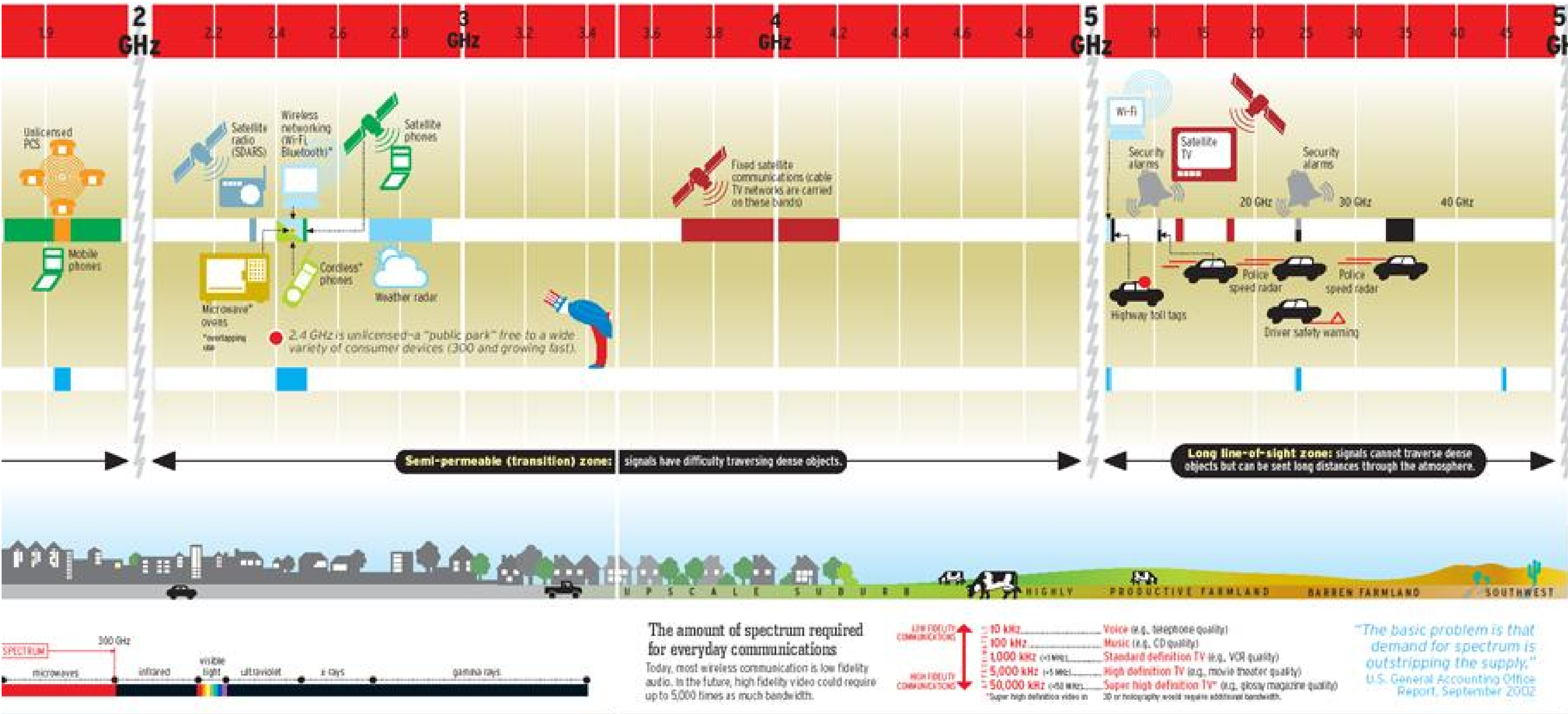
source: NASA, public domain



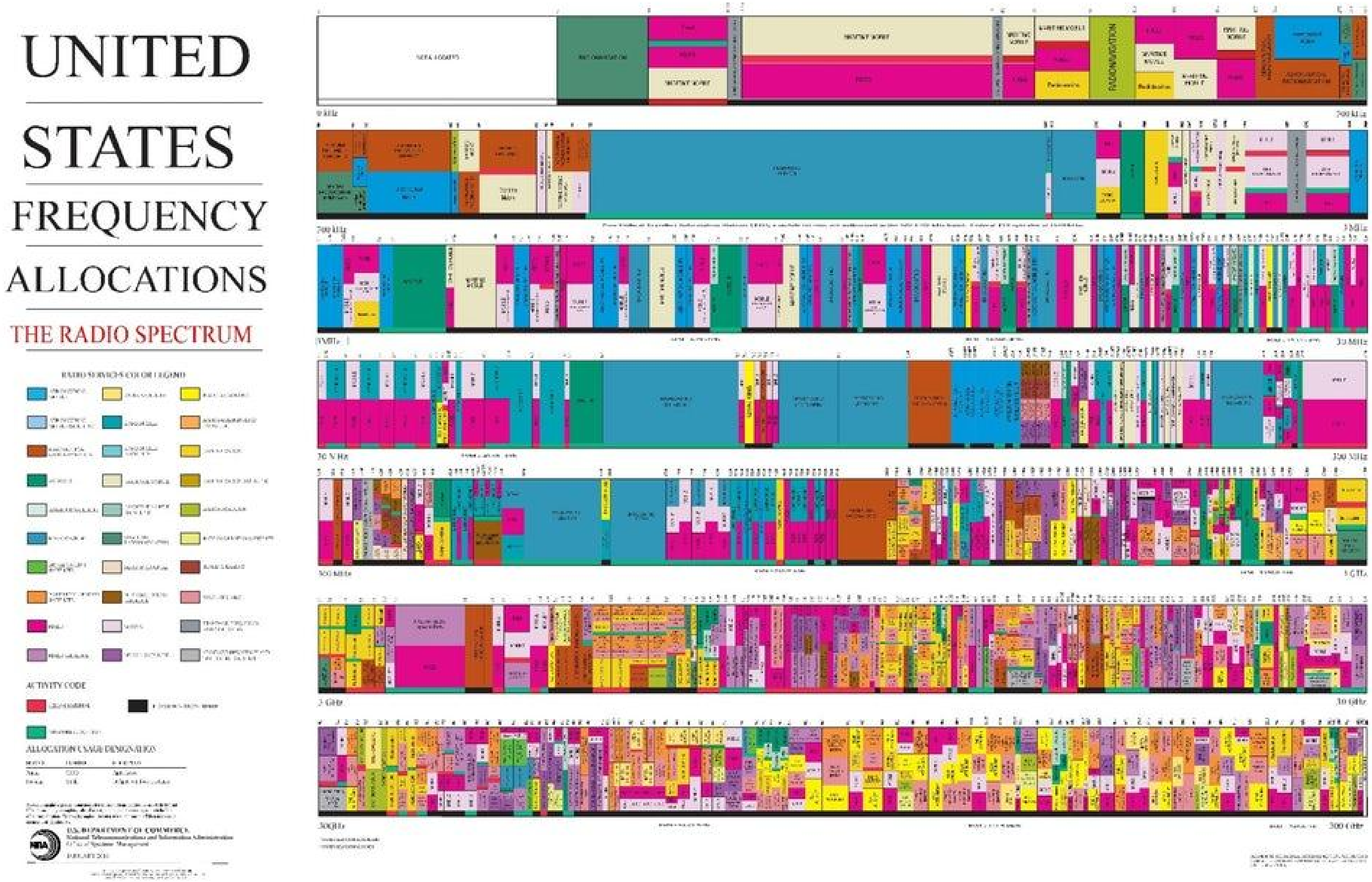
# Frequency spectrum



# Frequency spectrum



# Frequency allocation






source: DARPA, https://newatlas.com/darpa-radio-bandwidth-grand-challenge/

# Frequencies are highly valuable 'real estate' ...

*5G VS. WEATHER SATELLITES —*

## 5G likely to mess with weather forecasts, but FCC auctions spectrum anyway

FCC auctions 24GHz spectrum despite likely interference with weather satellites.

JON BRODKIN - 5/14/2019, 10:06 PM

**... and source of many conflicts:**

- **5G vs weather satellites**
- **ISM in 6GHz vs proprietary mobile**

The Pentagon Is Sitting on a Chunk of Valuable Airwaves. Why?

*6. maj 2019*

Resultatet af 700 MHz-, 900 MHz- og 2300 MHz-auktionen blev følgende:

- Hi3G Denmark ApS har vundet 2x10 MHz i 700 MHz-frekvensbåndet og 2x10 MHz i 900 MHz-frekvensbåndet til en samlet tilladelsespris på 485.233.000 kr.
- TDC A/S har vundet 2x15 MHz i 700 MHz-frekvensbåndet, 2x10 MHz i 900 MHz-frekvensbåndet, 60 MHz i 2300 MHz-frekvensbåndet og 20 MHz til SDL i 700 MHz-frekvensbåndet til en samlet tilladelsespris på 1.619.599.000 kr.
- TT-Netværket P/S har vundet 2x5 MHz i 700 MHz-frekvensbåndet og 2x10 MHz i 900 MHz-frekvensbåndet til en samlet tilladelsespris på 107.600.000 kr.

# Bandwidth, throughput, data rates

The **Shannon–Hartley theorem** describes the **maximum rate** at which information can be transmitted over a communications **channel** of a specified **bandwidth** in the presence of **noise**.

## Statement of the theorem [ edit source ]

The Shannon–Hartley theorem states the channel capacity $C$, meaning the theoretical tightest upper bound on the information rate of data that can be communicated at an arbitrarily low error rate using an average received signal power $S$ through an analog communication channel subject to additive white Gaussian noise of power $N$:

$$\boxed{C = B \log_2 \left(1 + \frac{S}{N}\right)}$$

where

- $C$ is the channel capacity in bits per second, a theoretical upper bound on the net bit rate (information rate, sometimes denoted $I$) excluding error-correction codes;
- $B$ is the bandwidth of the channel in hertz (passband bandwidth in case of a bandpass signal);
- $S$ is the average received signal power over the bandwidth (in case of a carrier-modulated passband transmission, often denoted C), measured in watts (or volts squared);
- $N$ is the average power of the noise and interference over the bandwidth, measured in watts (or volts squared); and
- $S/N$ is the signal-to-noise ratio (SNR) or the carrier-to-noise ratio (CNR) of the communication signal to the noise and interference at the receiver (expressed as a linear power ratio, not as logarithmic decibels).

# The Essence of the Shannon-Hartley Theorem

**Capacity ~ Bandwith x log(Signal-to-Noise)**

Capacity (Data Rate) does NOT directly depend on operating frequency,
however
**larger bandwidths are available at higher frequencies.**


source: https://en.wikipedia.org/wiki/Shannon%E2%80%93Hartley_theorem

# Frequencies relevant to us

- **ISM** (Industrial Scientific Medical - license exempt) bands at
  - 169 MHz – 170 cm - emerging ...
  - 433 MHz – 70 cm
  - 868 (EUR, Africa) / 915 (US) MHz – 35 cm
  - 2.4 GHz – 802.11b/g – 12 cm
  - 5.x GHz – 802.11a – 5...6 cm
- Other (non-ISM) bands interesting to us
  - 470 – 790 MHz (TVWS)
  - 700-800-900 MHz (GSM)
  - All cellular (e.g. 1.8 – 2.7 GHz)
  - New 5G bands FR1 (<6 GHz, e.g. 3.5 GHz), FR2 (>26 GHz)
  - Other proprietary

# Modulation & encoding

In electronics and telecommunications, **modulation is the process of varying one or more properties of a periodic waveform, called the carrier signal, with a modulating signal that typically contains information to be transmitted.** Most radio systems in the 20th century used frequency modulation (FM) or amplitude modulation (AM) to make the carrier carry the radio broadcast.

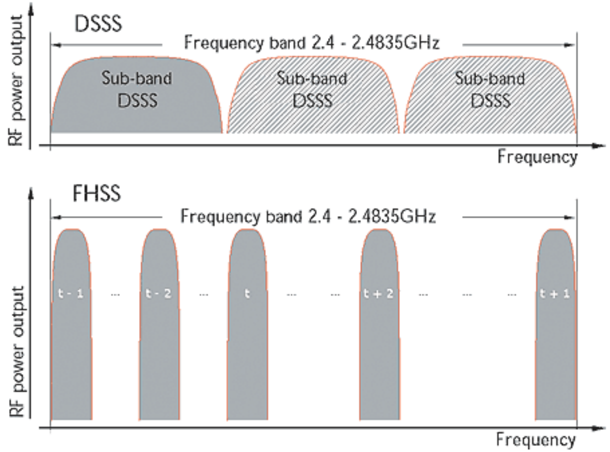
Modulation techniques include
**Spread Spectrum** (e.g. FHSS Frequency Hopping) used in Bluetooth,
direct-sequence spread spectrum (DSSS) used in 802.11b,
Orthogonal frequency-division multiplexing (OFDM) used in 802.11a/g/n/c,
Chirp spread spectrum (CSS) as used in LoRa.

These techniques are crucial for the **robustness against noise and utilization of spectrum.**

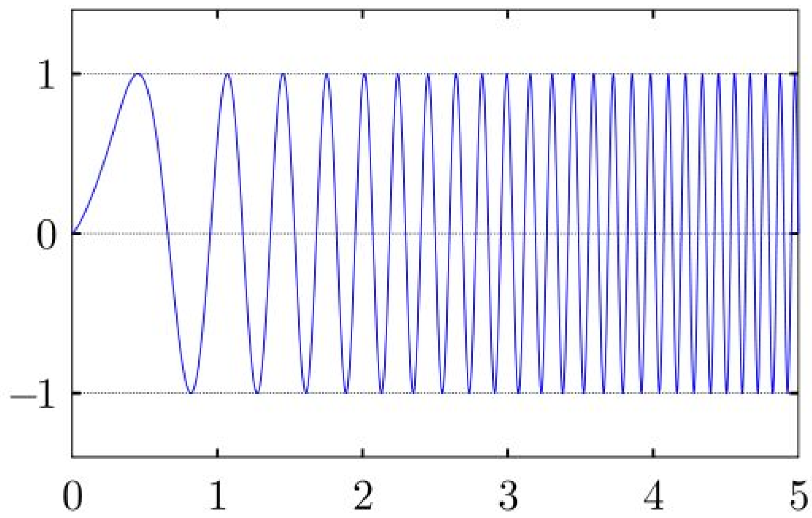
Read more here:
https://en.wikipedia.org/wiki/Frequency-hopping_spread_spectrum

# Modulation & encoding

Spread Spectrum (e.g. **FHSS Frequency Hopping**) used in Bluetooth,
**direct-sequence spread spectrum (DSSS)** used in 802.11b,



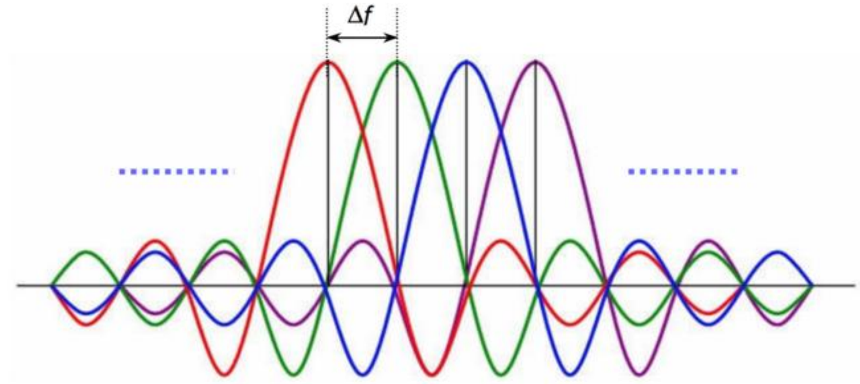

**Chirp spread spectrum (CSS)** as used in LoRa.



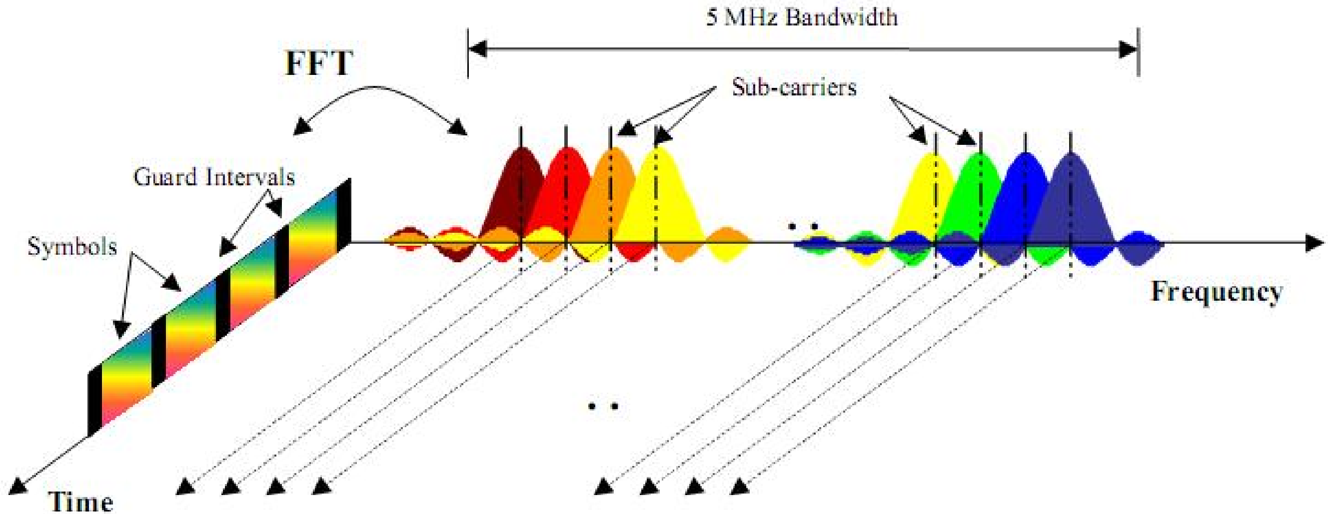

Source:
IEBMedia http://www.iebmedia.com/index.php?id=4466,
wikipedia

# Modulation & encoding: OFDM

Idea: Overlapping carriers with a spacing such that neighbouring carriers' sidebands cancel each other out.
(Orthogonality)




Source:
IEBMedia http://www.iebmedia.com/ir
wikipedia

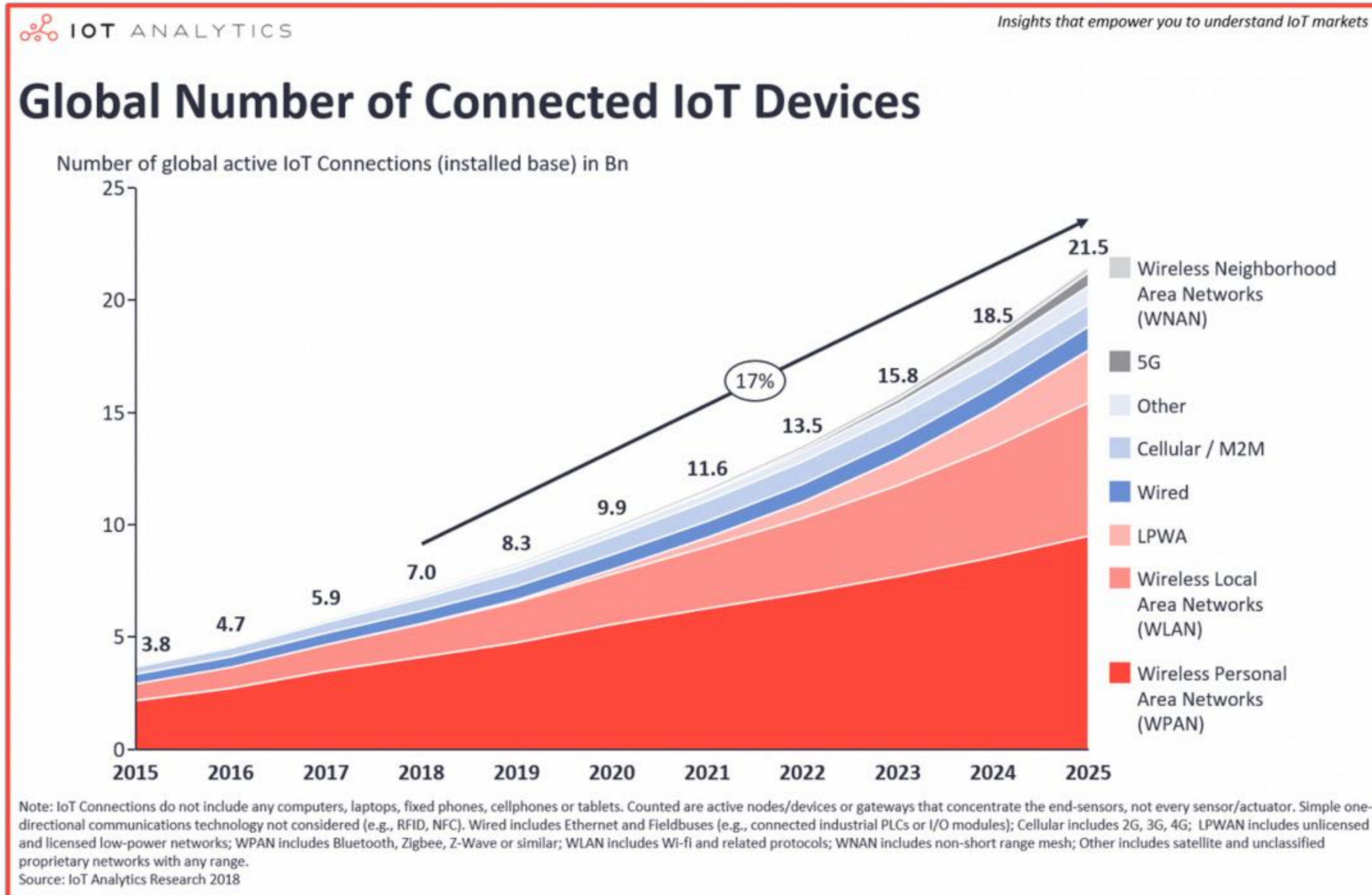


# IoT Options – first overview

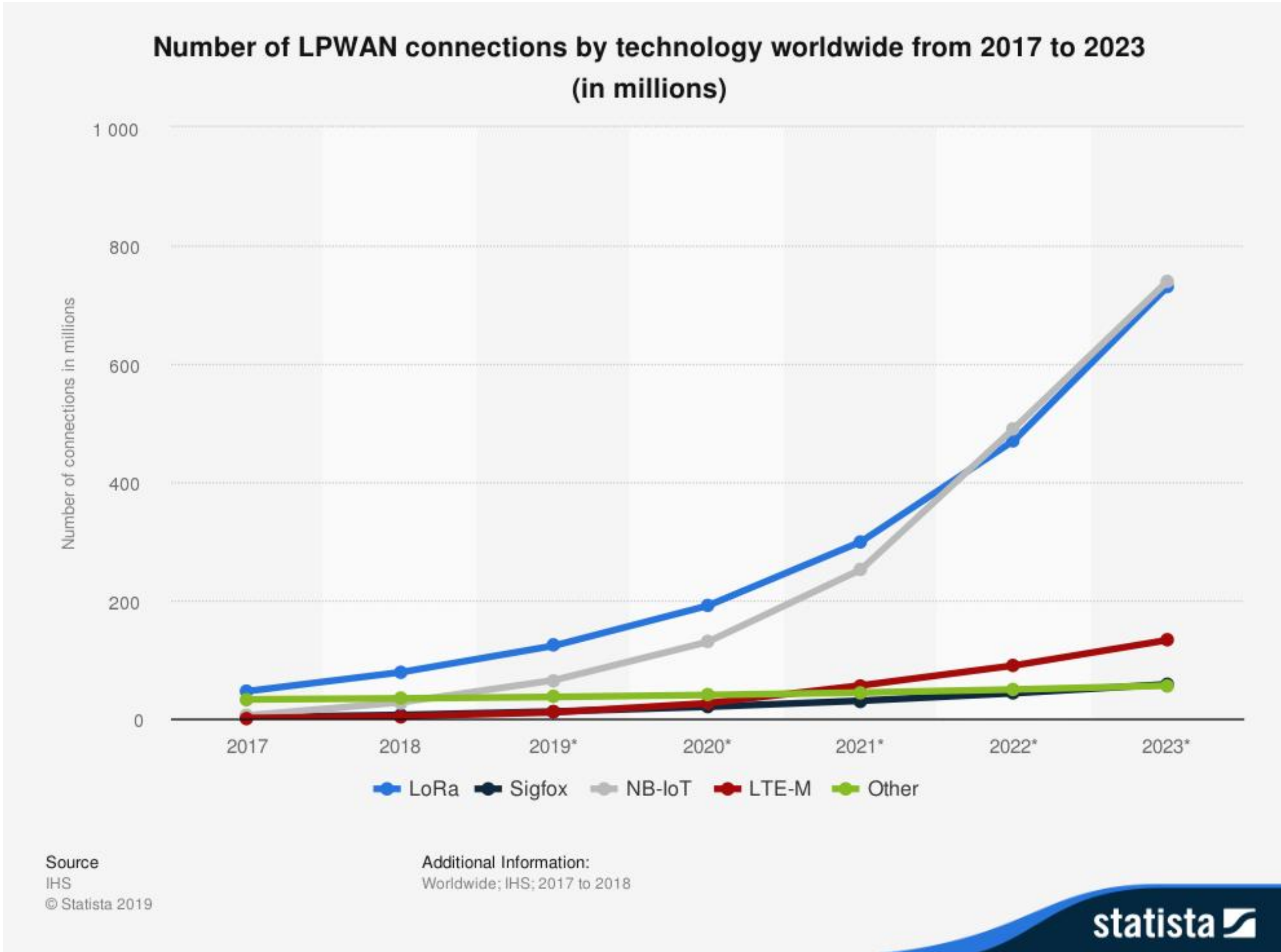
**Main technologies:**

| | | |
|---|---|---|
| WPAN | Wireless Personal Area | Bluetooth, Zigbee, ... |
| WLAN | Wireless Local Area | Wi-Fi, Bluetooth |
| LPWAN | Low Power Wide Area | LoRa, NB-IOT, (Sigfox) |
| Cellular | 3G<br>4G<br>5G | |
| Wired | | |
| Other | Acoustic | |

# IoT Options – first overview



# IoT Options – first overview



# IoT Options – detailed comparisons

Be aware of

**bias and varying definitions in all technology comparisons**,

and of doing “apples vs. oranges”.

A seemingly term like “range” is a good example.

**Take a look at the graphic:**

How far does LoRa go?

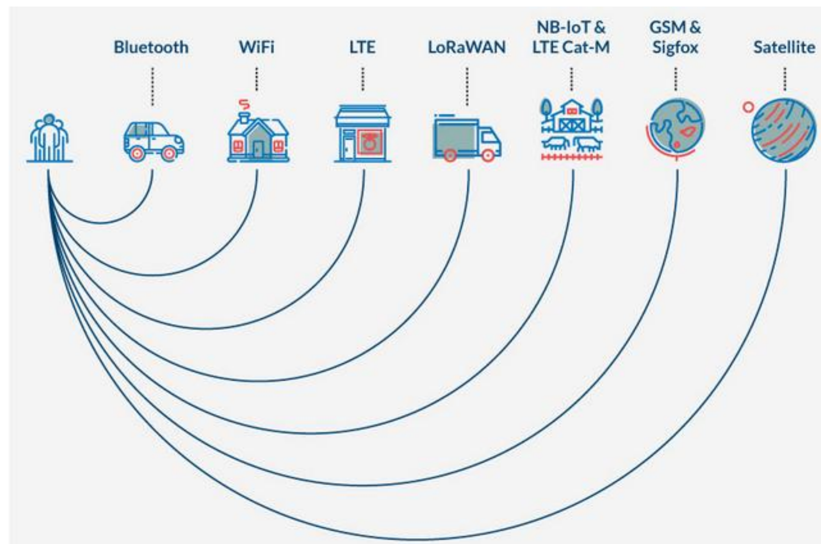
What about WiFi?

Does LTE beat Wi-Fi?

Do satellites belong

in the same graphic?

**Discuss!**



# IoT Options – rough overview

| | Frequency | Modulation | Reach | Bandwidth | Data Rates | Power | Cost |
|---|---|---|---|---|---|---|---|
| LoRa | 433, 868/915, 2400 MHz | Chirp SpreadS | 10s of kms | 125 kHz | Some 100 Bytes | low | Low (..) |
| Sigfox | 868/915 MHz | UNB | 10s of kms | 100 Hz | Some Bytes | low | Low |
| LTE-_ | 1.8-2.7 GHz | OFDM | (km) | 200 kHz | high | Mid | Mid |
| WiFi | 2.4/5 Ghz | OFDM | 100m .. 100 km | 20/40 MHz/channel | high | high | Mid |
| Bluetooth | 2.4 GHz | FHSS | 10 m | 1 MHz/channel | mid | mid | Low |
| RPMA | 2.4 GHz | DSSS | 10s of kms | 80 MHz | (flexible) | low | Low (...) |
| Zigbee | 433, 868/915 MHz | DSSS | 100 m | MHz | bytes | Low | Low |

# IoT Options – detailed overviews

Comparison of Low-Power WAN Alternatives

| Name of Standard | Weightless | | | SigFox | LoRaWAN | LTE-Cat M | IEEE P802.11ah (low power WiFi) | Dash7 Alliance Protocol 1.0 | Ingenu RPMA | nWave |
|---|---|---|---|---|---|---|---|---|---|---|
| | -W | -N | -P | | | | | | | |
| Frequency Band | TV whitespace (400-800 MHz) | Sub-GHZ ISM | Sub-GHZ ISM | 868 MHz/902 MHz ISM | 433/868/780/915 MHz ISM | Cellular | License-exempt bands below 1 GHz, excluding the TV White Spaces | 433, 868, 915 MHz ISM/SRD | 2.4 GHz ISM | Sub-GHz ISM |
| Channel Width | 5MHz | Ultra narrow band (200Hz) | 12.5 kHz | Ultra narrow band | EU: 8x125kHz, US 64x125kHz/8x125kHz, Modulation: Chirp Spread Spectrum | 1.4MHz | 1/2/4/8/16 MHz | 25 KHz or 200 KHz | 1 MHz (40 channels available) | Ultra narrow band |
| Range | 5km (urban) | 3km (urban) | 2km (urban) | 30-50km (rural), 3-10km (urban), 1000km LoS | 2-5k (urban), 15k (rural) | 2.5- 5km | Up to 1Km (outdoor) | 0 – 5 km | >500 km LoS | 10km (urban), 20-30km (rural) |
| End Node Transmit Power | 17 dBm | 17 dBm | 17 dBm | 10µW to 100 mW | EU:<+14dBm, US:<+27dBm | 100 mW | Dependent on Regional Regulations (from 1 mW to 1 W) | Depending on FCC/ETSI regulations | to 20 dBm | 25-100 mW |
| Packet Size | 10 byte min. | Up to 20 bytes | 10 byte min. | 12 bytes | Defined by User | ~100 -~1000 bytes typical | Up to 7,991 Bytes (w/o Aggregation), up to 65,535 Bytes (with Aggregation) | 256 bytes max / packet | Flexible (6 bytes to 10 kbytes) | 12 byte header, 2-20 byte payload |
| Uplink Data Rate | 1 kbps to 10 Mbps | 100bps | 200 bps to 100 kbps | 100 bps to 140 messages/day | EU: 300 bps to 50 kbps, US:900-100kbps | ~200kbps | 150 Kbps ~ 346.666 Mbps | 9.6 kb/s, 55.55 kbps or 166.667 kb/s | AP aggregates to 624 kbps per Sector (Assumes 8 channel Access Point) | 100 bps |
| Downlink Data Rate | 1 kbps to 10 Mbps | No downlink | 200 bps to 100 kbps | Max 4 messages of 8 bytes/day | EU: 300 bps to 50 kbps, US:900-100kbps | ~200kbps | 150 Kbps ~ 346.666 Mbps | 9.6 kb/s, 55.55 kbps or 166.667 kb/s | AP aggregates to 156 kbps per Sector (Assumes 8 channel Access Point) | -- |
| Devices per Access Point | Unlimited | Unlimited | Unlimited | 1M | Uplink:>1M, Downlink:<100k | 20k+ | 8191 | NA (connectionless communication) | Up to 384,000 per sector | 1M |
| Topology | Star | Star | Star | Star | Star on Star | Star | Star, Tree | Node-to-node, Star, Tree | Typically Star. Tree supported with an RPMA extender | Star |
| End node roaming allowed | Yes | Yes | Yes | Yes | Yes | Yes | Allowed by other IEEE 802.11 amendments (e.g., IEEE 802.11r) | Yes | Yes | Yes |
| Governing Body | Weightless SIG | | | Sigfox | LoRa Alliance | 3GPP | IEEE 802.11 working group | Dash7 Alliance | Ingenu (formerly OnRamp) | Weightless SIG |
| Status | Limited deployment awaiting spectrum availability | Deployment beginning | Standard in development. Scheduled release 4Q 2015 | In deployment | Spec released June 2015, in deployment | Release 13 expected 2016 | Targeting 2016 release | Released May 2015 | In Deployment | In Deployment |

Source: EDN.com - Copyright 2015 UBM Americas Rev. 9/15/15

Source: https://www.cnx-software.com/2015/09/21/comparison-table-of-low-power-wan-standards-for-industrial-applications/

# IoT Options – detailed overviews

## COMPARISON – main LPWAN technologies

Vertical M2M

| Feature | LORAWAN | SIGFOX | LTE Cat 1 | LTE M | NB - LTE |
|---|---|---|---|---|---|
| Modulation | SS chip | UNB / GFSK / BPSK | OFDMA | OFDMA | OFDMA |
| Rx Bandwith | 500 – 125 KHz | 100 Hz | 20 MHz | 20 – 1.4 MHz | 200 KHz |
| Data Rate | 290bps – 50Kbps | 100 bit / sec<br>12 / 8 bytes Max | 10 Mbit /sec | 200 kbps – 1 Mbps | Average 20K bit / sec |
| Max. # Msgs/day | Unlimited | UL: 140 msgs / day | Unlimited | Unlimited | Unlimited |
| Max Outpu 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 |
| Battery lifetime – 2000 mAh | 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<br>Oui | Yes | Yes |
| Mobility / localization | Yes | Limited mobility, No localization | Mobility | Mobility | Limited mobility, No localization |

Source: LoRAWAN Alliance, 2015

www.vertical-m2m.com

Source: LoraWAN Alliance, 2015

# IoT Options – views: license

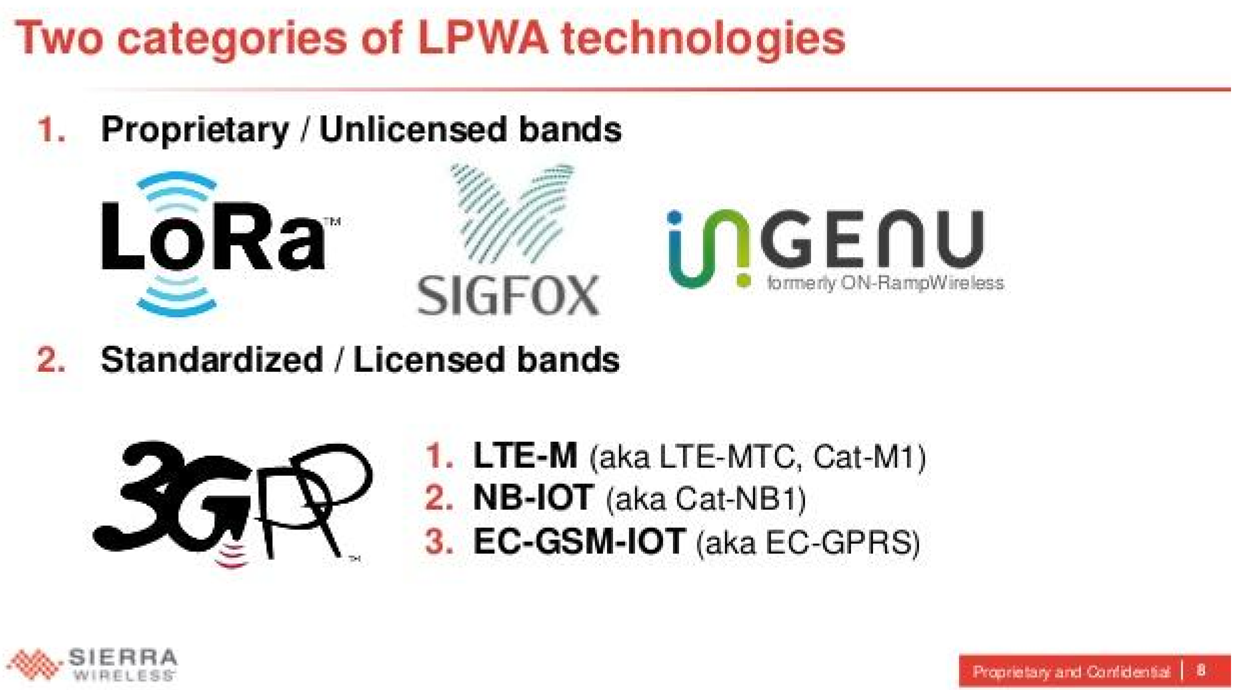
Pros and cons of **proprietary vs unlicensed spectrum** will be discussed differently, depending on where people come from.

As a mobile operator, you will favour close frequencies.

As a community networker, researcher or educator, you might disagree.

Source: Sierra Wireless

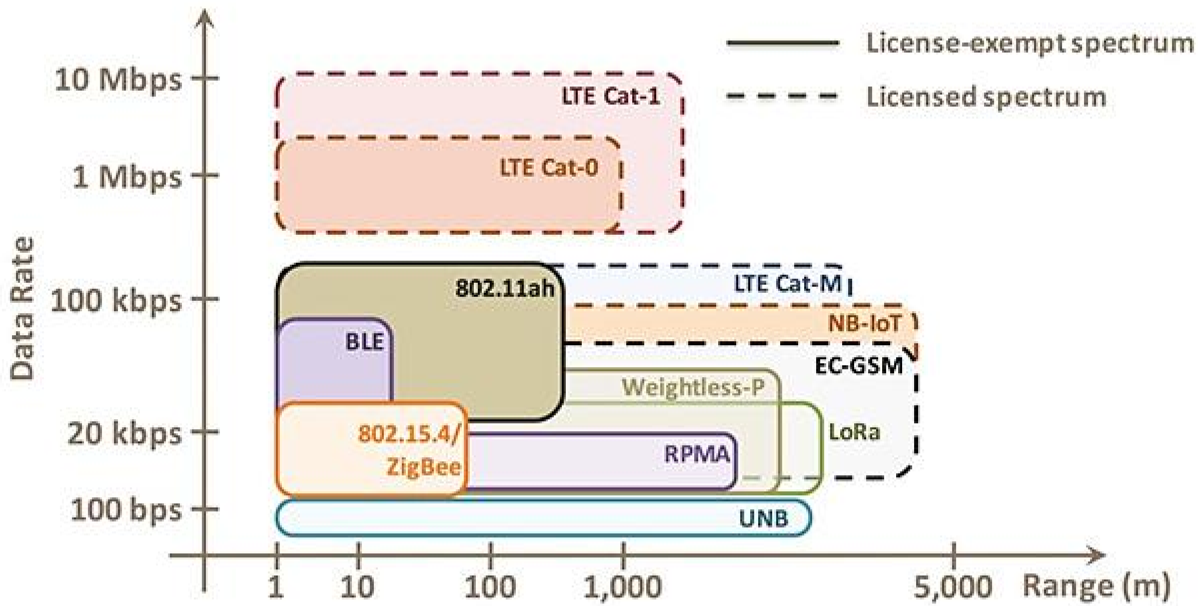
# IoT Options – views: license




Note: this graphic deserves a second view? Discuss!

Source: Sierra Wireless

# IoT Options – views: range



# IoT Options – comments on range

***Range*** depends on who you ask …. some hints:

| | **Typical** | **Record** | **Realistic, stable** |
|---|---|---|---|
| **Bluetooth** | some 10 m | ? | 10 m |
| **Wi-Fi** | 100 m | 378 / 700+ km | 100 km |
| **LoRa** | 5-10 km | 766/1200 km | 100/500 km (...) |

# IoT Options – Wi-Fi World Record 382 km

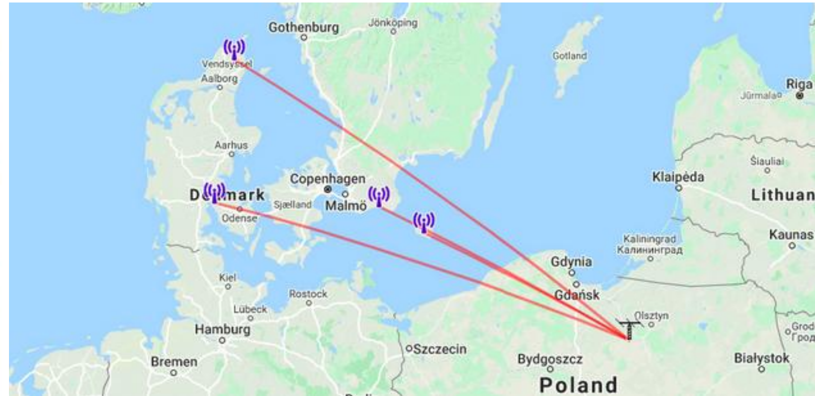
Ermanno Pietrosemoli (ICTP, Eslared) and team

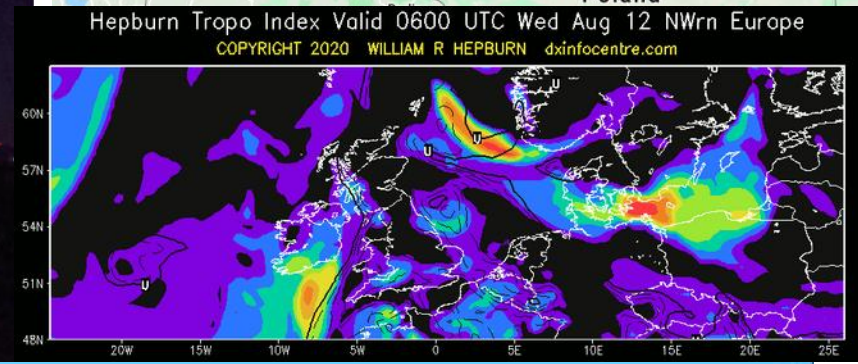
# Distances – Wi-Fi stray packets at 700 km

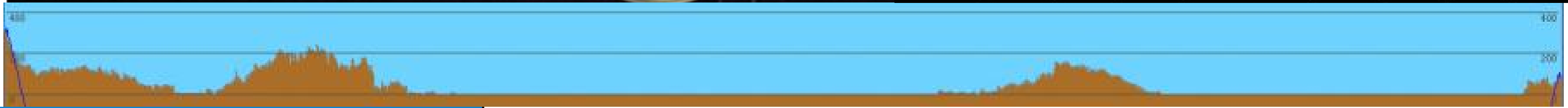
## 5 GHz Wi-Fi DX record – Denmark logged in Poland @ 745 km

by kkonrad 15-08-2020

A remarkable tropospheric ducting occurred on **August 11 and 12, 2020** between **Poland**, **Sweden** and **Denmark**. The propagation forecasts, which use color hue to scale their intensity, featured red shades over the Baltic Sea. Such a propagation strength is very rare, if ever seen on a forecast for this area. I was looking forward for something extraordinary, especially on the microwave bands. My stationary Wi-Fi DXing setup has been damaged three months ago. I could not miss such an opening, so a DX-pedition was the only option. In the evening of August 11 I made an opportunistic decision to visit the **Dylewska Góra** in north-eastern Poland. A few hours later, I was standing there with an antenna inside a lookout tower.



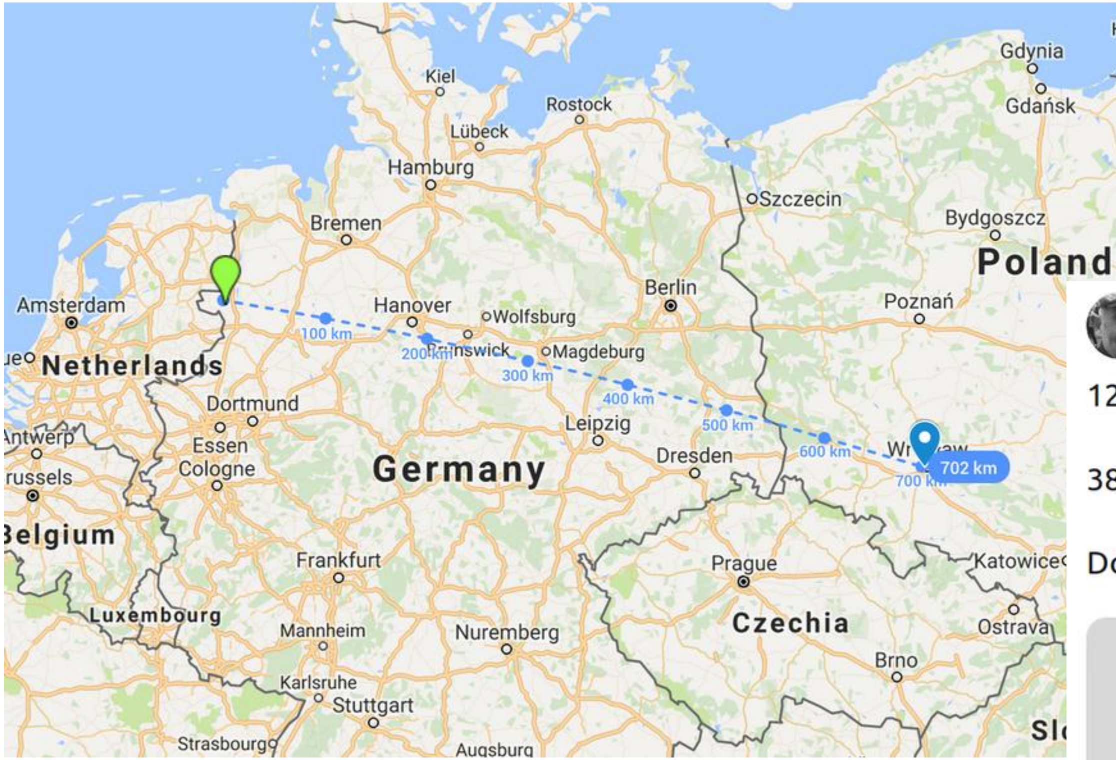





https://fmdx.pl/2020/08/5ghz-wifi-dx-record-denmark-logged-in-poland-745-km/

# IoT Options – LoRa World Record(s)

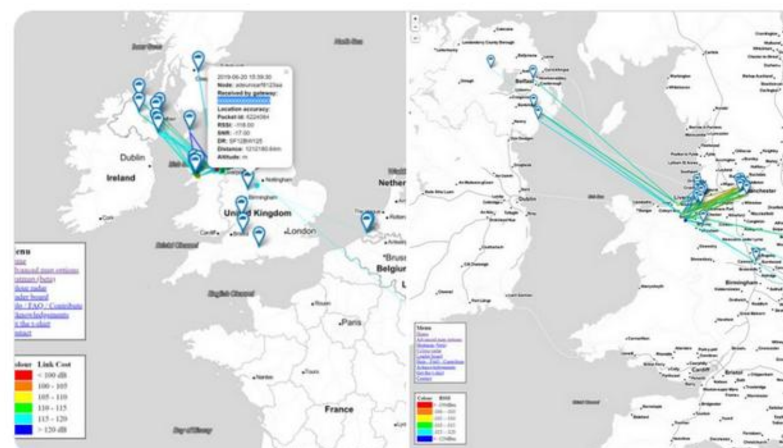



**John Cassidy (M7DXO)**
@JohnCassidyGB

1212km (SF12) from England to Italy.

385km (SF7) from Wales to England.

Done on @adeunisrf and @pycomIOT devices.



Terrestrial & with balloon

# IoT Options – LoRa World Record(s)

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1212km (SF12) from England to Italy.

385km (SF7) from Wales to England.

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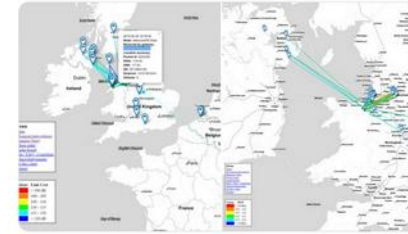
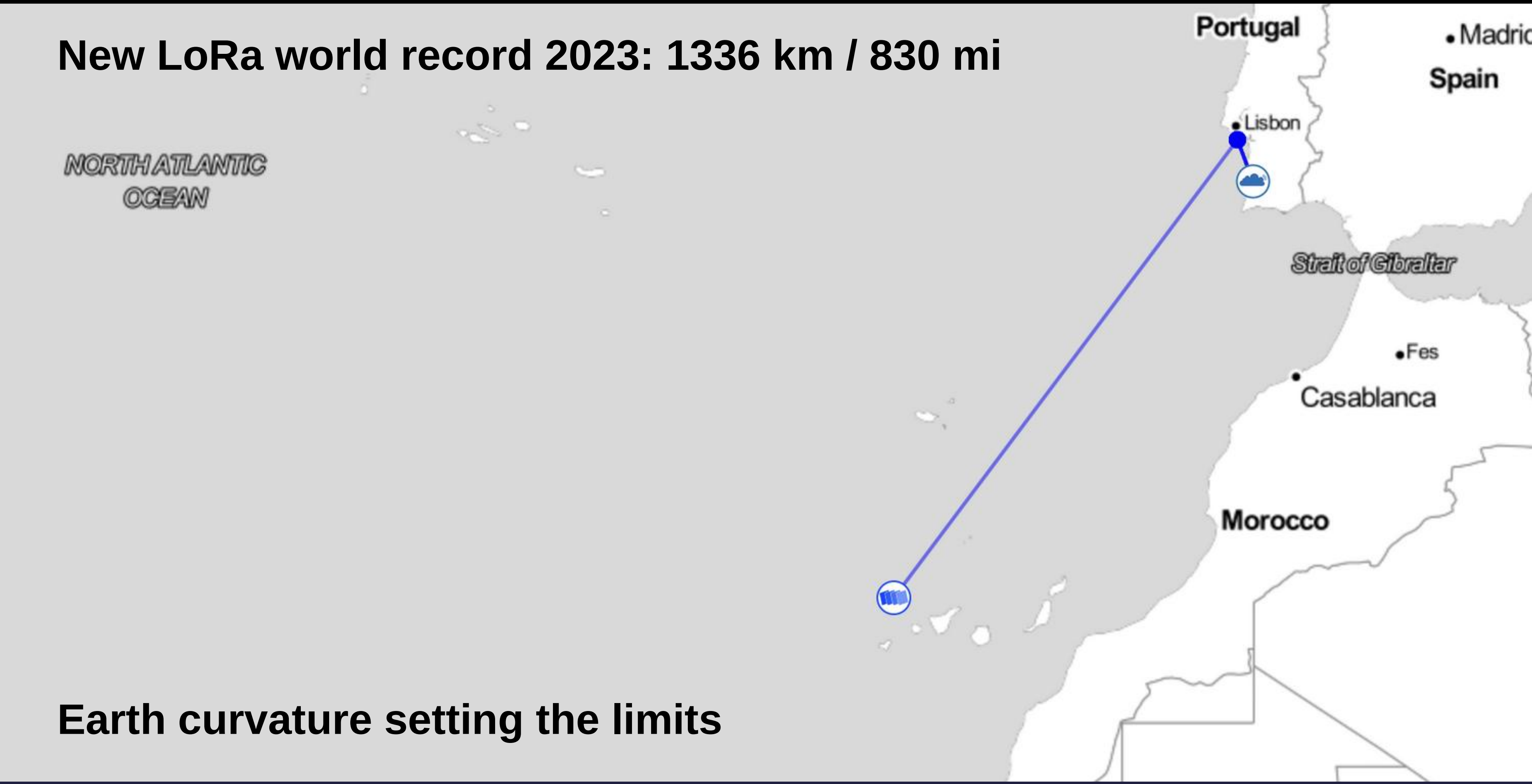


14 dBm / 25 mW! Pycom gear

# Terrestrial LoRa - distance

## New LoRa world record 2023: 1336 km / 830 mi

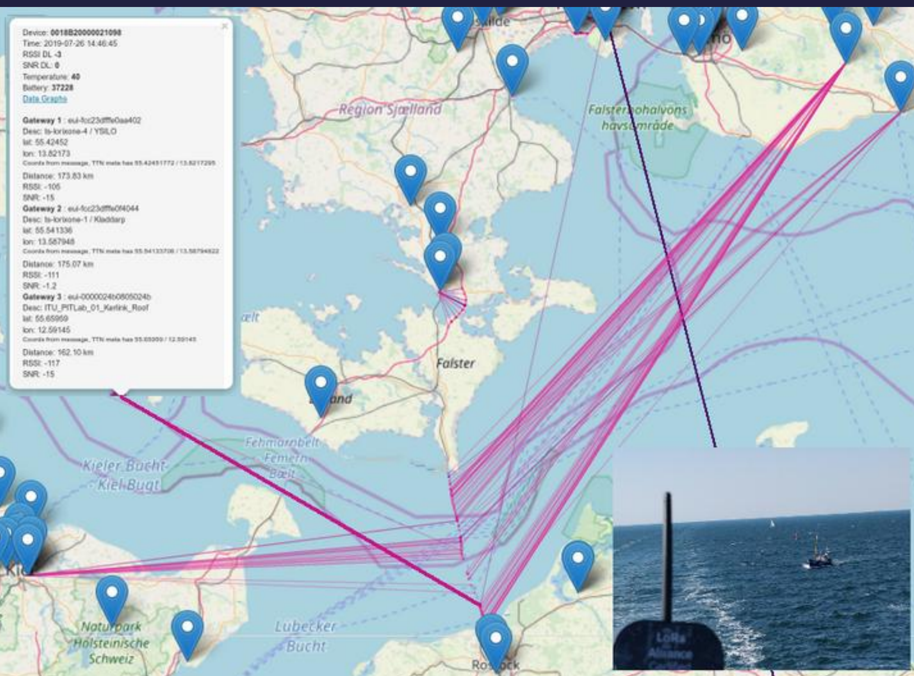


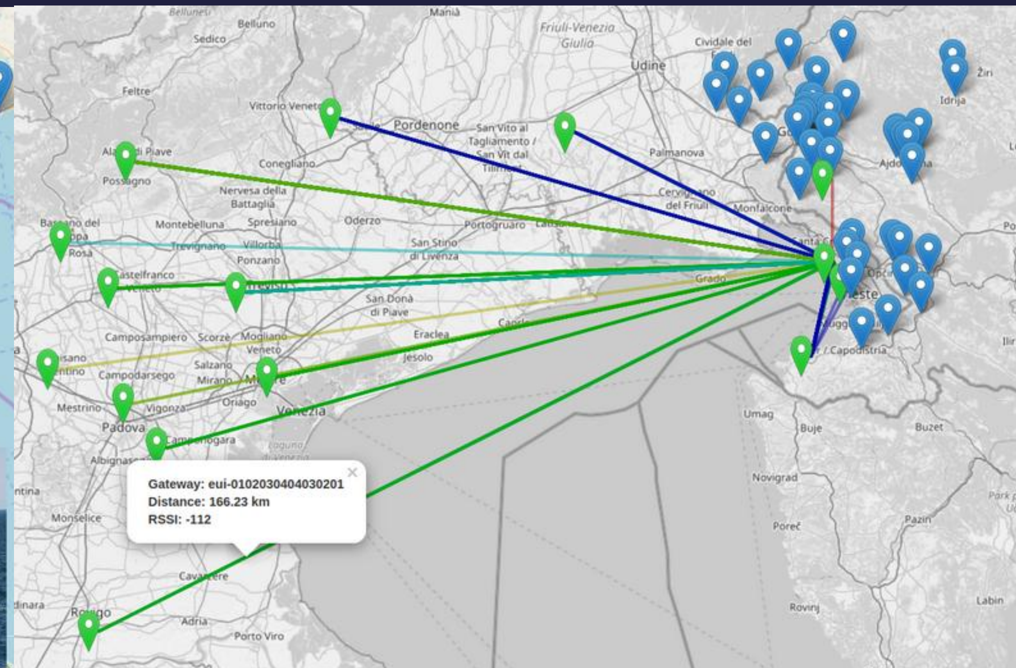

## Earth curvature setting the limits

Source: TheThingsNetwork

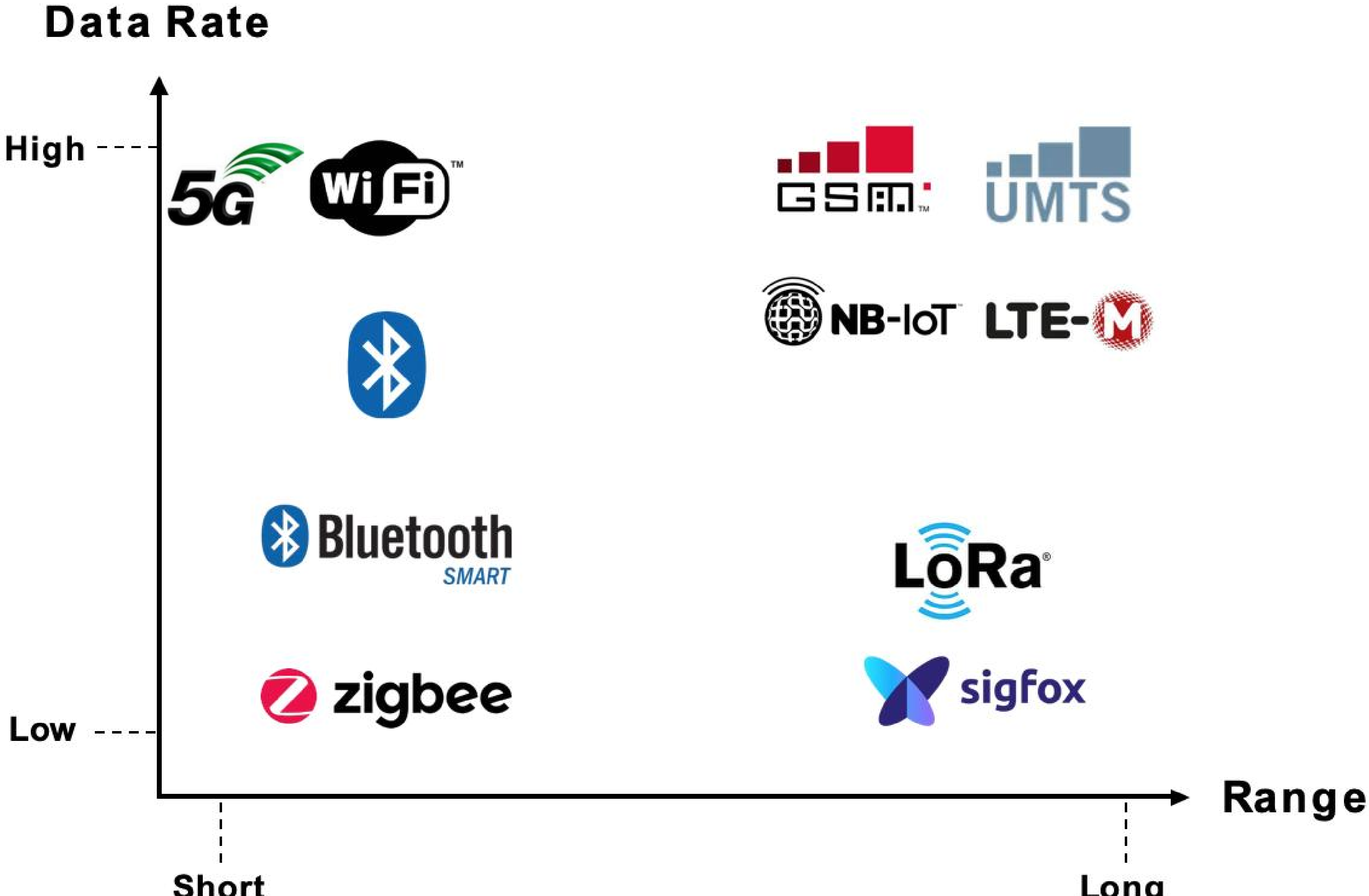
# Context – terrestrial LoRa

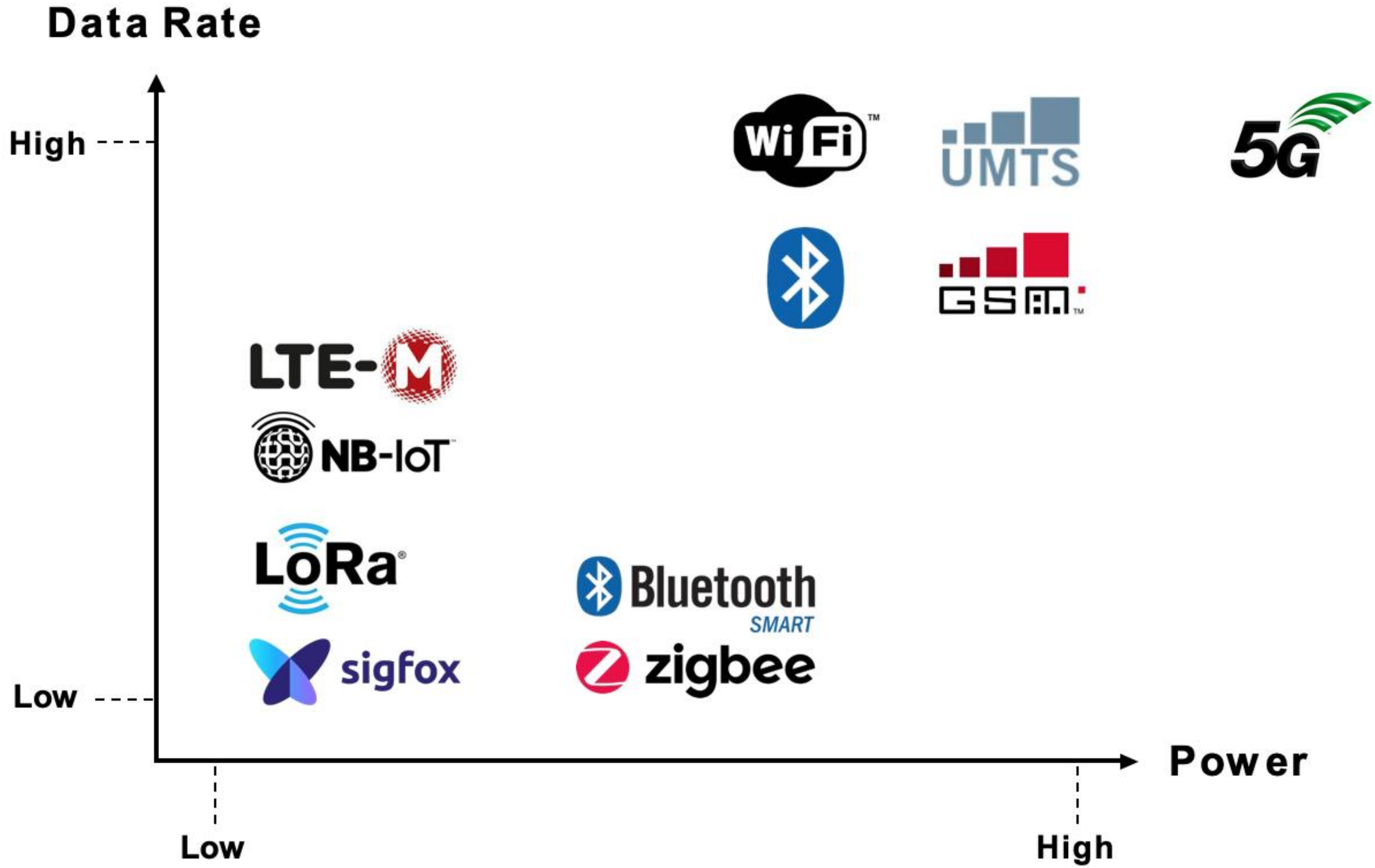
## LoRa at ITU: 100 km are every day standard, 200 km on good days

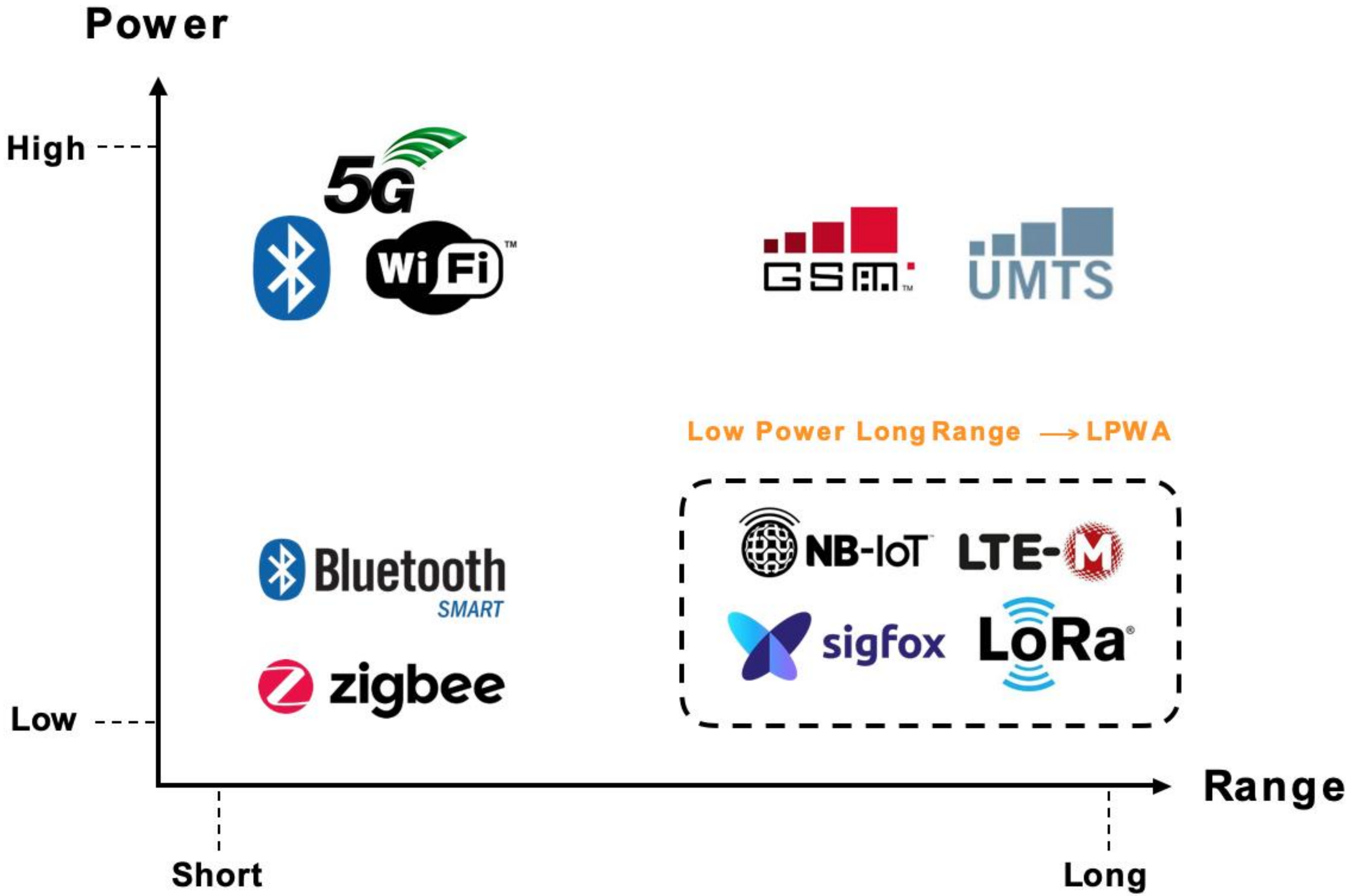


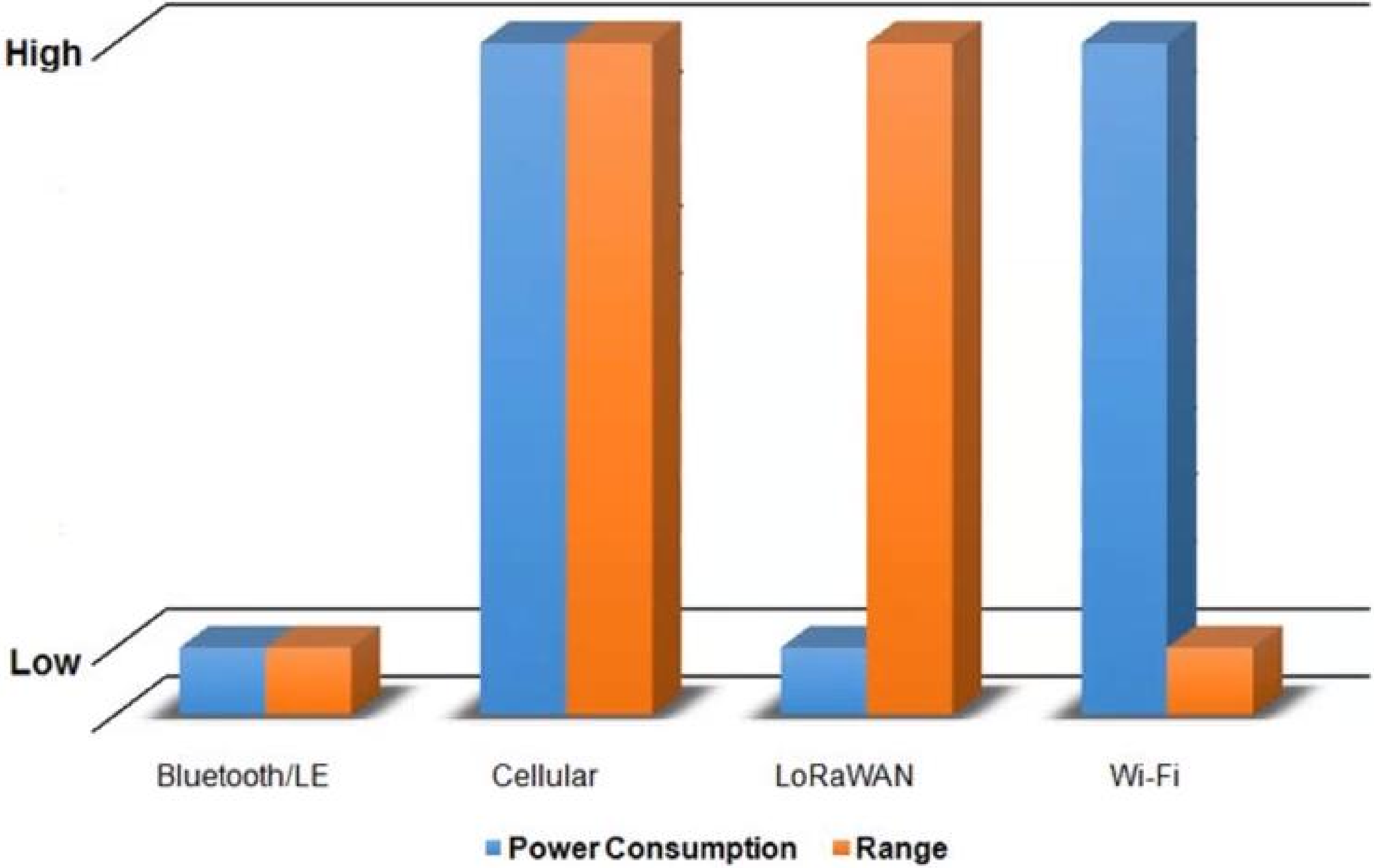





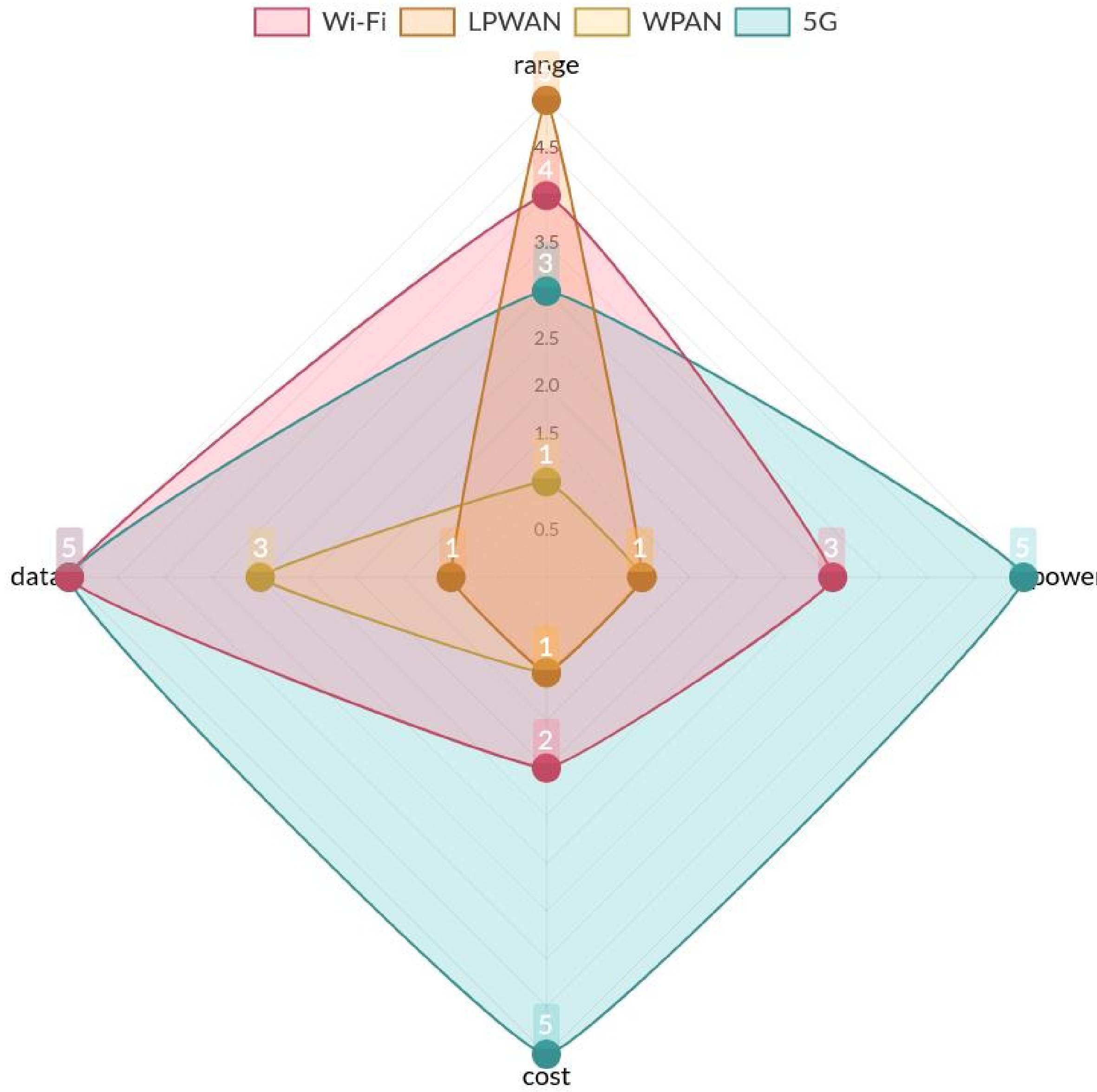

Data Rate
High
Low
Range
Short
Long
5G
WiFi
Bluetooth SMART
zigbee
GSM
UMTS
NB-IoT
LTE-M
LoRa
sigfox


Data Rate
High
Low
Power
Low
High
Wi Fi
UMTS
5G
GSM
LTE-M
NB-IoT
LoRa
Bluetooth
SMART
sigfox
zigbee


Power
High
Low
Range
Short
Long
5G
Wi Fi
GSM
UMTS
Low Power Long Range ⟶ LPWA
NB-IoT
LTE-M
Bluetooth SMART
zigbee
sigfox
LoRa


High
Low
Bluetooth/LE
Cellular
LoRaWAN
Wi-Fi
Power Consumption
Range

T


Wi-Fi
LPWAN
WPAN
5G
range
data
power
cost
4.5
3.5
2.5
2.0
1.5
0.5
5
4
3
1
3
1
1
3
5
1
2
5

## Low Power Wide Area Networks (LPWAN):

**Long Range**

**Low Power**

**Low Cost**

**Small Data**

| 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 | -126 dBm | 100 b/s | Ultra Narrow Band |
| LoRa | -136 dBm | 18 b/s - 37.5 kb/s | Narrow Band |
| Cellular data | -104 dBm | Up to 1.4 Mb/s | Narrow Band |

\
**LPWAN**
/

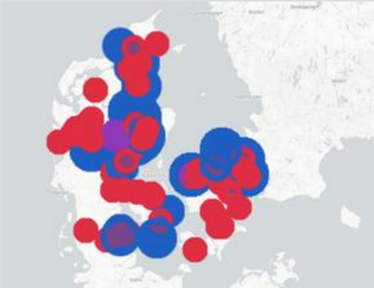
## Low Power Wide Area Networks

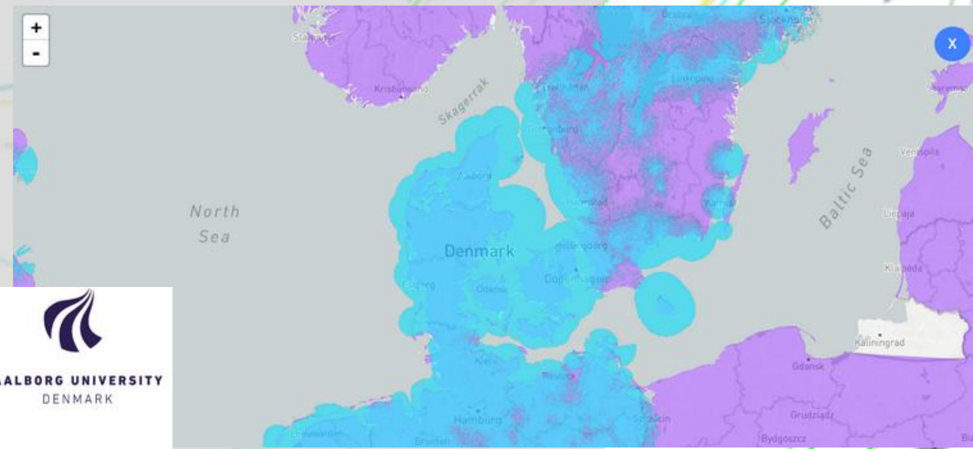
# LoRa

# (Sigfox)

# LTE-M

# NB-IoT






Aalborg Universitet

AALBORG UNIVERSITY DENMARK

**Coverage comparison of GPRS, NB-IoT, LoRa, and SigFox in a 7800 km2 area**

Lauridsen, Mads; Nguyen, Huan Cong; Vejlgaard, Benny; Kovacs, Istvan; Mogensen, Preben Elgaard; Sørensen, Mads

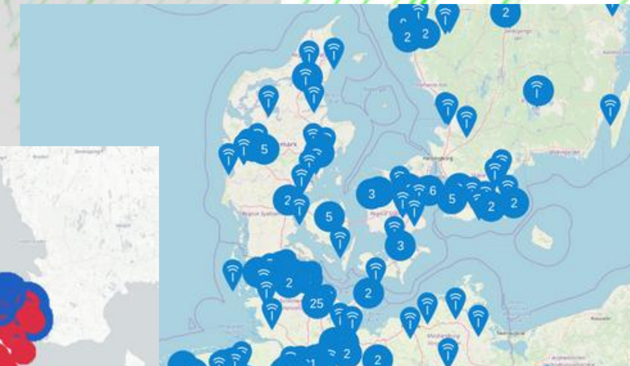
*Published in:*
2017 IEEE 85th Vehicular Technology Conference (VTC Spring)

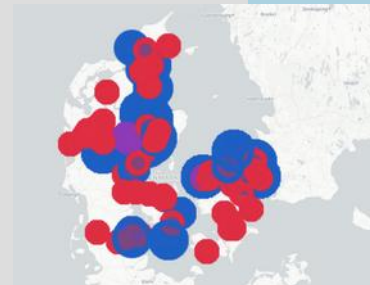
**Coverage ...**

**Low Power Wide Area Networks**

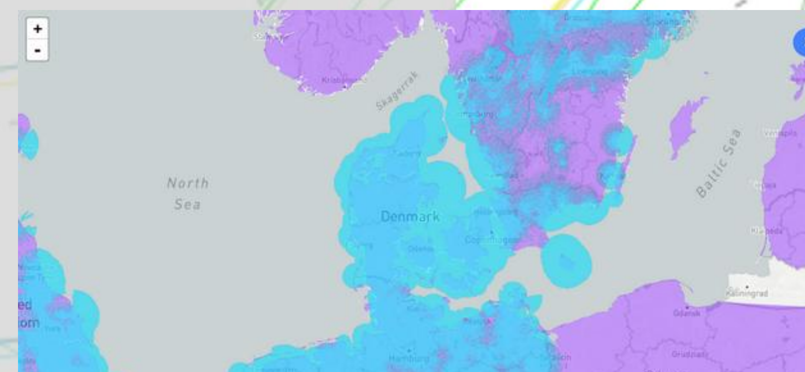
# Market shares &

# Metrics?





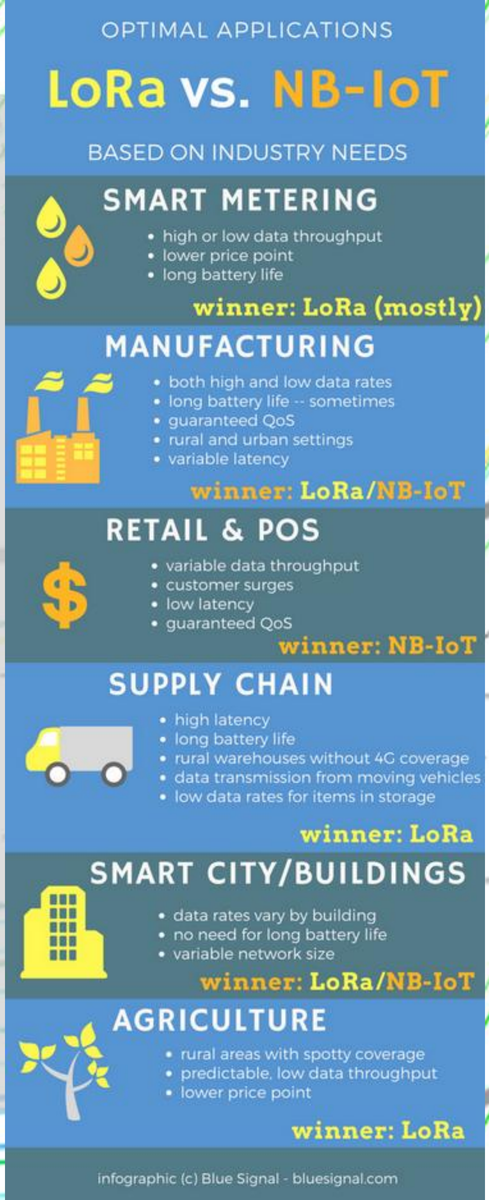
# Platform decisions




# not mainly tech-driven

## Low Power Wide Area Networks

# Tech-driven comparisons



# Criteria

**A quote by Nick Hunn - http://www.nickhunn.com/lora-vs-lte-m-vs-sigfox/**

There's a battle going on for the infrastructure technology that will support the Internet of Things. Currently the three most talked about contenders are Sigfox, LoRa and LTE-M. There are a lot of other alternatives and it's quite possible that none of LoRa, Sigfox nor LTE-M0 will win, but that's another story. If you search for LPWAN (Low Power Wireless Area Networks) you'll see that the battle for supremacy is a hot topic. It's largely because of the impending loss of the GPRS networks which power much of today's M2M business. As a result, almost every day you'll find another article debating their respective technical merits.

I'm going to argue that these comparisons miss the point. Which technology will win depends far more on the business model than on the underlying technology. The three technologies listed above are interesting to compare, as they exemplify three significantly different approaches to an IoT business, which can be broadly summed up as:

**Sigfox – become a global Internet of Things operator**
**LoRa – provide a technology that lets other companies enable a global Internet of Things**
**LTE-M – evolve an existing technology to make more money for network operators**

# LoRa

## “LoRa – provide a technology that lets other companies enable a global Internet of Things”

**LoRa** PHY is a **proprietary**, chirp spread spectrum (CSS) radio modulation technology for LPWAN used by LoRaWAN, Haystack Technologies, and Symphony Link.

**LoRaWAN** is a media access control layer (MAC) protocol for managing communication between LPWAN gateways and end-node devices, maintained by the LoRa Alliance.

LoRaWAN defines the communication protocol and system architecture for the network while the LoRa physical layer enables the long-range communication link.

LoRa works on 169, 433 and 868/915 MHz ISM bands.

**TheThingsNetwork** is a “people’s IoT” project based on LoRa.

Commercial providers include **LORIOT.IO, Linklabs**

# Sigfox

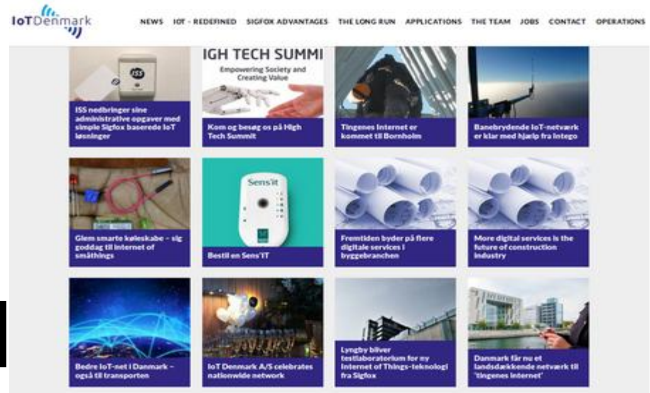
## “Sigfox – become a global Internet of Things operator”

Like LoRa, Sigfox works on 433 and 868/915 MHz ISM bands.

It uses UNB (Ultra narrow band) modulation technique.

A main difference lies in the business model: Sigfox is provided by an (exclusive) provider, just like mobile networks, on a subscriber basis.
In Denmark offered by http://iotdanmark.dk/

Update 2023:
Sigfox went bankrup 2022,
Aquired by Unabiz,
Now converging with LoRa and NB-IoT





Semtech Collaborates with UnaBiz to integrate Sigfox 0G Technology on Market-Leading LoRa® Platforms

# Sigfox – update 2022

## “Sigfox – did not quite become a global Internet of Things operator …”

Sigfox had raised more than $300 million from investors that included Salesforce, Intel, Samsung, NTT, SK Telecom, energy groups Total and Air Liquide. In November 2016 Sigfox was valued at around €600 million.
**In January 2022 Sigfox filed for bankruptcy.** [5]
In April 2022 Singapore-based IoT network firm Unabiz subsequently acquired Sigfox and its French network operations for a reported €25 million ($27m).[6]
[wikipedia]

IoT Denmark

Ved dekret af 20220505 har Sø- og Handelsrettens skifteret taget **IOT Denmark A/S under konkursbehandling** på grundlag af en begæring modtaget den 29.04.2022.
https://kapwatch.dk/nyheder/investeringsselskaber/article14011267.ece
https://finans.dk/erhverv/ECE14004157/efter-10-aar-med-underskud-nu-er-dansk-techhaab-gaaet-konkurs/?ctxref=forside

# Sigfox

**January 2022**

## Sigfox, the French IoT startup that had raised more than $300M, files for bankruptcy protection as it seeks a buyer

Ingrid Lunden @ingridlunden / 4:14 PM GMT+1 • January 27, 2022

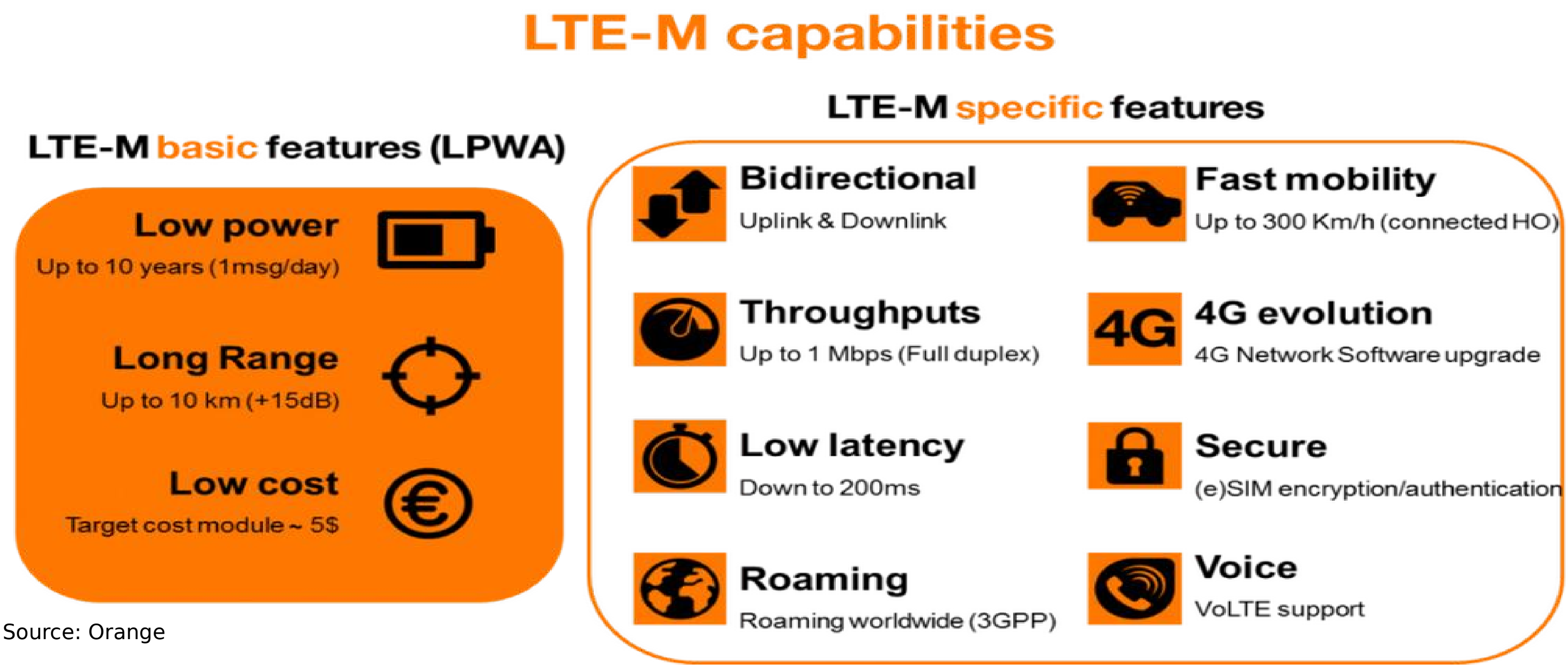
Comment

Image Credits: chombosan/iStock

We are continuing to see fallout from the COVID-19 pandemic and its impact on the tech industry, with one of the latest developments coming out from France. Sigfox — a high-profile IoT startup that had raised over $300 million in venture funding and had ambitions to build a global communications network using a new approach to wireless networking — has filed for bankruptcy protection in France, citing slow sales of its products and challenging conditions in the IoT industry due to COVID-19.

## "LTE-M – evolve an existing technology to make more money for network operators"

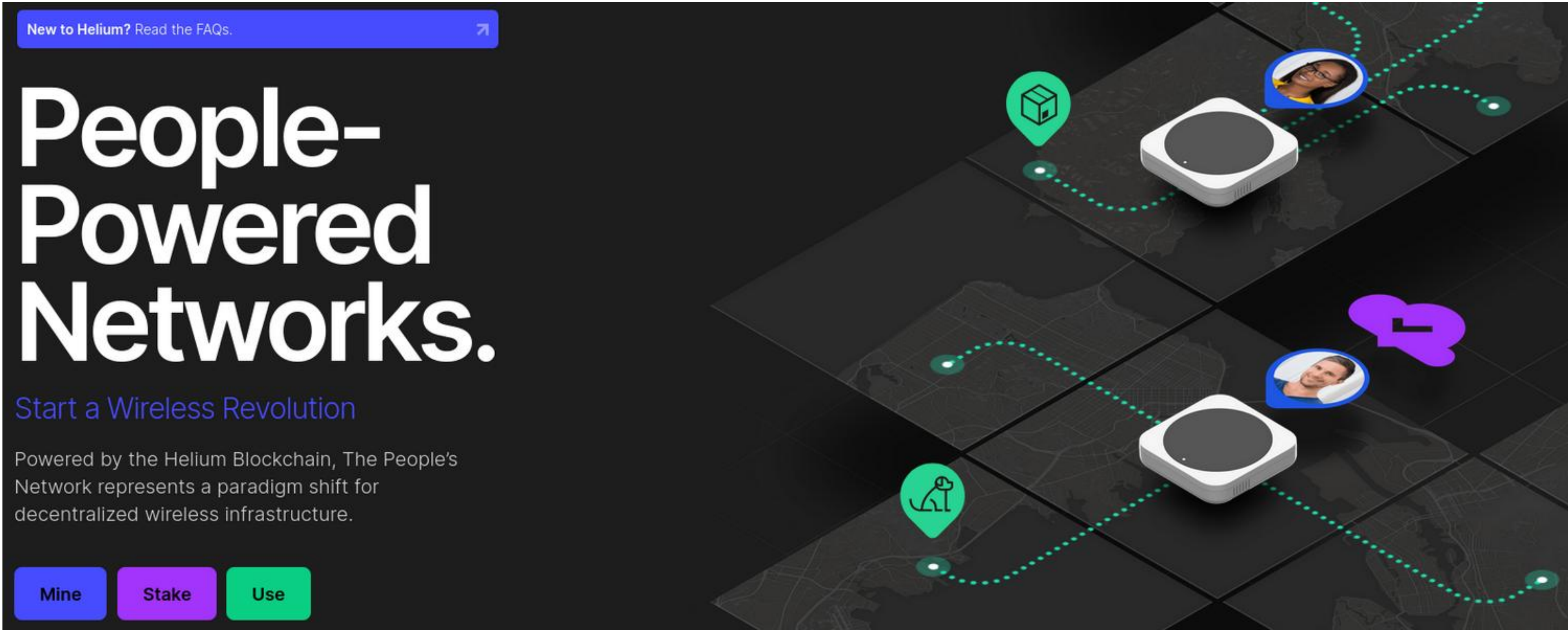
Utilizing existing 5th generation mobile networks, seeking to enable those for IoT.




Source: Orange

# IoT networks in 2024 – need to mention Helium?

**Helium** is blockchain-based LoRaWAN network.
Gateways as mining devices (proof of coverage, traffic)

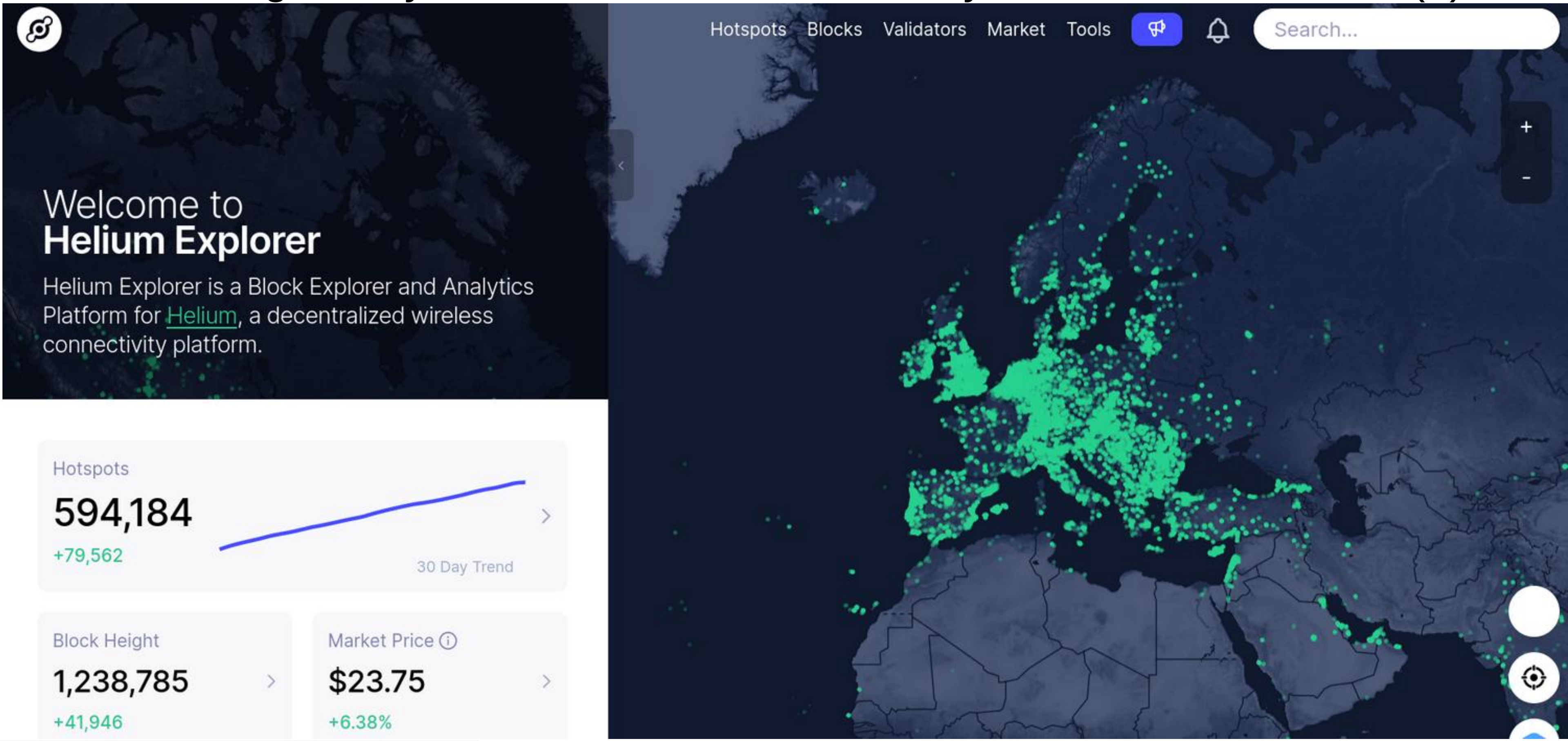





Many open questions … time will tell.

# IoT networks in 2024 – need to mention Helium?

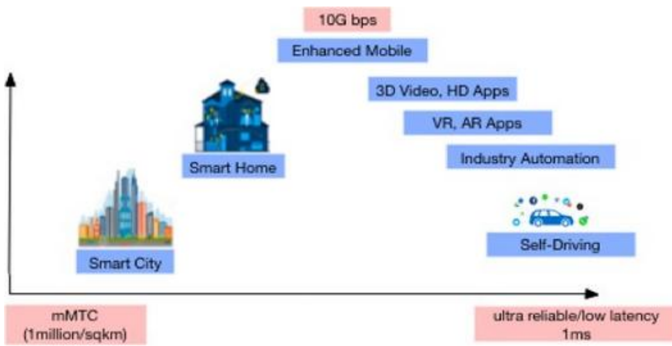
500,000 gateways, but < 20% active, and only 100 with real traffic ...(?)

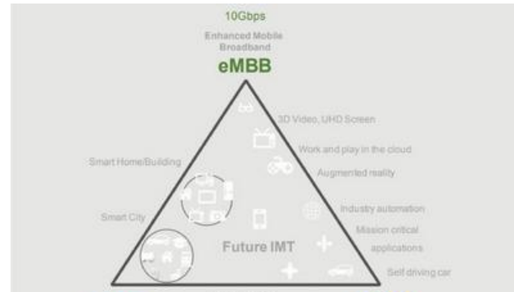



Research ongoing (e.g. at ITU / DASYA)

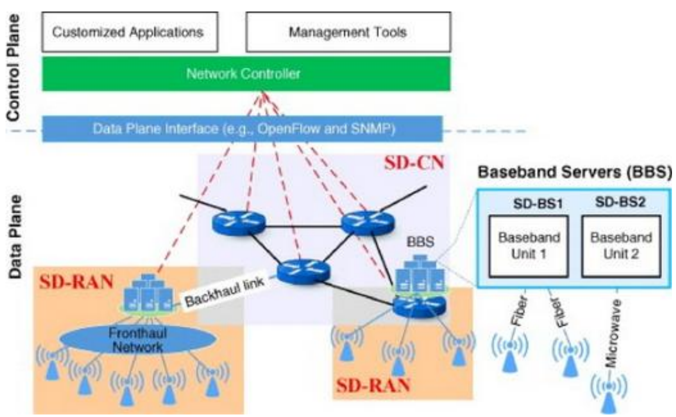
# IoT networks in 2024 – 5G

## Key advantages: Bandwidth, Latency, Commercial Support








| | Peripheral connectivity | Local (home) networking | Wide area networking |
|---|---|---|---|
| Typical range | <30 ft. | <300 ft. | Outdoor (miles) |
| Content distribution<br>Focus on high data rates<br>Energy consumption secondary | Bluetooth | WiFi<br>.11ah: HaLow<br>IEEE 802.11ax | GSM<br>lte<br>5G |
| Sense and control<br>Low energy/long battery life<br>Data rate is secondary | Bluetooth SMART | ZigBee | GPRS<br>LTE Cat-M<br>NB-IoT |
| Proprietary solutions | ANT | enocean<br>Sub-GHz | LoRa<br>SIGFOX<br>INGENU |
| Typical applications | Personal appliances<br>(wristband, smartwatch, step counter, keyboard, mouse, pointer, etc.) | Indoor networks<br>(internet, email, phone, security, energy management, smart home monitoring, etc.) | Outdoor networks<br>(smartphone, internet, city, industry 4.0, agriculture, smart logistics, etc.) |

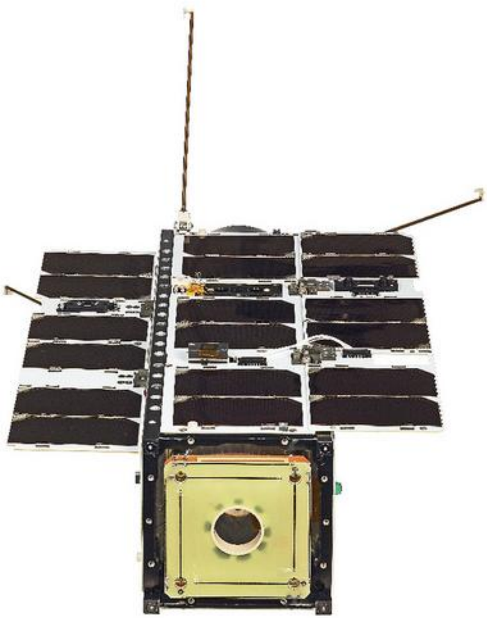
Li, Shancang, Li Da Xu, and Shanshan Zhao. "5G Internet of Things: A survey." Journal of Industrial Information Integration 10 (2018): 1-9.

**802.15.4** is a Layer 1 & 2 standard, comparable to 802.11 for wireless

**Zigbee** is a specification for a suite of high level communication protocols using small, low-power digital radios based on the IEEE 802.15.4-2003 standard for Low-Rate Wireless Personal Area Networks (LR-WPANs).
It specifies a.o. mesh routing, a slightly modified the AODV (Ad hoc On-Demand Distance Vector) standard (compare e.g. 802.11s)

**6lowPAN =** IPv6 over LoW Power wireless Area Networks.
6lowpan is the name of a working group in the internet area of the IETF. IPv6 packets over IEEE 802.15.4 based networks.
RFC 4944/ RFC 4919.

# Satellites
# HAP
# Blimps



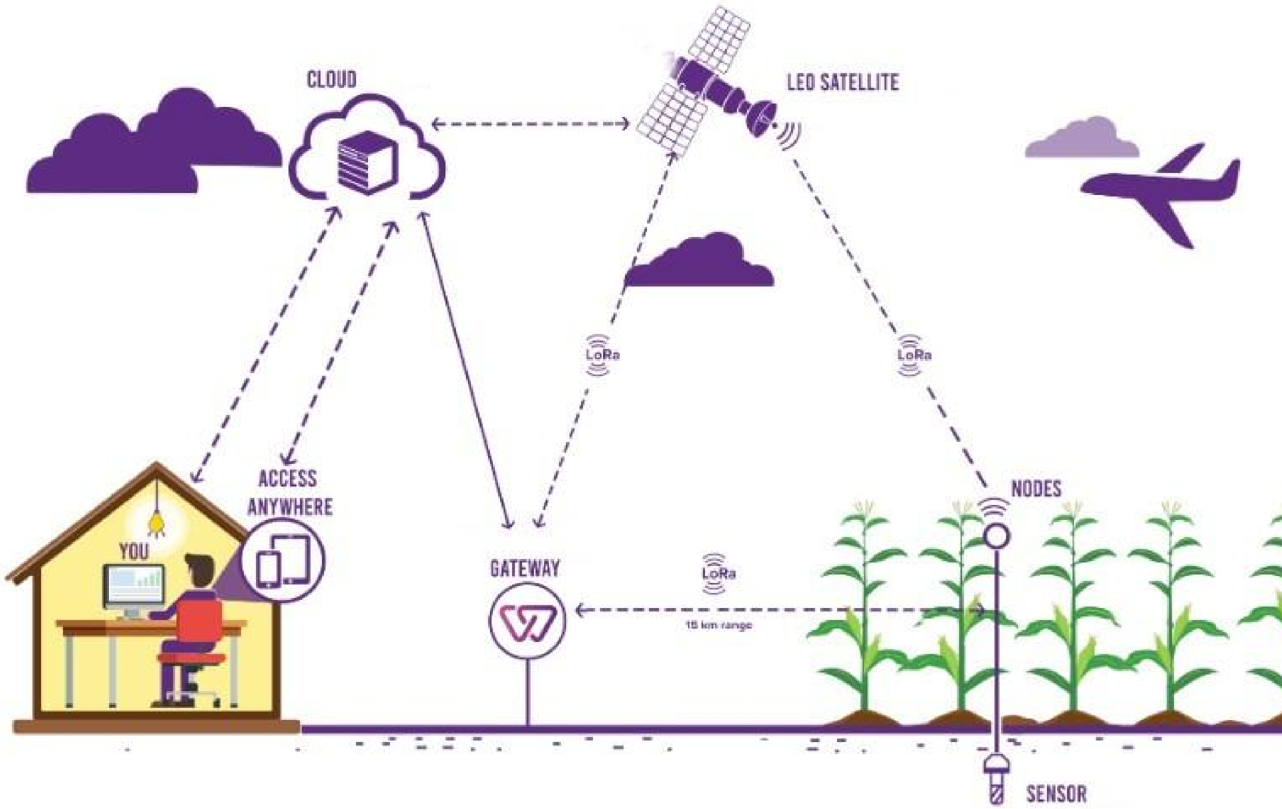
Satellites are well established communication infrastructure

Can provide networks for people (Starlink) as well as Things … e.g. via LoRa

**Echostar**
**EutelSat**
**Fleet**
**Kineis**
**Lacuna**
**Myriota**
**Swarm**
**Wyld**
**+ new ones constantly**

# Satellite IoT

# Principle




source: https://wyldnetworks.com/

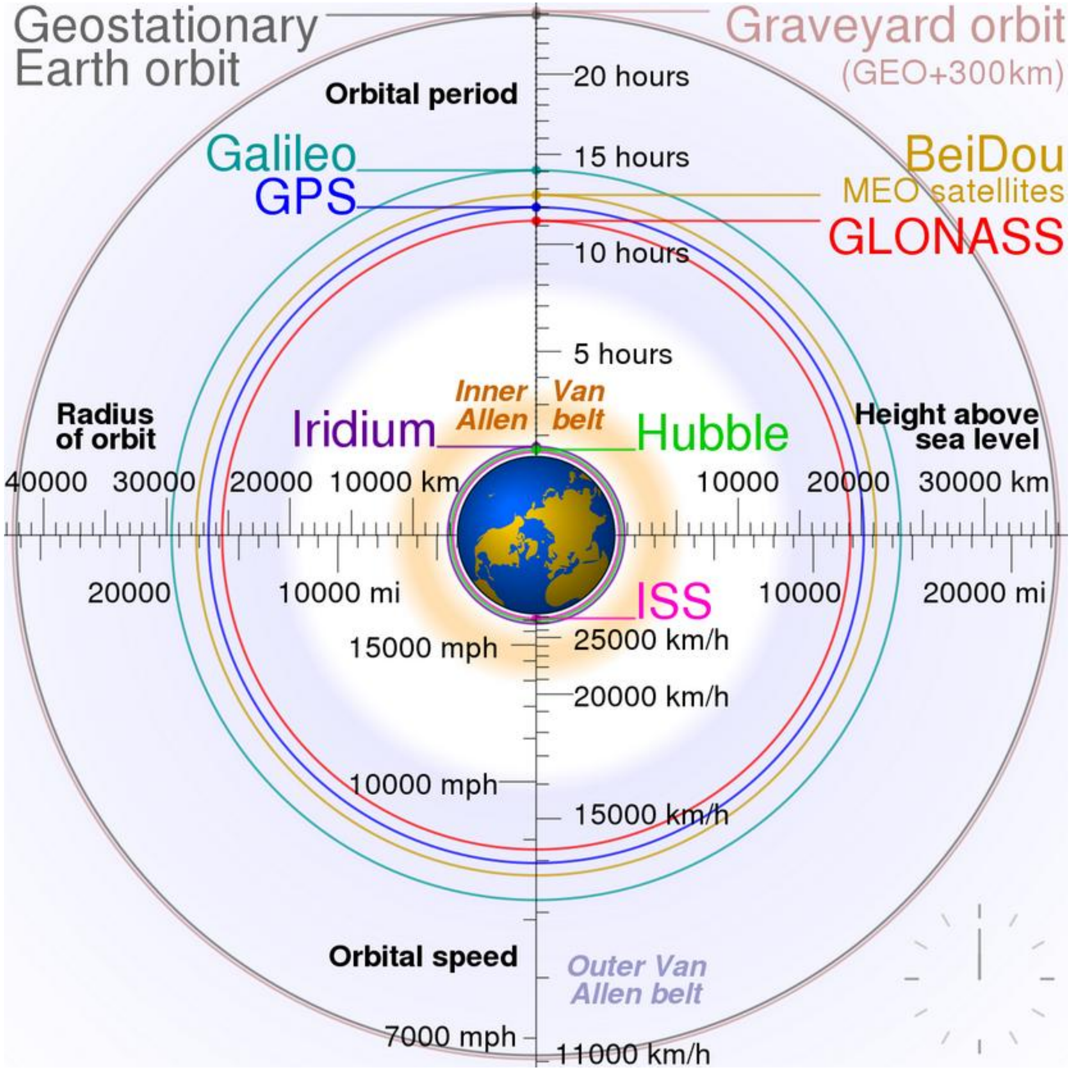
# Satellite IoT

# Orbits:

# LEO

# Low Earth Orbit

## (200-1000 km)




source: wikipedia

# Satellit IoT

# SmallSats
# CubeSats
# NanoSats

Satellite Executive BRIEFING

Vol. 14 No. 3 April 2021

SATELLITE Markets & Research

Industry Trends, News Analysis, Market Intelligence and Opportunities

## Is 2021 the Year Smallsat IoT Takes Off?

by Hub Urlings

Will 2021 be the year that a new generation of smallsat Internet of Things (IoT) networks take off?

Smallsats offer ubiquitous low-cost and low power connectivity for the global IoT industry. If it is up to some of the new operators, it sure will be, as the launch activities in the first quarter of 2021 demonstrate.



**Last January SpaceX's Transporter-1 rideshare mission launched 133 smallsats in a sun-synchronous orbit (SSO).** (image coutesy of SpaceX)

commercial services are becoming available to end-users.

In March a second launch by Soyuz-2 that carried smallsats for 3 IoT operators: Hiber and Kepler were again on board carrying the Hiber Three satellite and Kepler 6 and 7, and UK-based Lacuna launched its 5th smallsat.

The day after that Rocketlab

### What's Inside

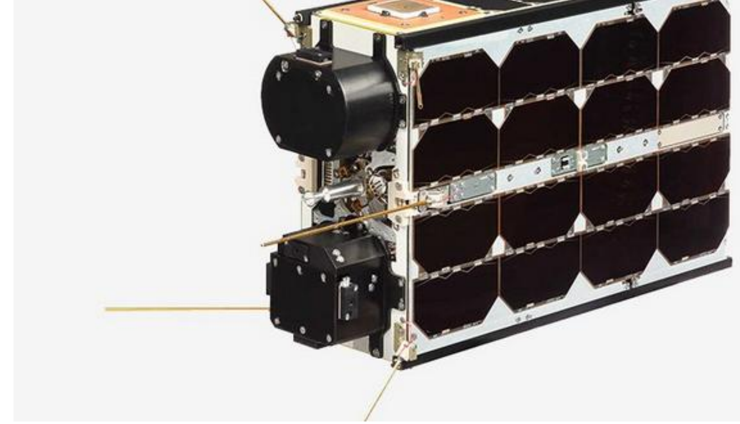


IT UNIVERSITY OF COPENHAGEN

DASYA

# Satellite IoT

space
Lacuna



# Satellite LoRaWAN: Lacuna


Sources: Lacuna.space

# Lower: Aerostats, blimps a la Loon


Sources: World Mobile 2021

# Satellite: DISCO @ ITU – your idea might fly!

# Take-Aways

- Criteria for networking options in IoT:
  Power, reach, bandwidth, cost,
  security, business aspects and more

- Properties of the physical layer: Frequency, bandwidth and their impact

- Basic terms: LPWA(N), LOS/NLOS, Modulation (Spread Spectrum),

- dBs, Link Budgets

- The most relevant options and their main characteristics:
  LoRa, NB-IoT, Zigbee, Bluetooth, WiFi, Cellular (GSM, LTE-..)