Connecting low power devices @ long range: technologies to make the balance work

April 16th 2018, EIT U Lund, Sweden
Liesbet Van der Perre, Liesbet.Vanderperre@kuleuven.be

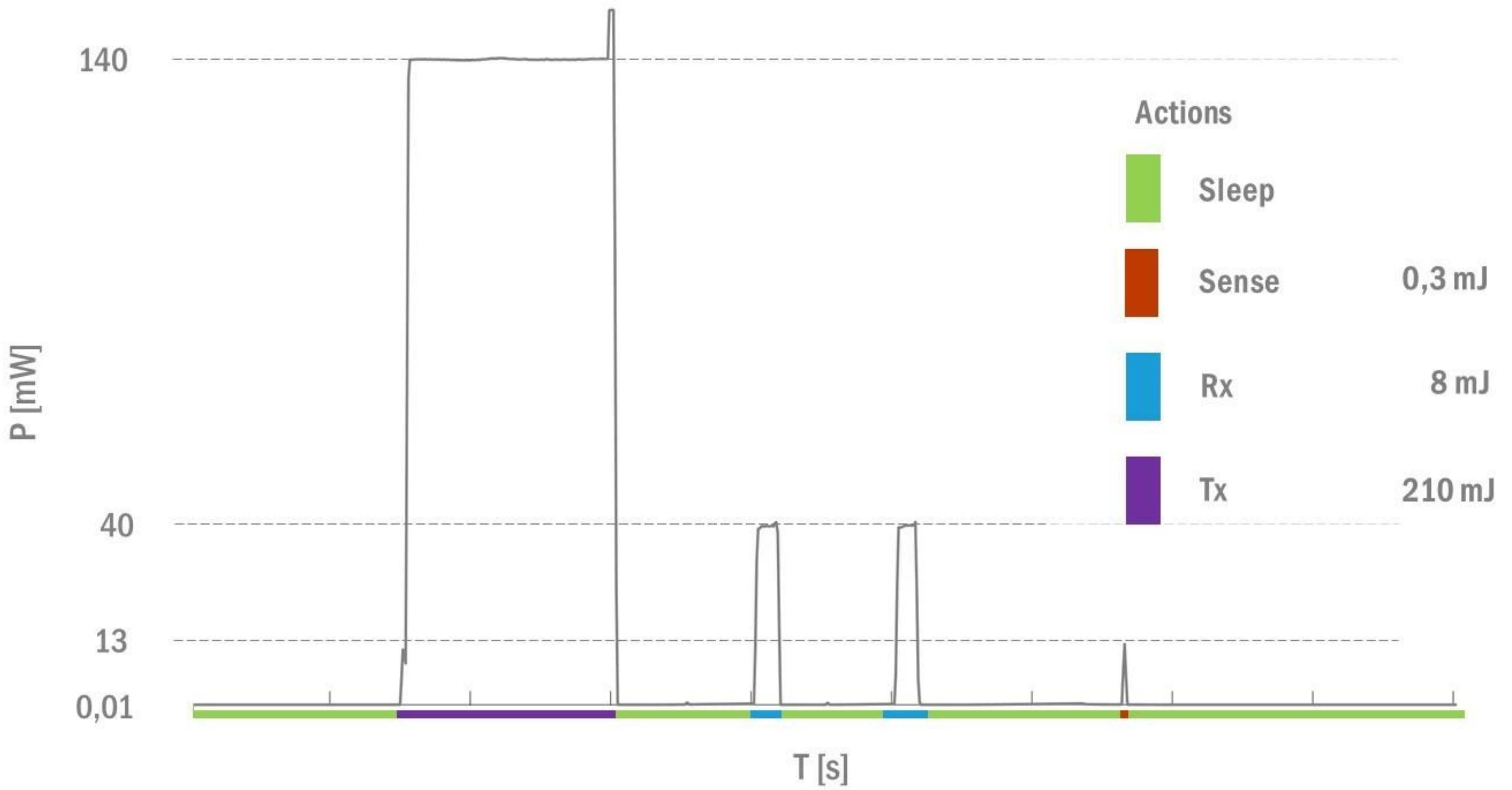
LPWAN resources: https://dramco.be/tutorials/low-power-iot/ieee-sensors-2017/

1. The **Things**, which are embedded with sensors and/or actuators
2. The **network** that connects them
3. The systems that **process** data to/from the Things

source: https://www.linkedin.com/pulse/internet-things-iot-dummies-rajat-kochhar

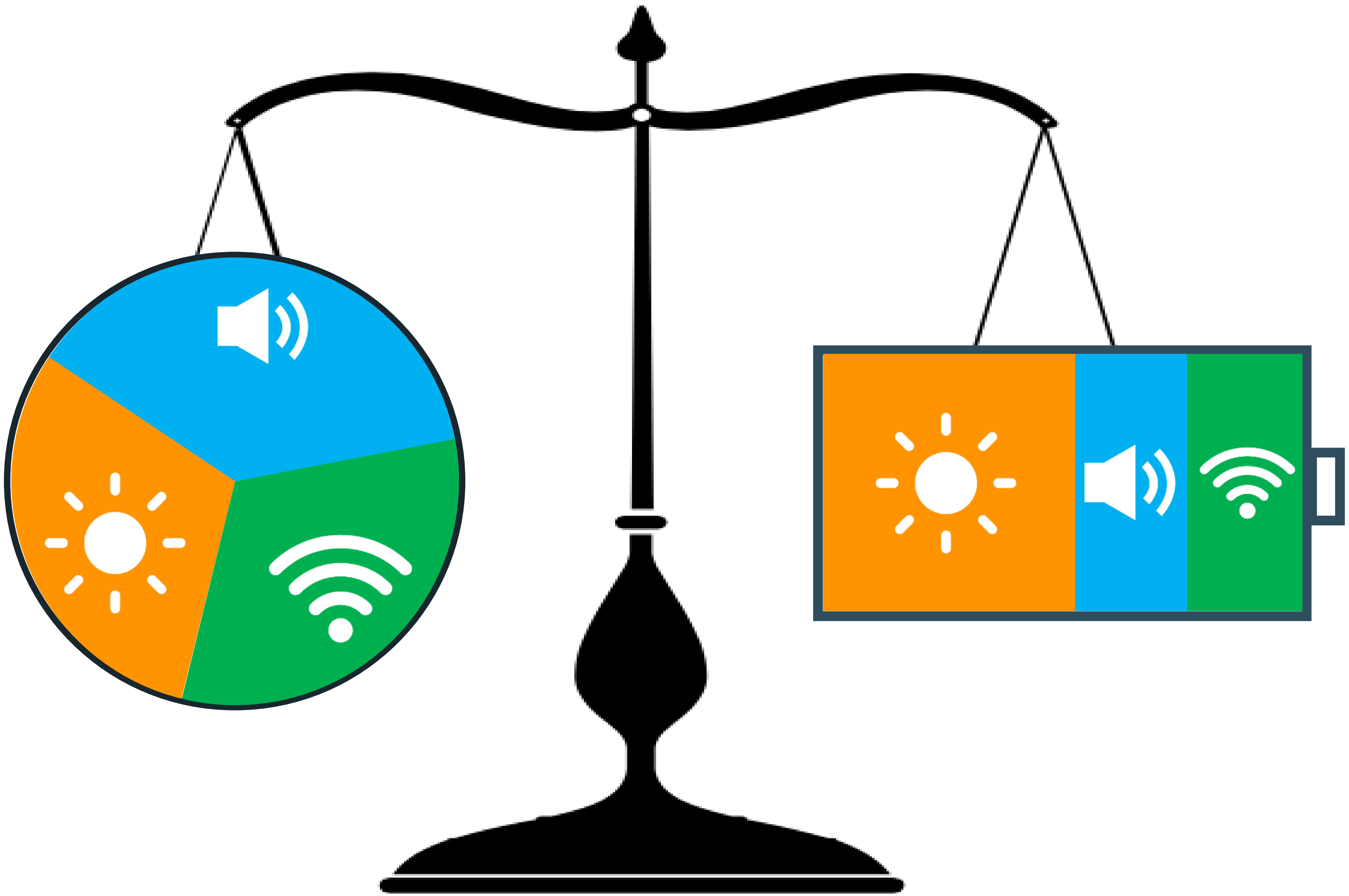
Sensors on bridges communicate to update their health

batteries eventually drain out

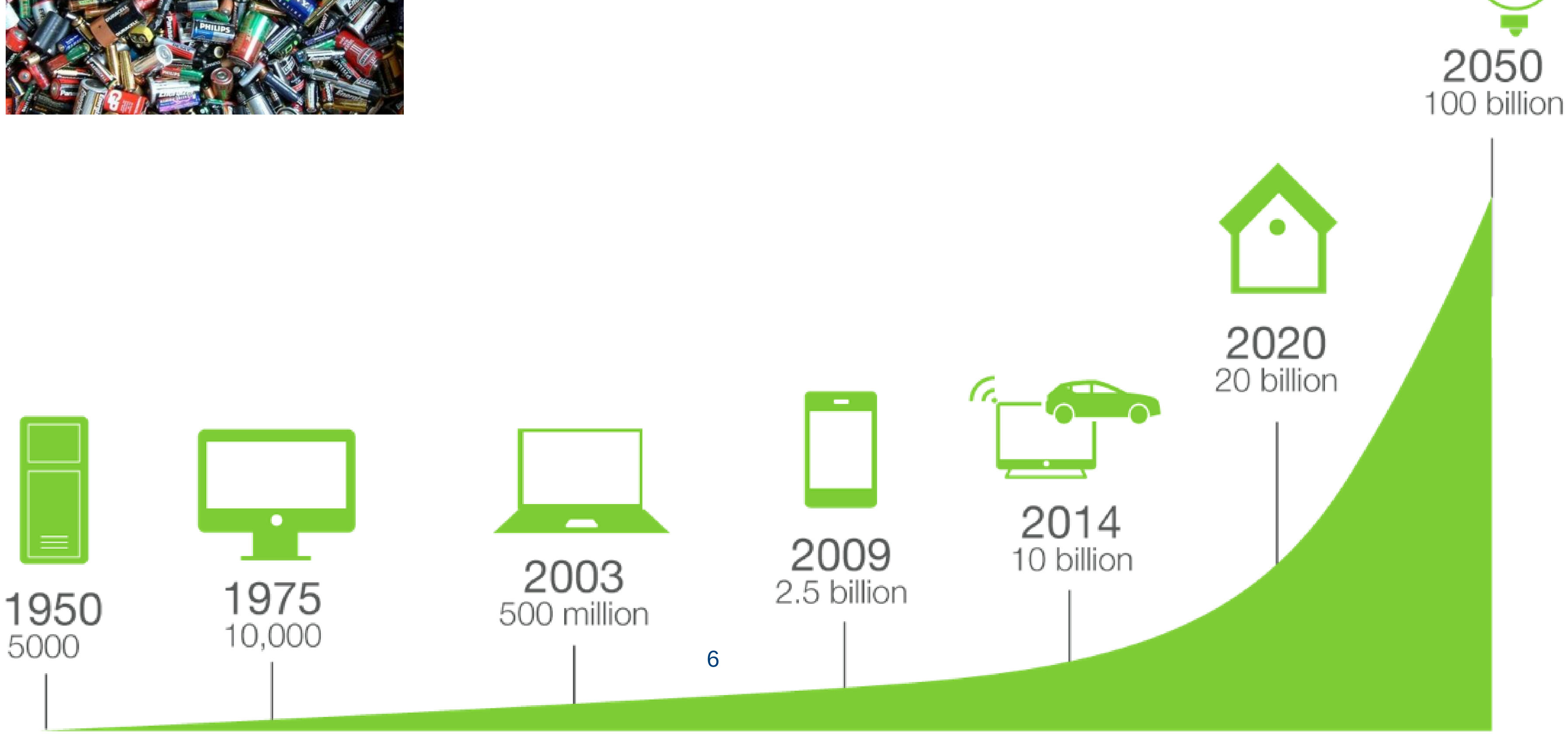


140
40
13
0,01
P [mW]
T [s]
Actions
Sleep
Sense
0,3 mJ
Rx
8 mJ
Tx
210 mJ

In balance?



Massive IoT: we'll need energy-neutral nodes.

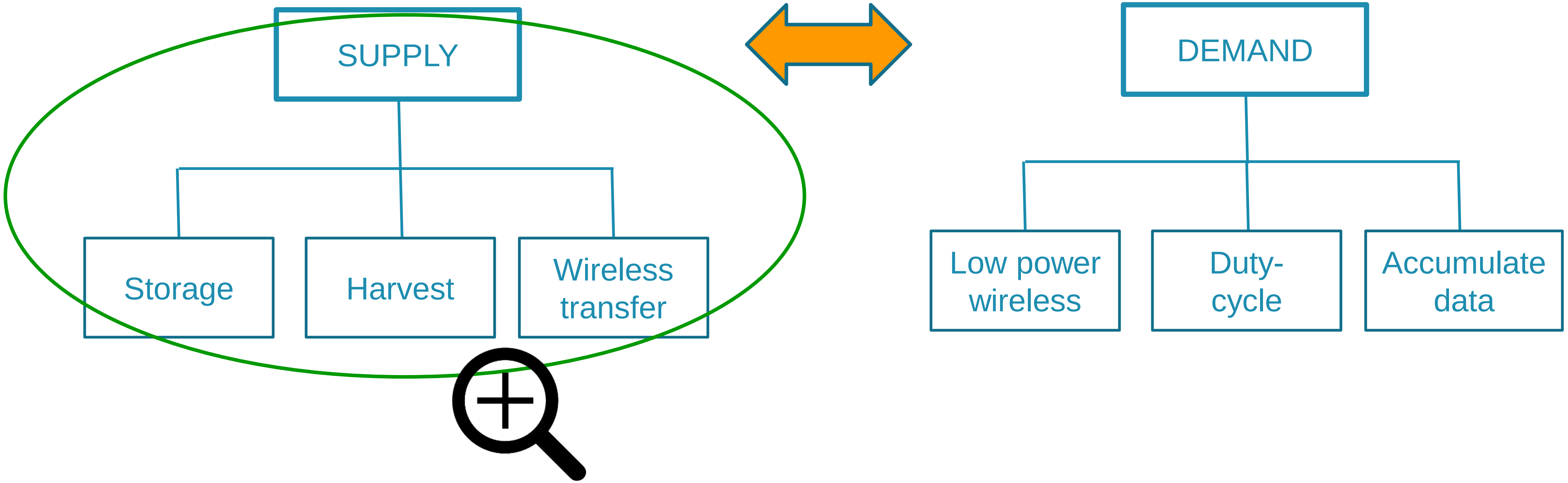


Connecting low power devices @ long range: technologies to make the balance work

1. Battery-powered devices: what is (not) possible?
   - Storage facilities: batteries and supercaps
   - Energy harvesting: options and limitations

2. Low Power Wide Area Networks (LPWAN): fit for purpose
   - What matters and the connectivity landscape for connecting things
   - Case Sigfox
   - Case LoRa

Autonomous wireless devices: mastering the supply - demand balance



Battery-powered devices: what is (not) possible?

April 16th 2018

Liesbet Van der Perre

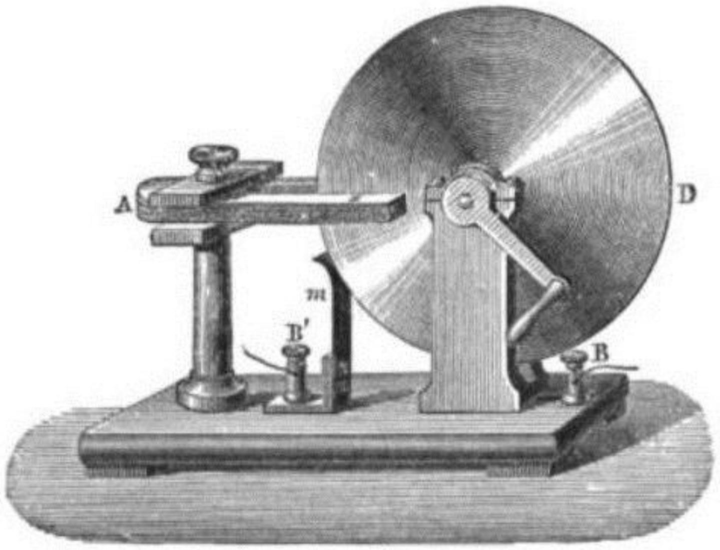
Electricity (electrical energy) provision: a little history

- 1799: Alessandro Volta invented the battery

- 1831: Michael Faraday invented dynamo principle

Batteries: world's first practical electricity source until the wiring of cities in the late 1800s!

Today: many situations require electricity without being wired to the grid (mobile/wireless devices, remote areas, …)



Energy supply: the options

- Batteries:
  - Considered the most viable solution for sensor nodes (with low power requirements, often deployed remotely)
  - Unfortunately, no matter how large the capacity of the battery or how efficient the protocols: batteries eventually drain out

- Harvesting:
  - Energy obtained (‘harvested’) from the environment
  - Transformed to electric (DC) power

- Transfer:
  - Near-field
  - Far-field: radio frequency transport

Energy storage:
Battery categories and popular items

- Primary: single use devices
  - can provide high density and low initial cost
  - when drained out: replacement only option if further operation of the device is required or desired

- Secondary (rechargeable): multiple use devices

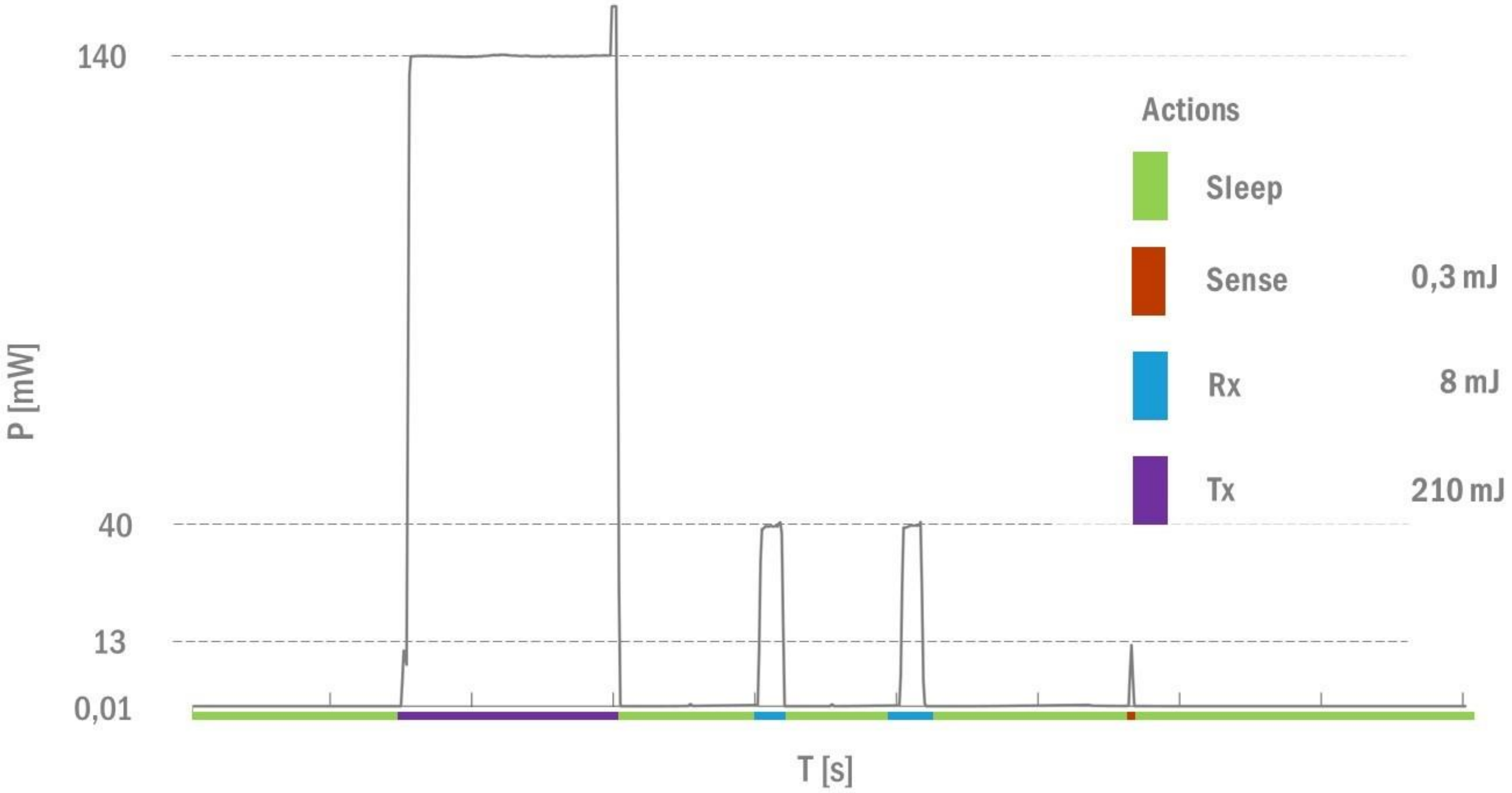
- Super-capacitor: allows fast and many recharges, embedded as stand-alone storage solution or in support of a battery

Selecting a battery:
which characteristics to consider?

- Battery capacity: C (mA.h) – battery life t (h)
  Consider average current *I* (mA) and duty cycle *n* (e.g. 2 min/hour):

$$t = \frac{C}{I.n}$$

- Voltage: nominal *and* stability
- Peak current delivery capability (potentially upgraded by super-cap)
- Life-time – self discharge
- Density: in terms of capacity/weight or capacity/volume
- Cost, ecological footprint, availability



~1V, ~150mAh

Transmit message 6/h?

Transmit message 2/day?

1/week + on demand?

Batteries: different capabilities from clever work with materials

champion in density (today)

Battery type	Vol. Energy density Wh/dm^3	Grav. Energy density Wh/kg	Self-discharge % per year	Cycle Life no.
Alkaline	300	125	4%	1
Ni-Cd	100	30-35	15-20%	300
Ni-MH	175	50	20%	300
Li-ion	200	90	5-10%	500

Popular, best-in-class, option: the lithium-ion battery

- Invented: first brought to market by Sony in 1991
- Lithium-ion batteries have significant advantages over nickel cadmium in terms of energy density, rapid recharging and cost.

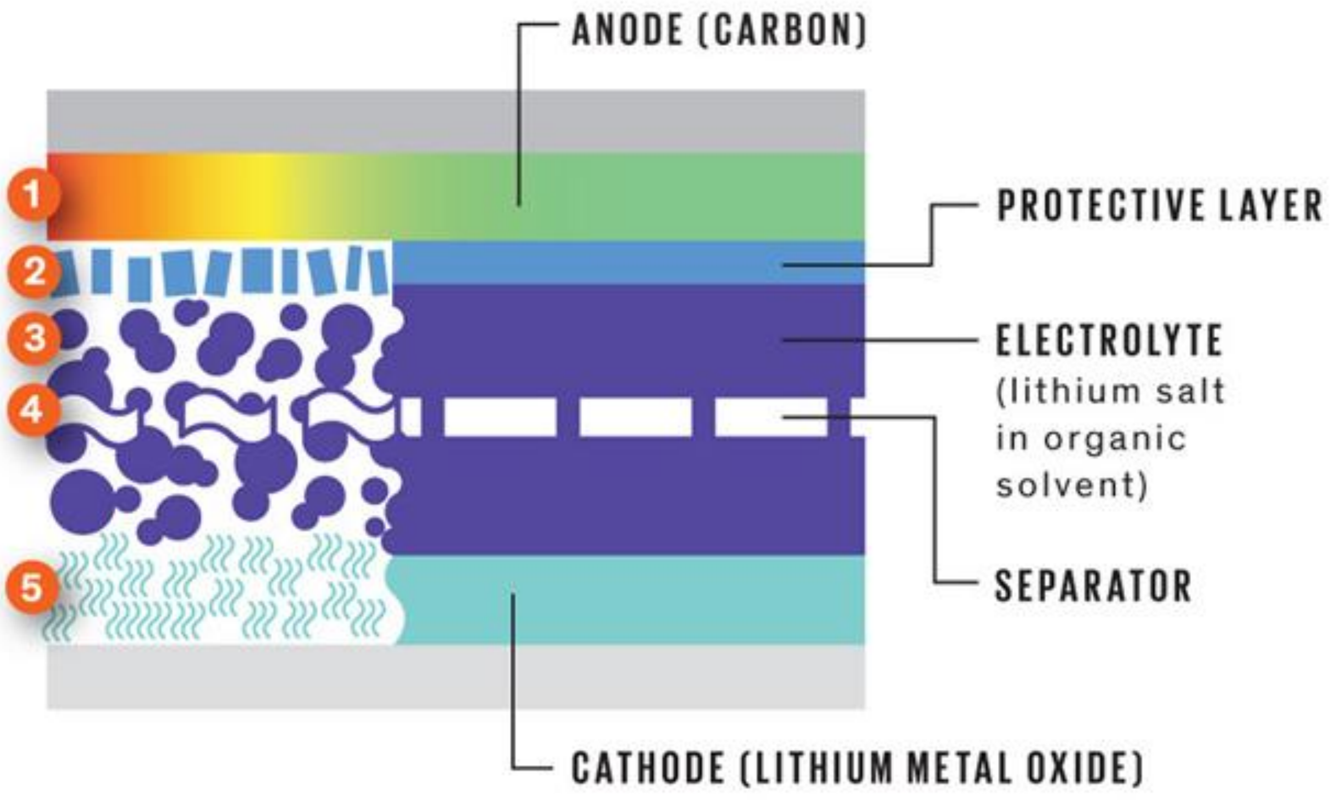
- However: Their chemistry and cell structure present a potential risk of fire (estimated one in a million to one in 50 million).




At the heart of the matter: thermal runaway

Thermal Runaway in a Lithium-Ion Battery

1. Heating starts.
2. Protective layer breaks down.
3. Electrolyte breaks down into flammable gases.
4. Separator melts, possibly causing a short circuit.
5. Cathode breaks down, generating oxygen.



Energy storage:
Battery categories and popular items

- Primary: single use devices
  - can provide high density and low initial cost
  - when drained out: replacement only option if further operation of the device is required or desired

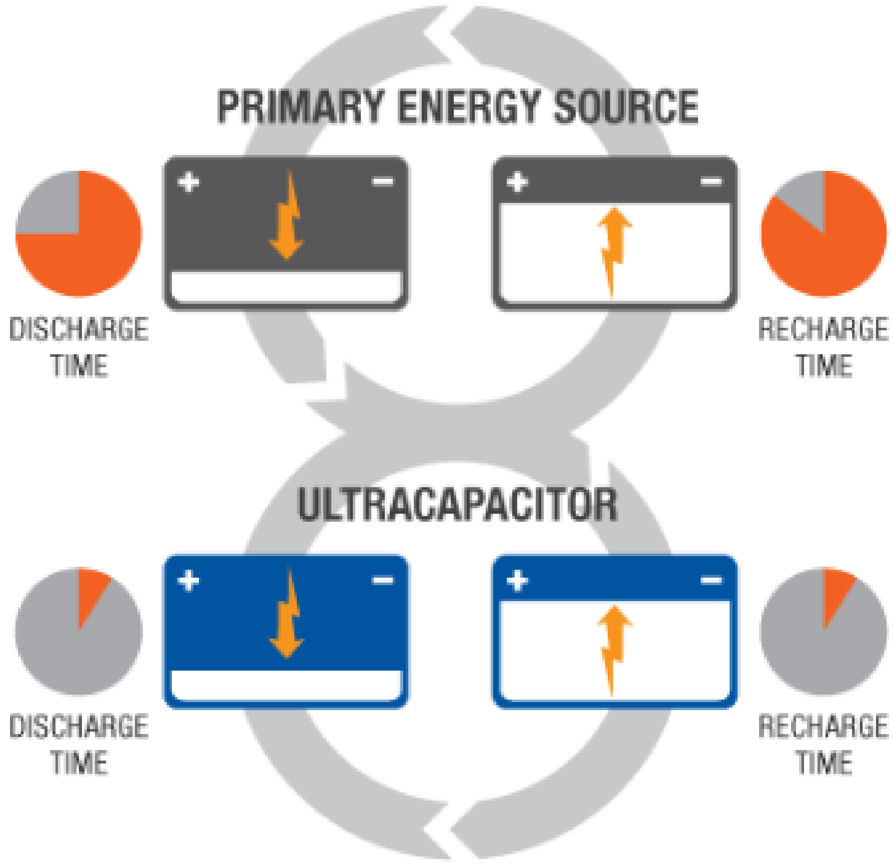
- Secondary (rechargeable): multiple use devices

- Super-capacitor: allows fast and many recharges,
  embedded as stand-alone storage solution or in support of a battery

Super- or ultra-capacitors: how they work

PRIMARY ENERGY SOURCES like internal combustion engines, fuel cells and batteries work well as a continuous source of low power. However, they cannot efficiently handle peak power demands or recapture energy in today's applications because they discharge and recharge slowly.

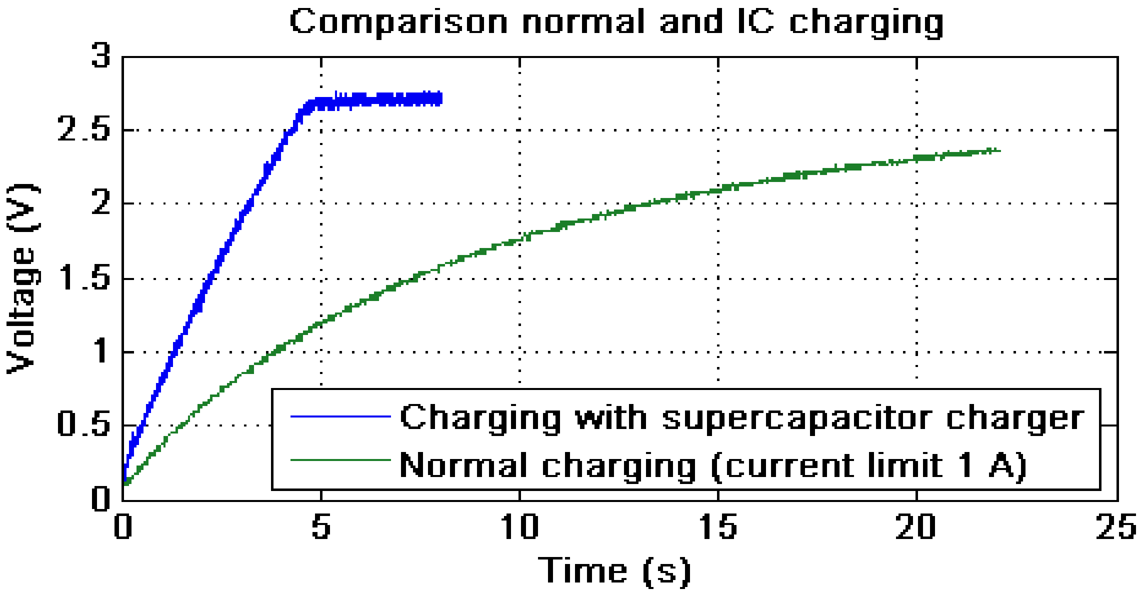
ULTRACAPACITORS deliver quick bursts of energy during peak power demands, then quickly store energy and capture excess power that is otherwise lost. They efficiently complement a primary energy source in today's applications because they discharge and recharge quickly.



Supercapacitor (de)charging: high current – high speed

Exemplary supercap:

- 3 F supercap
- Charging in < 5 seconds
- 38 patient measurements
- 81 hours standby



Energy supply: the options

- Batteries:
  - Considered the most viable solution for sensor nodes (with low power requirements, often deployed remotely)
  - Unfortunately, no matter how large the capacity of the battery or how efficient the protocols: batteries eventually drain out

- Harvesting:
  - Energy obtained (‘harvested’) from the environment
  - Transformed to electric (DC) power

- Transfer:
  - Near-field
  - Far-field: radio frequency transport

‘Free Electricity Folks’

The benefits of adequate energy harvesting solutions for embedded devices

- More active and longer time operation
- Potential full autonomy
- Less installation/wiring cost
- Eliminate service visits
- Ecological friendly (depending on type, reduce need for batteries)

Cost factors?

- Initial cost penalty is probable
- Considering total product lifetime: may reduce costs for many use cases
- Incentives (financial benefit/penalty?) for companies to provide long autonomy – ecological friendly products?

Energy harvesting: concept

- Retrieve energy from the environment
- Transform into adequate electrical supply
- Result: ‘self-powered’ devices
- Energy provision vs. consumption need:
  - Typically not aligned in time
  - Storage/conditioning solutions required

Consider the small movie,
What could (not) work?

Reference paper: Paradiso, J., Starner, T.
Energy scavenging for mobile and wireless electronics.
Pervasive Computing, IEEE 2005;**4**(1):18-27.

Classes of energy harvesting resources

Energy Source	Type of Energy
Human	Kinetic, Thermal
Environment	Kinetic, Thermal, Radiation

Counting on the human ('bearer'):
- active = ok
- passive = problematic

Of specific interest for personal and wearable devices

Specifies source energy
For these types
diverse techniques exist
to transform to electric energy

Options and their potential:
mind the significant differences

Table 3.4 A comparison of typical power sources for energy scavenging.

Energy source	Power density	Duration
Solar cell (direct sun light)	15 mW/cm^2	Continuous
Solar cell (well illuminated room)	10 $\mu W/cm^2$	Continuous
Piezoelectric	200 $\mu W/cm^3$	Operation (e.g. button push)
Temperature difference	40 $\mu W/cm^3$ / 5 °C	Continuous
Air flow	380 $\mu W/cm^3$ / 5 m/s	Continuous

Energy harvesting devices: how they look like

Prime candidate: the sun

Concept: radiation-based, photovoltaic effect

Production: ~ efficiency x area

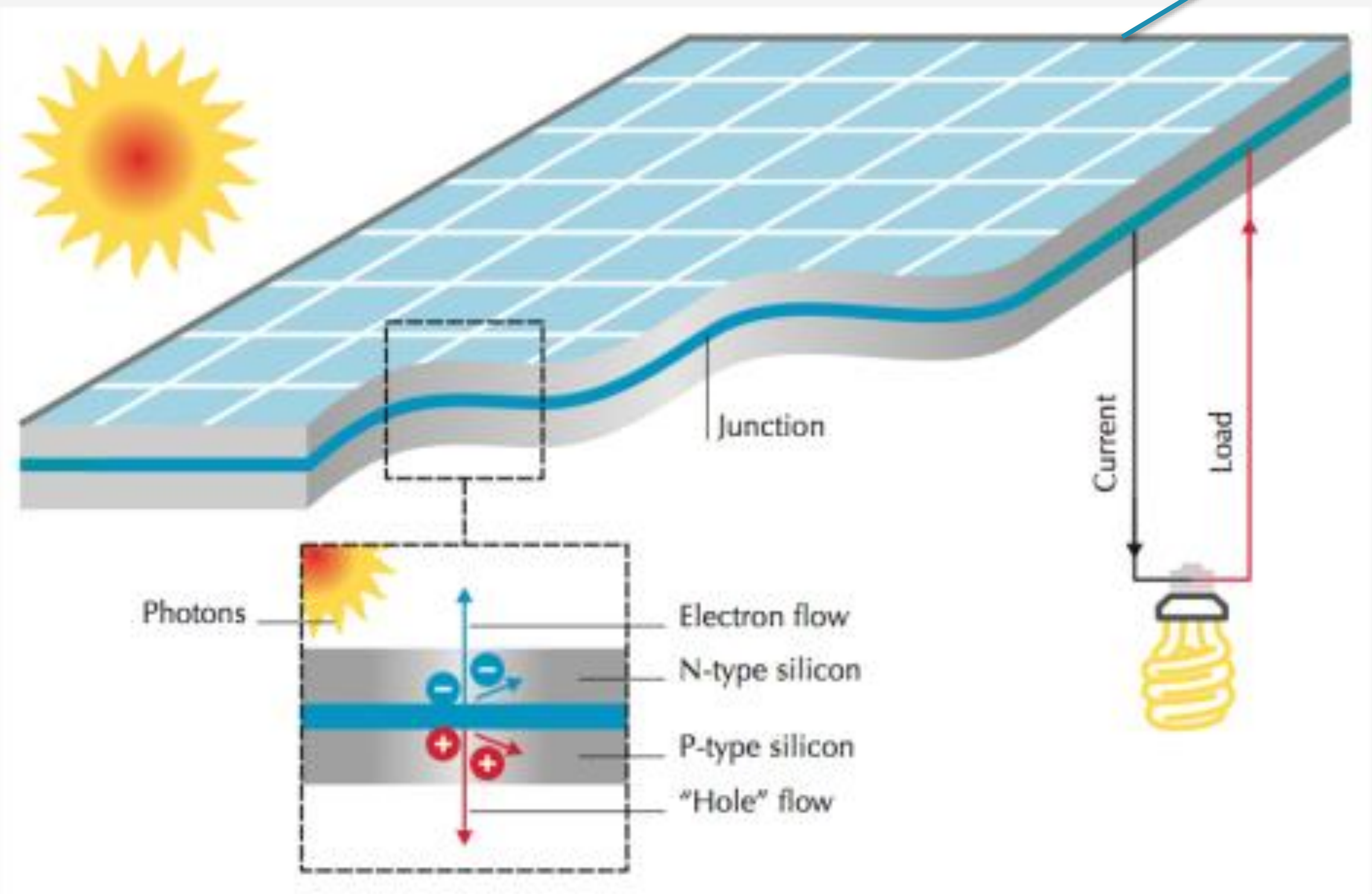
Efficiency: the portion of energy in the form of sunlight that can be converted via photovoltaic mechanism into electricity

- up to ~ 40% (based on complex semiconductor materials)
- Silicon-based: best in class – world record 26,6% (March 2017, theory says max ~29%)
- typical good ~20%

Area: typically very constraint in/for/on embedded systems

A conventional semiconductor PV system is based on crystalline silicon

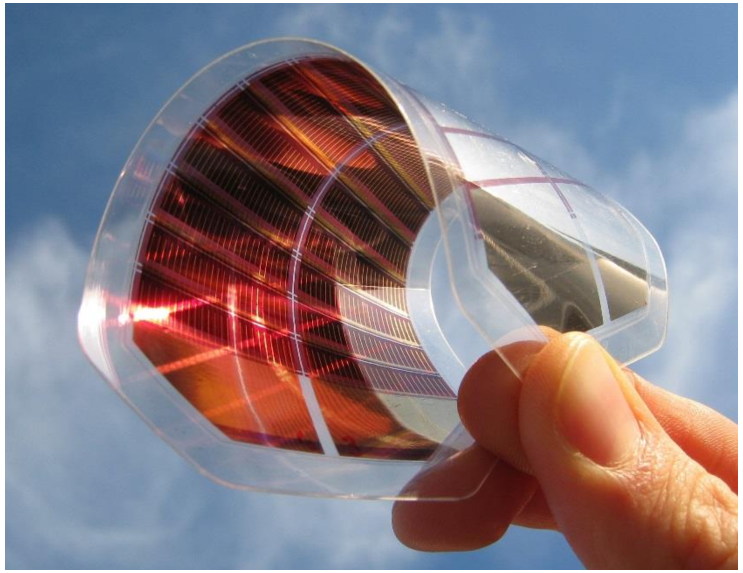
anti-reflective coating



A schematic illustration of a basic silicon photovoltaic cell. Figure taken from Solar Energy Perspectives, 2011, IEA.

Organic solar cells: interesting alternative?

- Advantages:
  - Low cost production
  - Flexible
  - Light-weight
  - Potentially disposable
  - Potentially printable electronics
  - Smaller ecological footprint!



- Shortcomings: efficiency significantly lower than semiconductor counterparts, gaining maturity
- www.heliatek.com: We hold the world record of 13,22% cell efficiency for opaque (non-transparent) organic solar cells. In production, we achieve 7-8 %. The latest development allows transparency levels up to 30% with an efficiency of 6%.

Energy supply: the options

- Batteries:
  - Considered the most viable solution for sensor nodes (with low power requirements, often deployed remotely)
  - Unfortunately, no matter how large the capacity of the battery or how efficient the protocols: batteries eventually drain out

- Harvesting:
  - Energy obtained (‘harvested’) from the environment
  - Transformed to electric (DC) power

- Transfer:
  - Near-field
  - Far-field: radio frequency transport

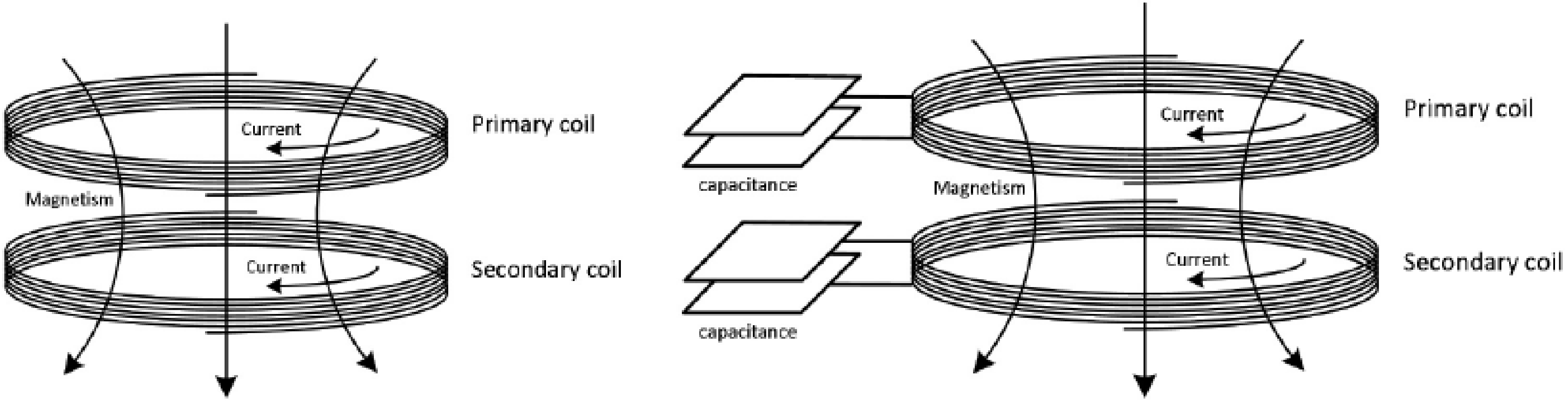
Wireless power transfer: two main directions of developments

1. Coupling-based:
   - Work on the near-field
   - Limited distance d (attenuation ~ d^{-3} and load impacts transmitter)

2. Radiation-based:
   - Transferred using Radio Frequency (RF) waves, far-field technique (attenuation ~ d^{-2})
   - Based on electric field of electromagnetic wave
   - Mostly low power (efficiency & exposure - safety)

© X. Lu, et Al, “Wireless Charging Technologies: Fundamentals, Standards, and Network Applications”, IEEE communication surveys & tutorials, Vol. 18.2, 2016

Coupling based power transfer: inductive and magnetic options



(a) Inductive Coupling

(b) Magnetic Resonance Coupling

cm’s up to 90% efficient
– 20cm few % efficient

dm’s up to 1m, up to 90% efficient

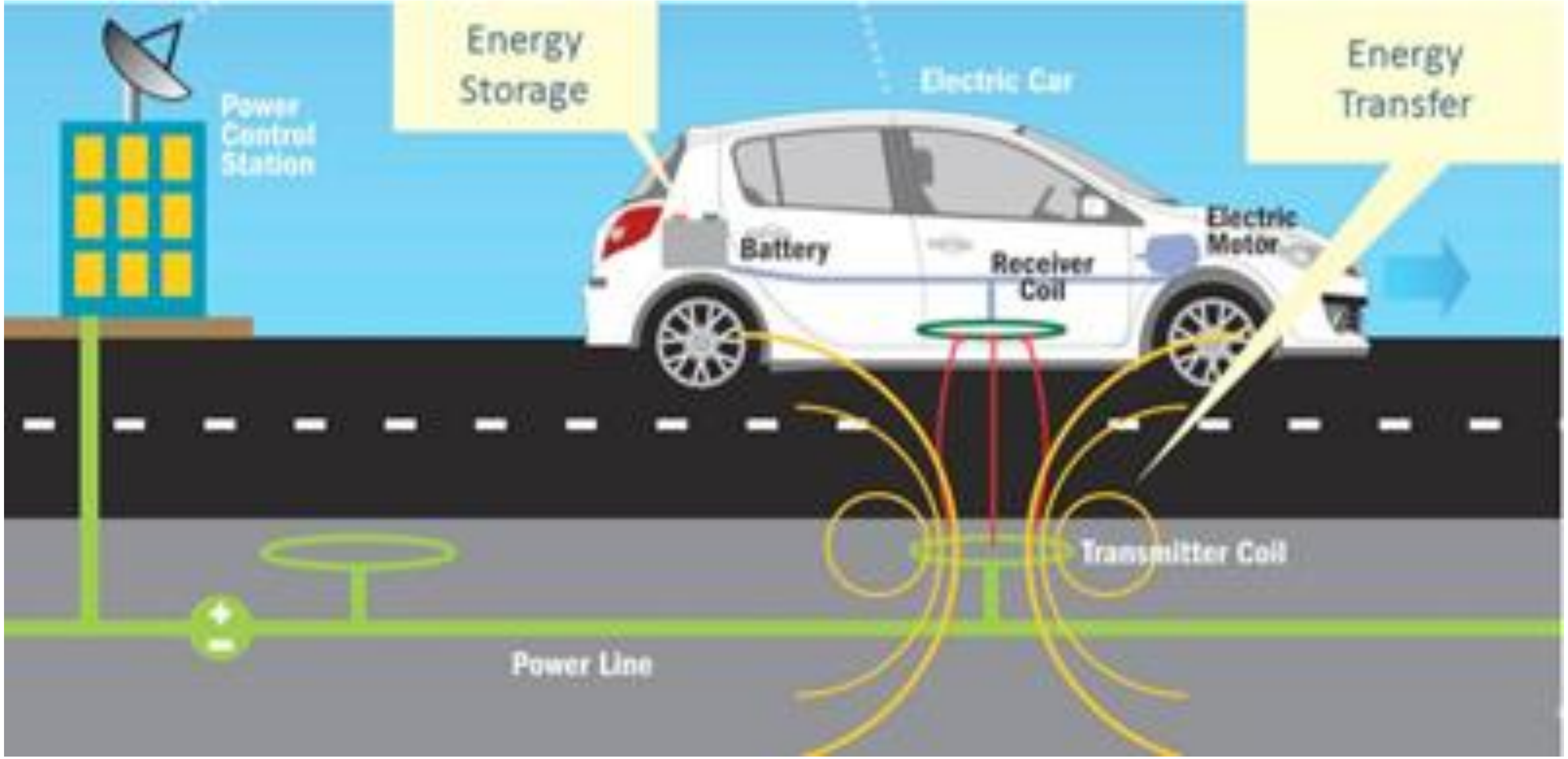
COUPLING is essential in near field transfer

Works both ways:
absorption of energy INFLUENCES the load on the transmitter

Applications of IPT and MPT

- Home appliances e.g. electrical toothbrush
- Mobile devices (e.g Smartphones)
- RFID
- Medical implants
- > kWatt:
  - industrial automation: Robots
  - Vehicles

‘Wireless power could revolutionize highway transportation’



Handy for personal devices – note the coil

A popular standard: Qi

Popping up in hotspots

Getting integrated in furniture

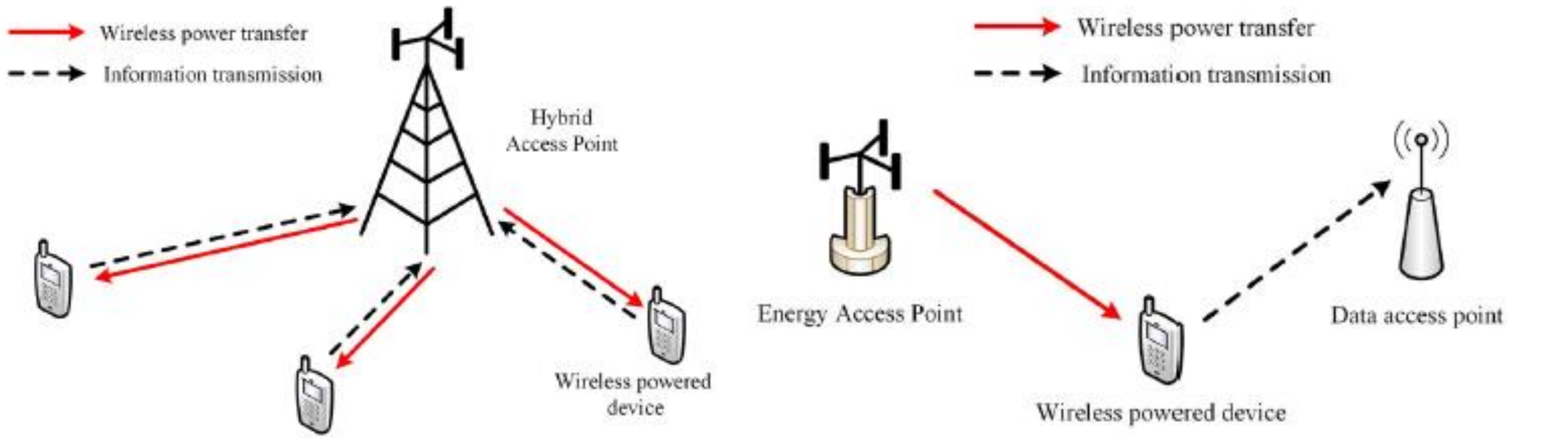
Energy provision: the options

- Batteries:
  - Considered the most viable solution for sensor nodes (with low power requirements, often deployed remotely)
  - Unfortunately, no matter how large the capacity of the battery or how efficient the protocols: batteries eventually drain out

- Harvesting:
  - Energy obtained (‘harvested’) from the environment
  - Transformed to electric (DC) power

- Transfer:
  - Near-field: coupling
  - Far-field: radio frequency transport

Wireless Powered Communication Network (WPCN) different architectural options

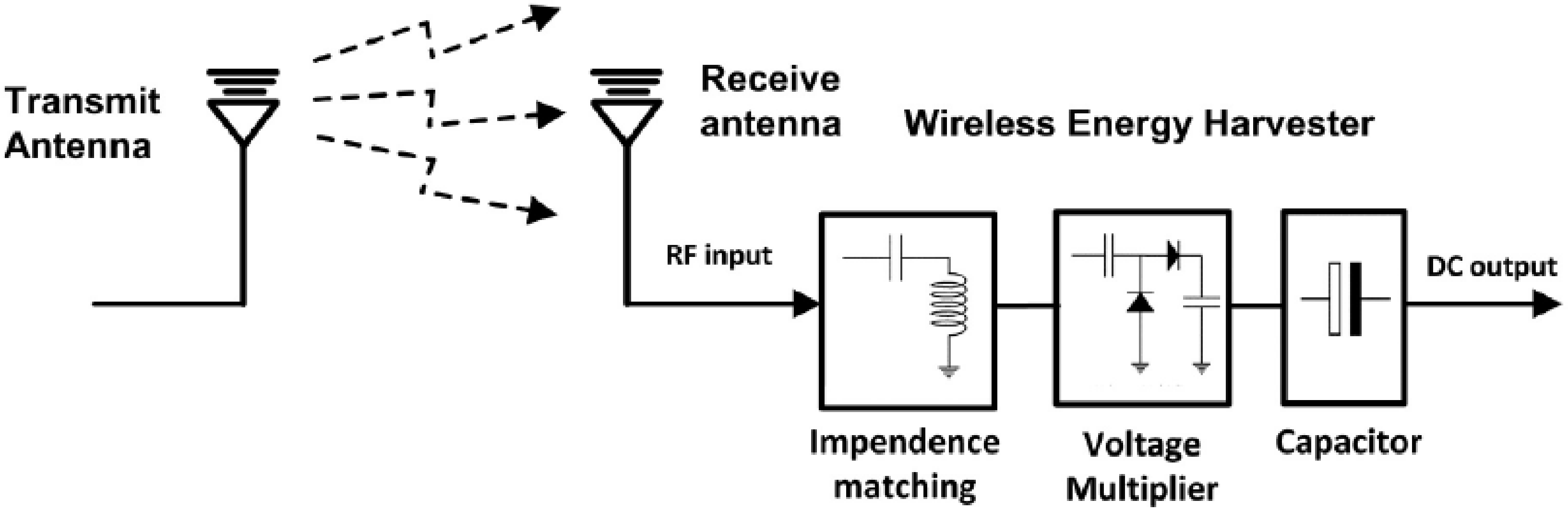


(a) Wireless powered communication Network with hybrid access point

(b) Wireless powered communication Network with separated energy access point and data access point

More options include relays, access points and stations with multiple antennas

RF-based wireless power transfer: concept



2 options:

- non-directive RF radiation: do not need Line-of-Sight, not very sensitive to antenna orientation, limited energy transfer
- directive RF beamforming

Special species: Instead of relying on dedicated wireless charger, charging based on ambient energy harvesting (e.g. from RF broadcasting signals)

Simultaneous Wireless Information and Power Transfer (SWIPT): a working combination?

- Concept:
  - Information in amplitude and/or phase of the wave
  - Energy transfer via vibration/radiation

- Efficiency in practice?
  - Large arrays/smart antennas favorable (or needed) at both side
  - Feasible for remote wake-up of nodes/devices

Overall status wireless RF-based power transfer:

- Popular R&D topic
- Practical experiments rather limited
- Option for waking up devices, more: to be confirmed
- No standards available (yet)

Energy/power provision of wireless devices: conclusions – lessons learned?

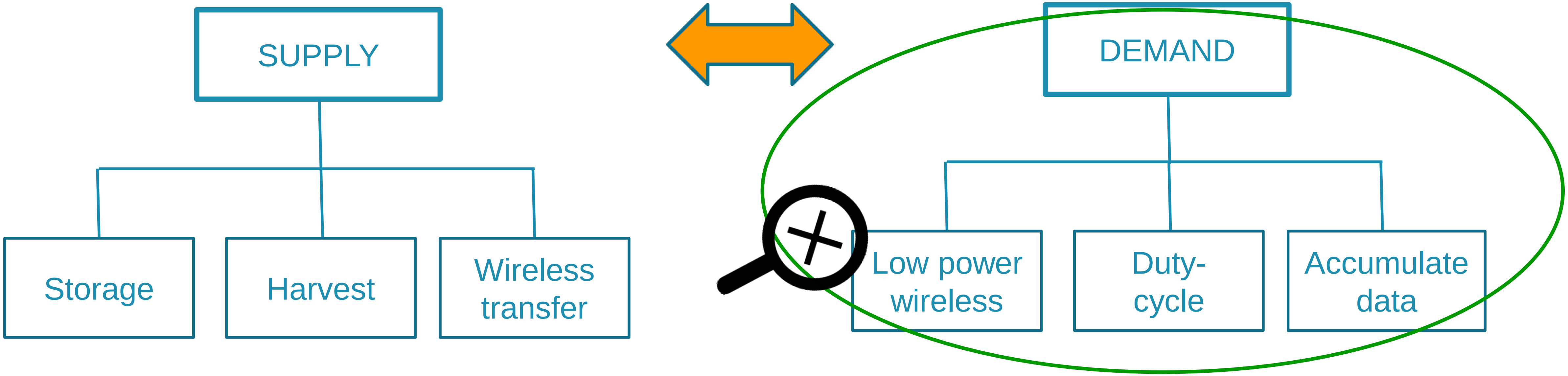
- There’s no one-fits-all solution! Adapt the solution to the application and service (lifetime)

- Energy harvesting may be a dream come true, where applicable and reliable

- Stay tuned for evolutions and new technological solutions

- Consider both sides of the balance: power consumption and management! -> next course topic

Autonomous wireless devices: mastering the supply - demand balance



Computation-communication trade-offs: silence is often gold

Early data reduction

Redundancy removal

Processing: nJ/operation scaled down with technology innovation

Communication: physics rule, attenuation typically ~ d^2 (and worse)

Low Power Wide Area Networks

How to overcome the dilemma?

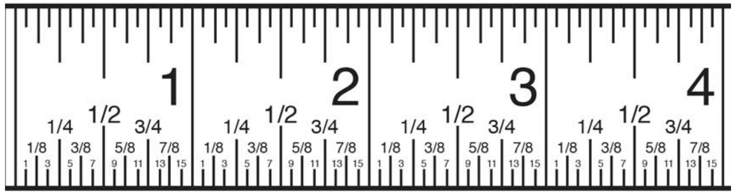
April 16th 2018

Liesbet Van der Perre


"POWER" [dBW]
Gain
Loss
$G_{TX|dB}$
$L_{free|dB}(d)$
$= 20\log_{10}\frac{4\pi d}{\lambda}$
$P_{TX|dBW}$
$P_{RX|dBW}$
$G_{RX|dB}$
Low Power
Wide Area


ONE-SIZE FITS ALL
STORE
SALE

Selecting an appropriate connectivity solution: what matters? Technical functional specifications



- Range: home – local area – wide area?
- Data rate – up and/or downlink
- Mobility
- Latency (~response time): maybe crucial for safety-critical control operations

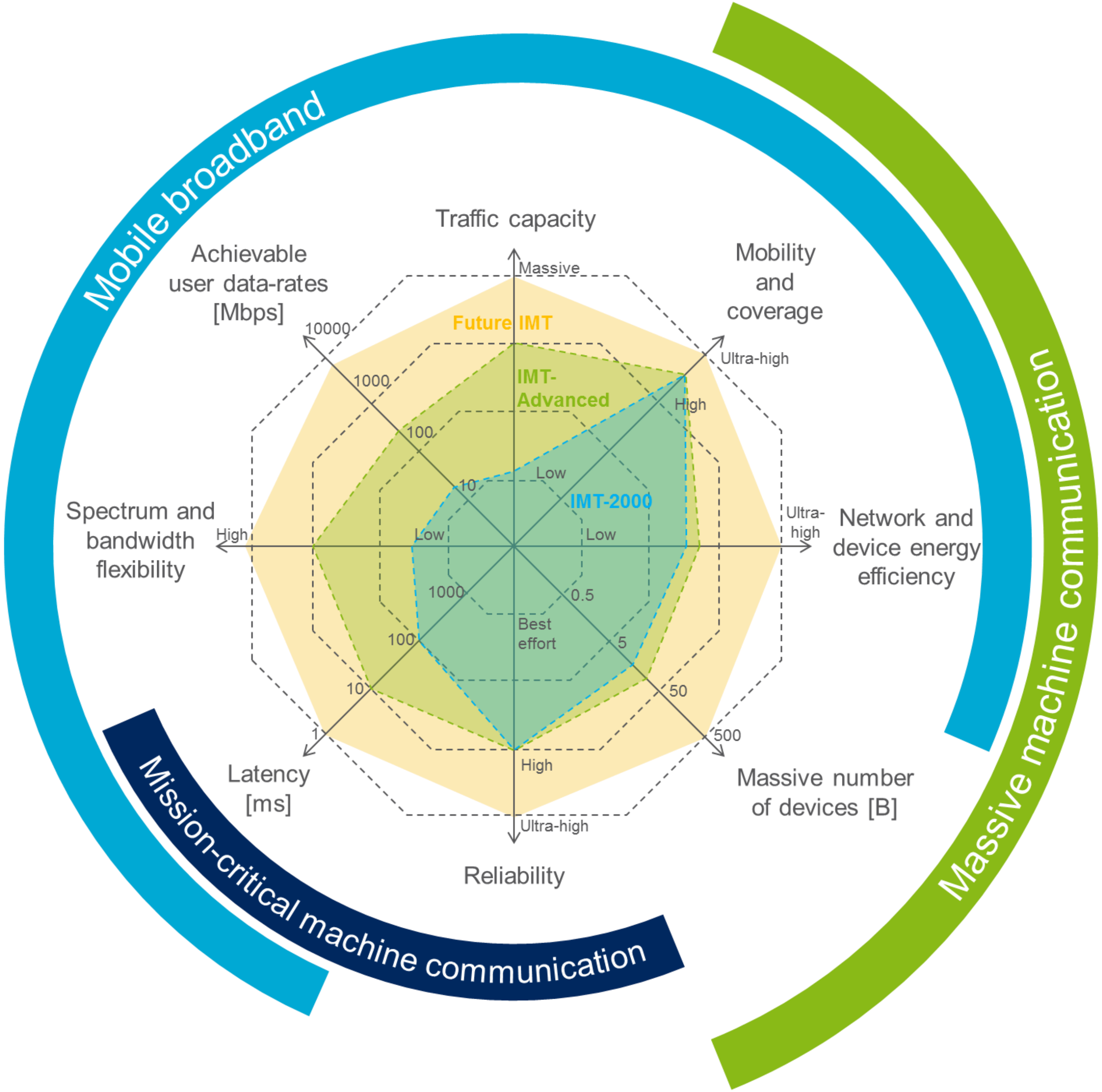
- Interference:
  - Has become non-negligible: number of wirelessly connected devices large and expected to grow steadily over the next years!
  - Especially in unlicensed bands and in open environments
  - Feature = difficult to predict and control

- Reliability: %’s or 0.000x%’s?

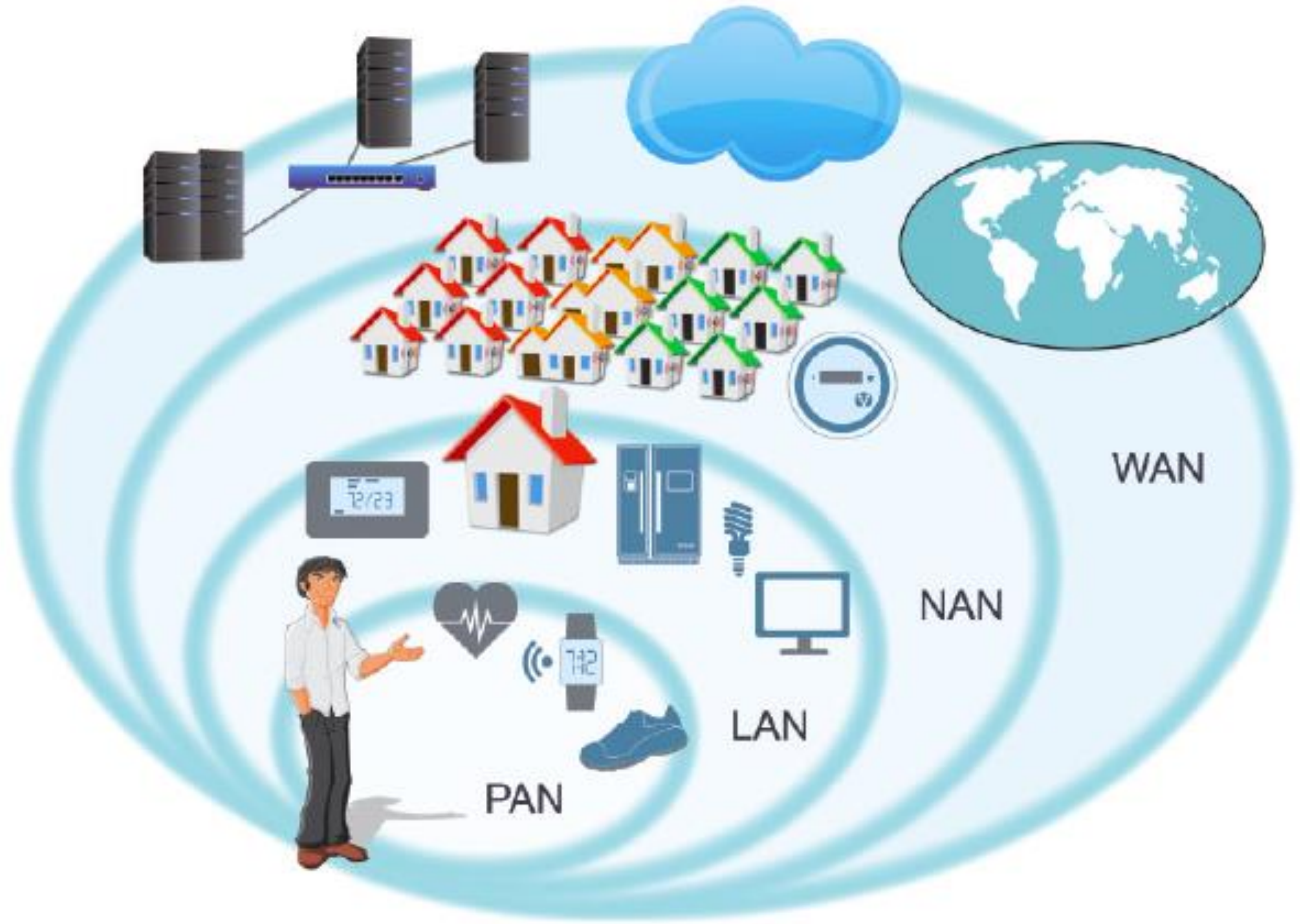
Selecting an appropriate connectivity solution: what matters? Technical non- functional specs

- Power options vs. autonomy requirements:
  - Grid power or battery?
  - Chargeable (e.g. outdoor solar cell – basement - …)?
  - How accessible (for battery replacement)?

- Integration and environmental aspects:
  - Size/weight
  - Outdoor/indoor – humidity – radiation - …
  - Design - esthetics?


Mobile broadband
Massive machine communication
Mission-critical machine communication
Traffic capacity
Massive
Mobility
and
coverage
Ultra-high
High
Achievable
user data-rates
[Mbps]
10000
1000
100
10
Future IMT
IMT-
Advanced
IMT-2000
Low
Spectrum and
bandwidth
flexibility
High
Low
Network and
device energy
efficiency
Ultra-
high
Low
1000
100
10
1
Latency
[ms]
Best
effort
High
Ultra-high
Reliability
0.5
5
50
500
Massive number
of devices [B]

Connecting things to the Internet: networks can be classified upon covered area



Personal
Local
Neighborhood
Wide

Area **N**etwork

http://thesedays.com/thoughts/understanding-connectivity-for-internet-of-things

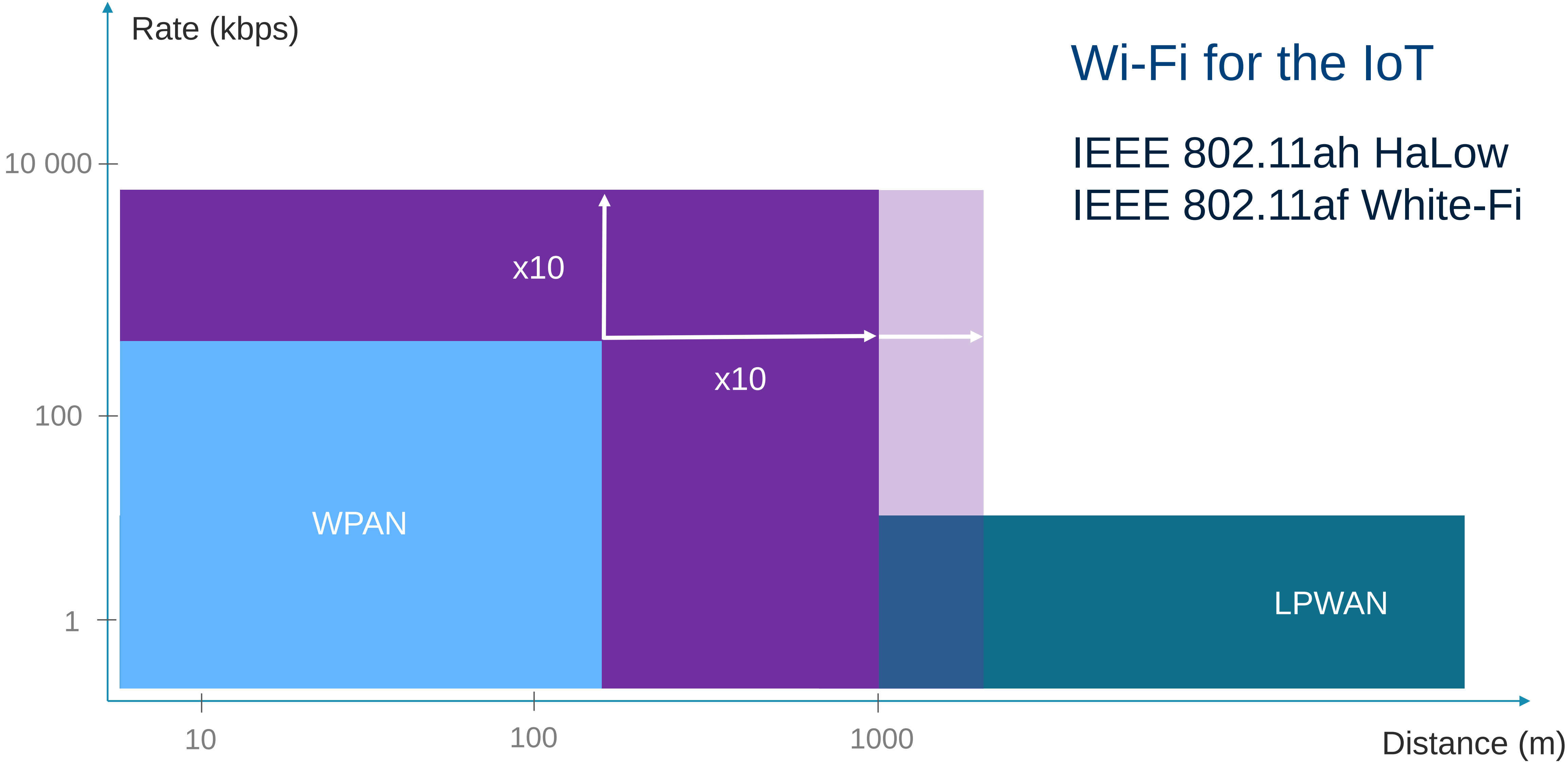
802.11 ah/af

Wi-Fi for the IoT

‘White-Fi’ – ‘Super Wi-Fi’

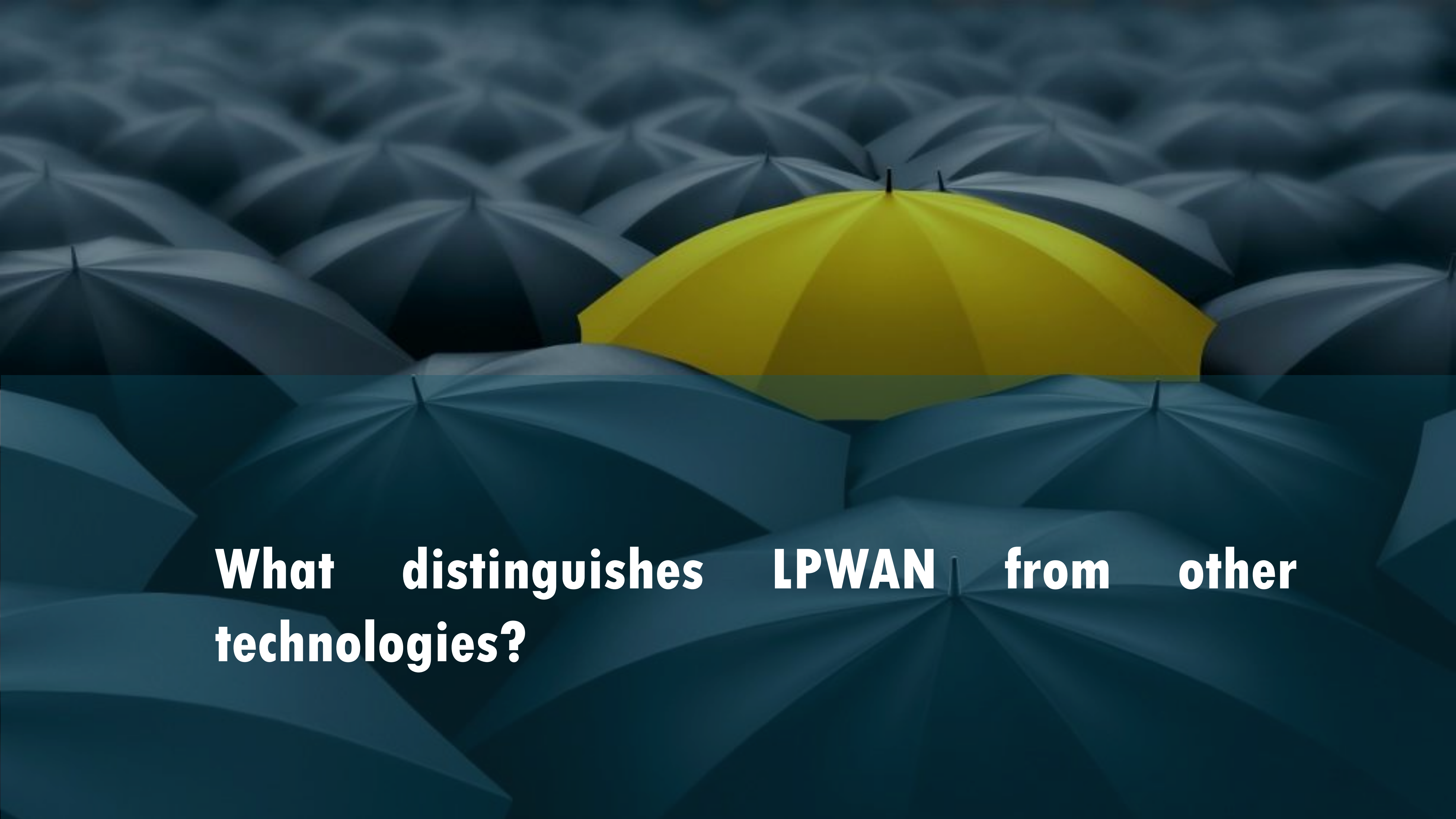
Wi-Fi for the IoT

IEEE 802.11ah HaLow
IEEE 802.11af White-Fi



LPWAN Technologies

Met dank aan Gilles Callebaut
gilles.callebaut@kuleuven.be



What distinguishes LPWAN from other technologies?

Cost

Mostly unlicensed spectrum (ISM bands)
Low chip and subscription cost

Data Rate

Simple coding
→ low data rate, low cost, low power

Energy

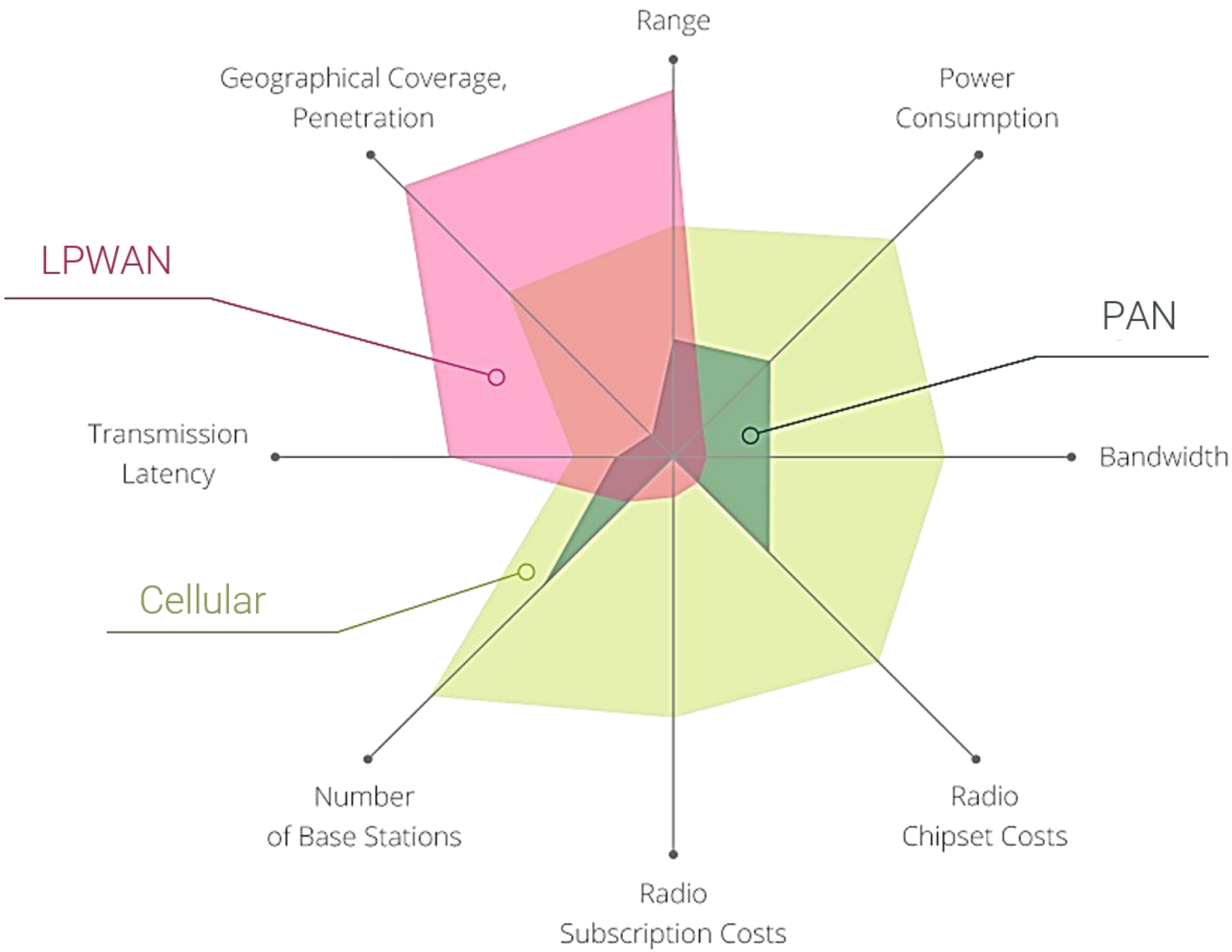
Reduce *radio on time*
Device induced communication, sleep, low data

Coverage

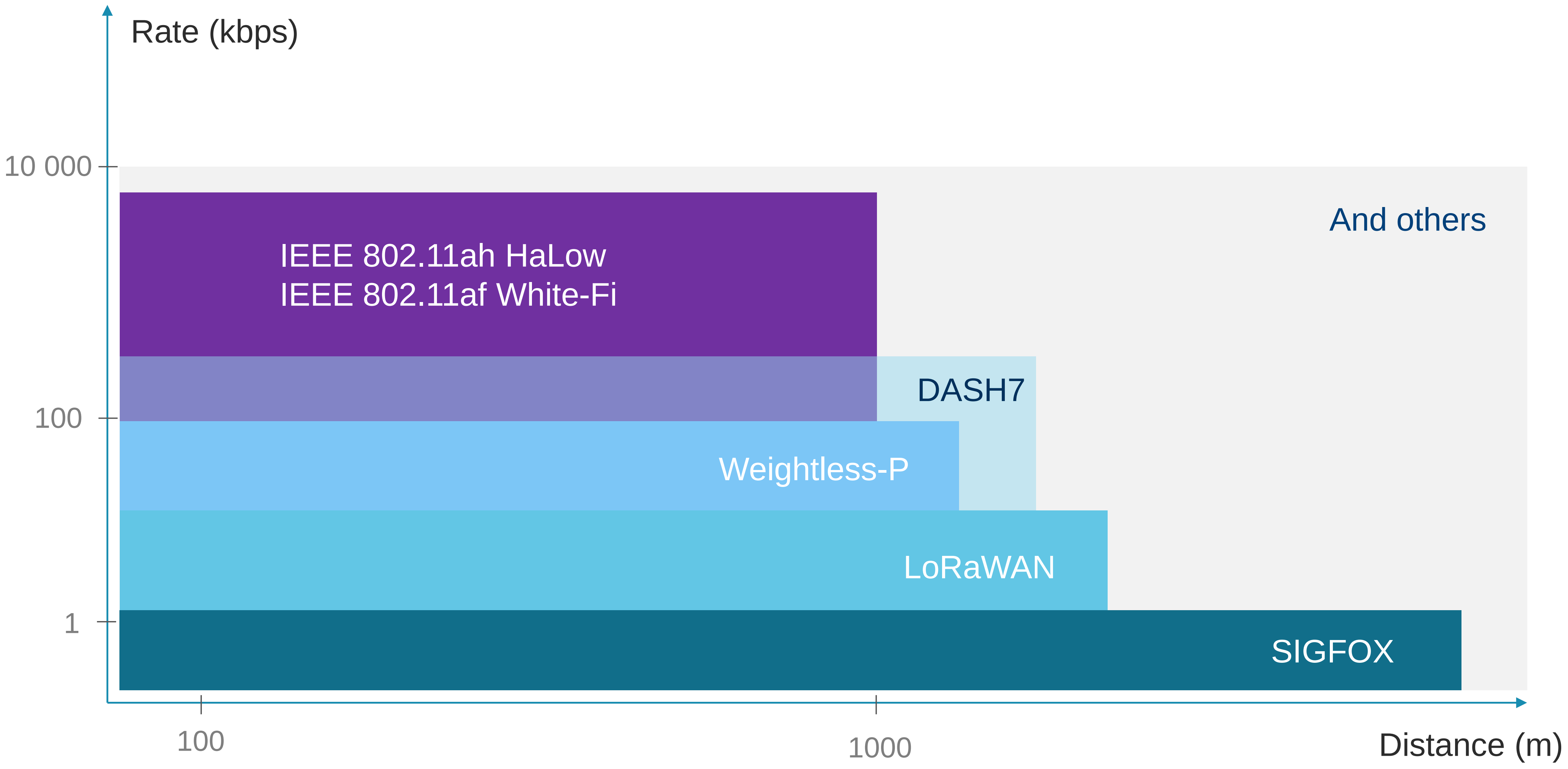
Lower frequency bands (i.e. sub-GHz)

Topology

Predominantly single hop star-of-stars topology
Easy deployment → low installation and maintenance cost


Range
Geographical Coverage,
Penetration
Power
Consumption
LPWAN
PAN
Transmission
Latency
Bandwidth
Cellular
Number
of Base Stations
Radio
Chipset Costs
Radio
Subscription Costs

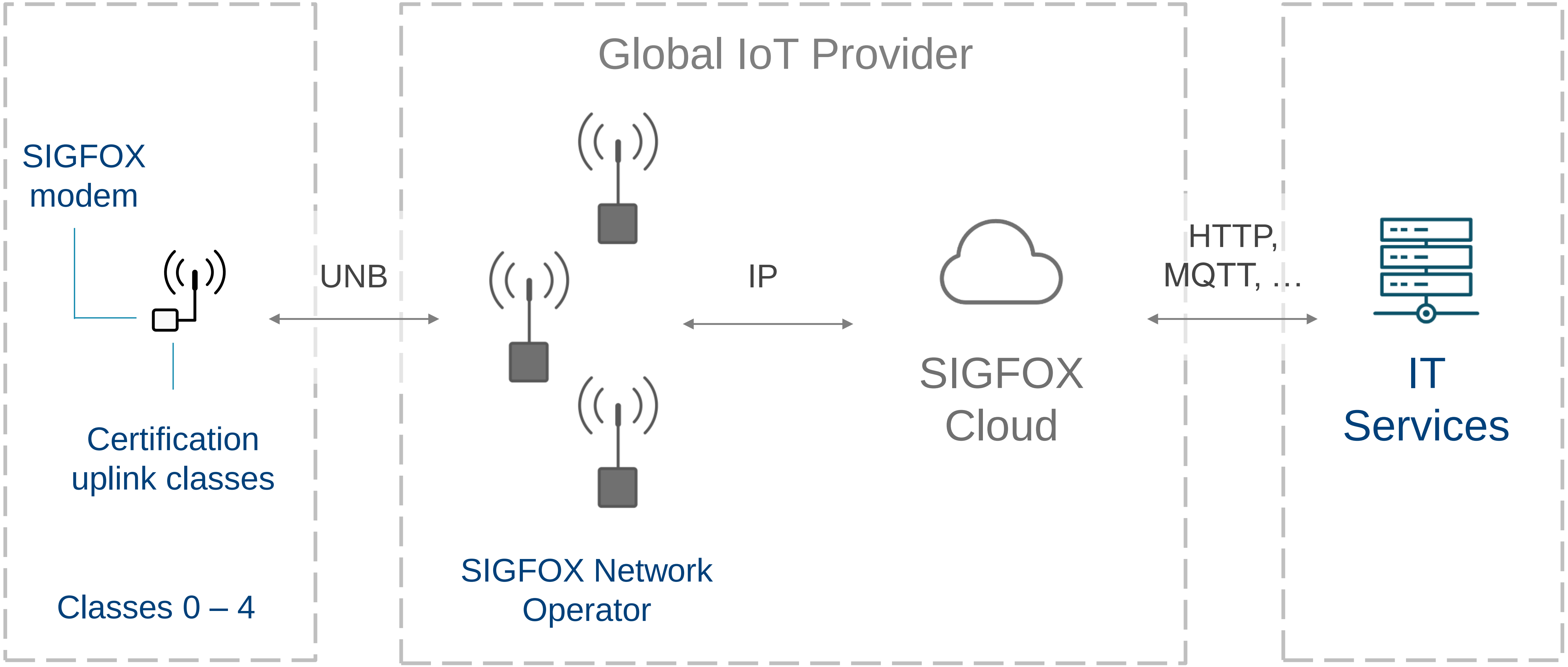
LPWAN Landscape


Rate (kbps)
10 000
100
1
IEEE 802.11ah HaLow
IEEE 802.11af White-Fi
And others
DASH7
Weightless-P
LoRaWAN
SIGFOX
100
1000
Distance (m)

SIGFOX

Global IoT Provider

SIGFOX: how things communicate in a service



SIGFOX

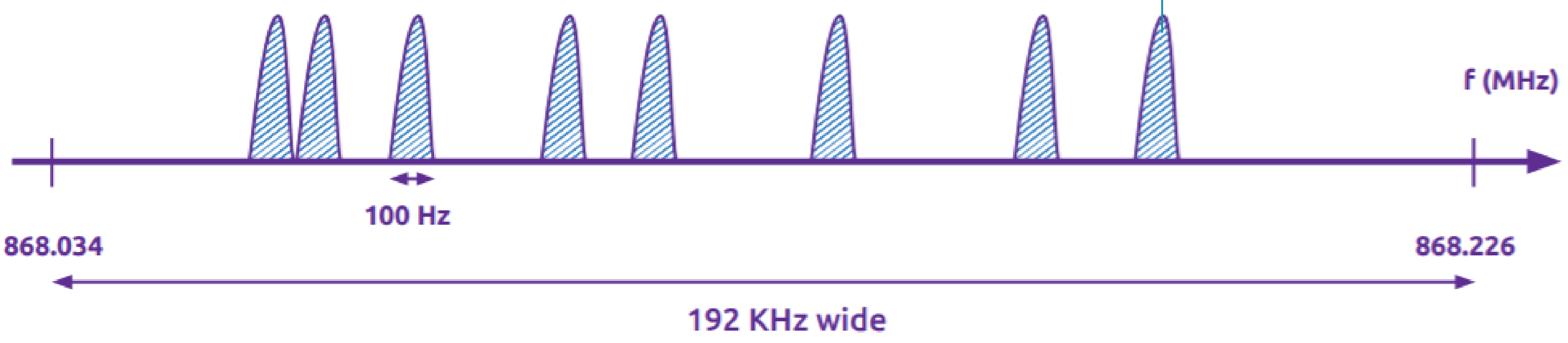
Radio Technology – UL (EU)

@ 100bps

140 msg/day

Payload 12 bytes
Frame 24 bytes

UNB DBPSK

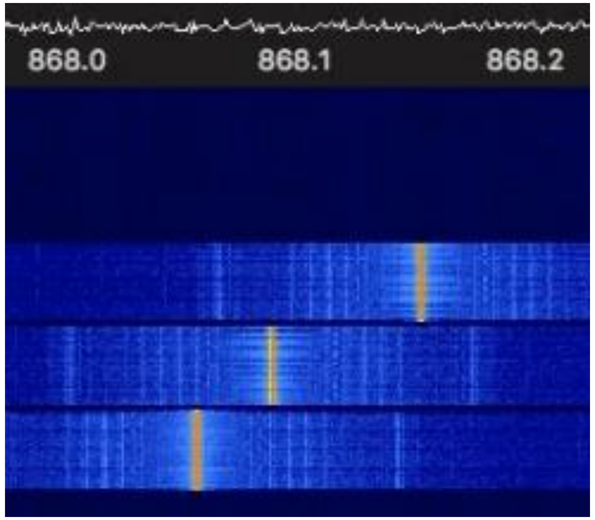


SIGFOX

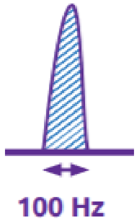
Very lean, yet scalable

SIGFOX

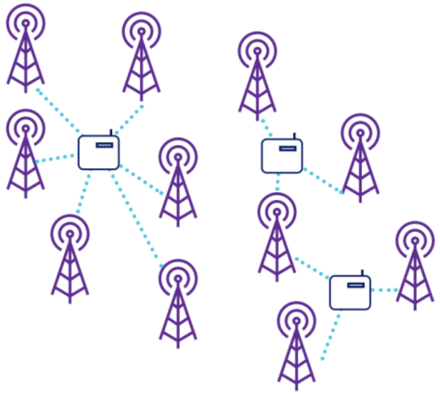
Radio Technology – UL (EU)



Time Diversity
Frequency Diversity
R-FDMA



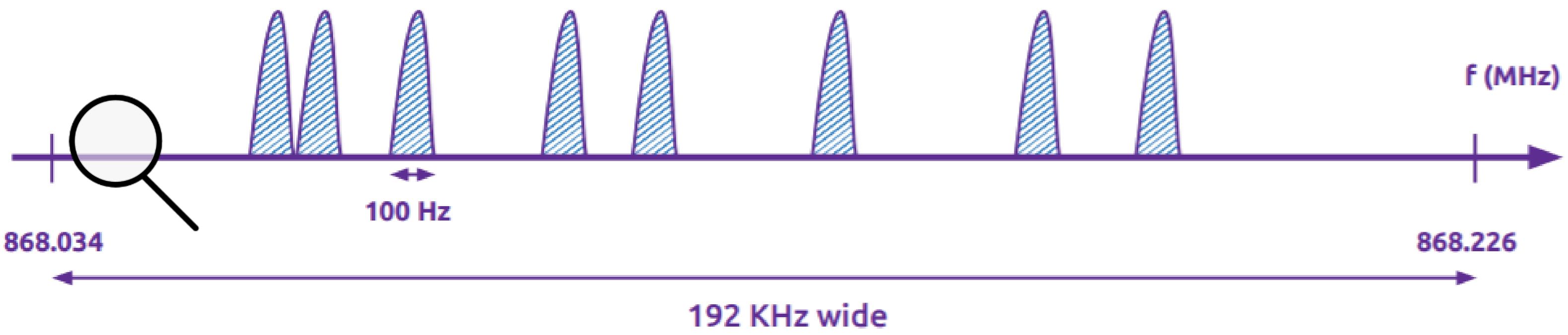
UNB



Space Diversity

SIGFOX

Radio Technology – DL: initiated by the object (EU)



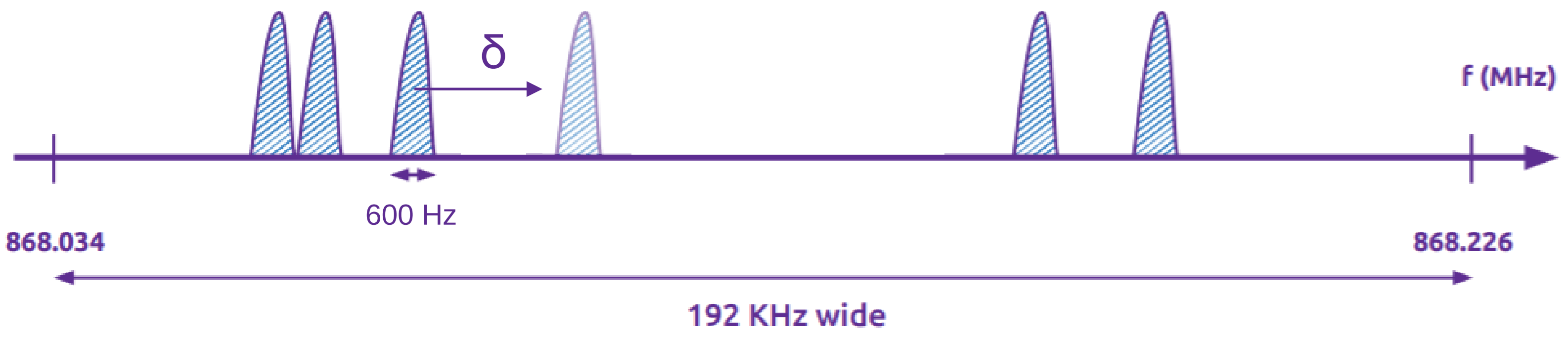
SIGFOX

Radio Technology – DL (EU)

GFSK @ 600bps

4 msg/day/device

Payload 8 bytes

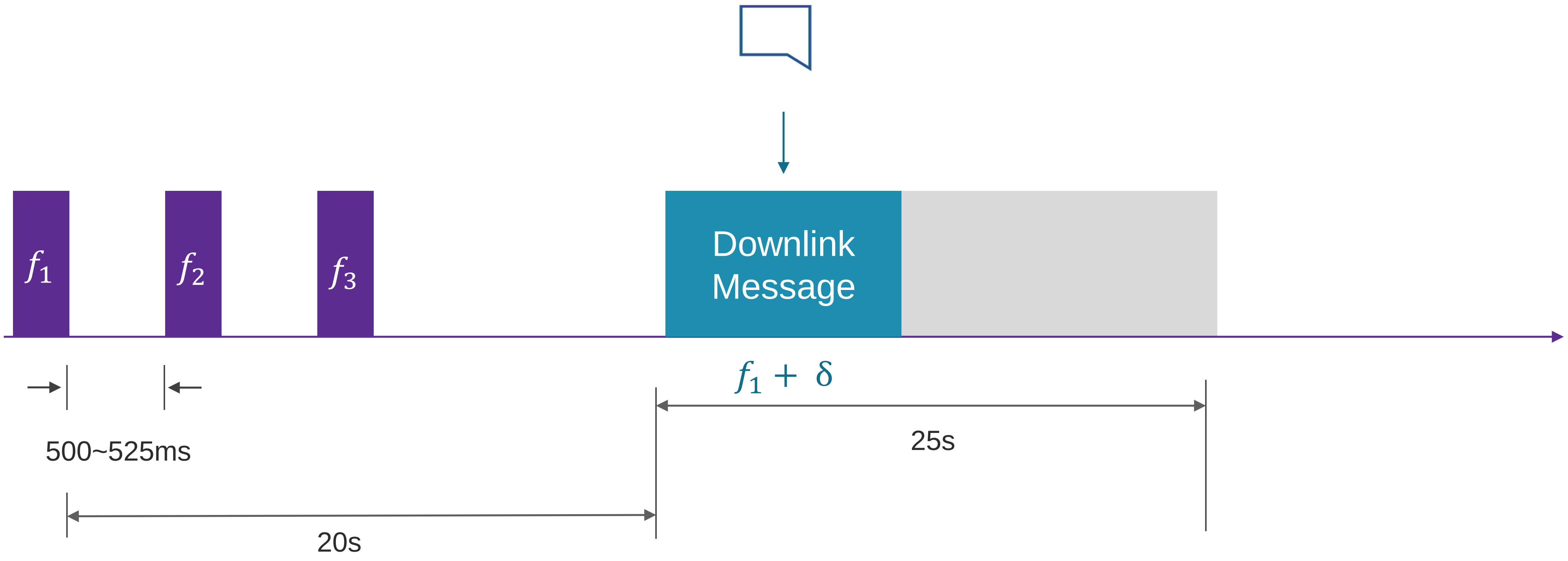


SIGFOX

Radio Technology – Object Initiated Communication (EU)

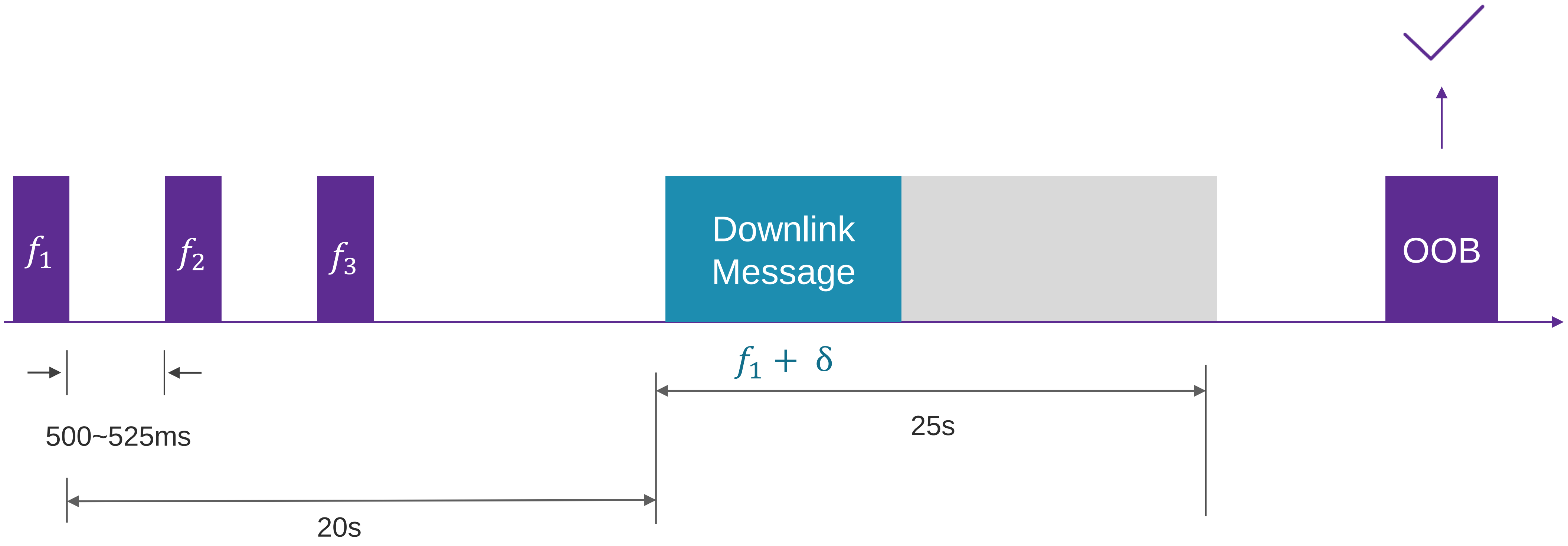
SIGFOX

Radio Technology – Object Initiated Communication (EU)



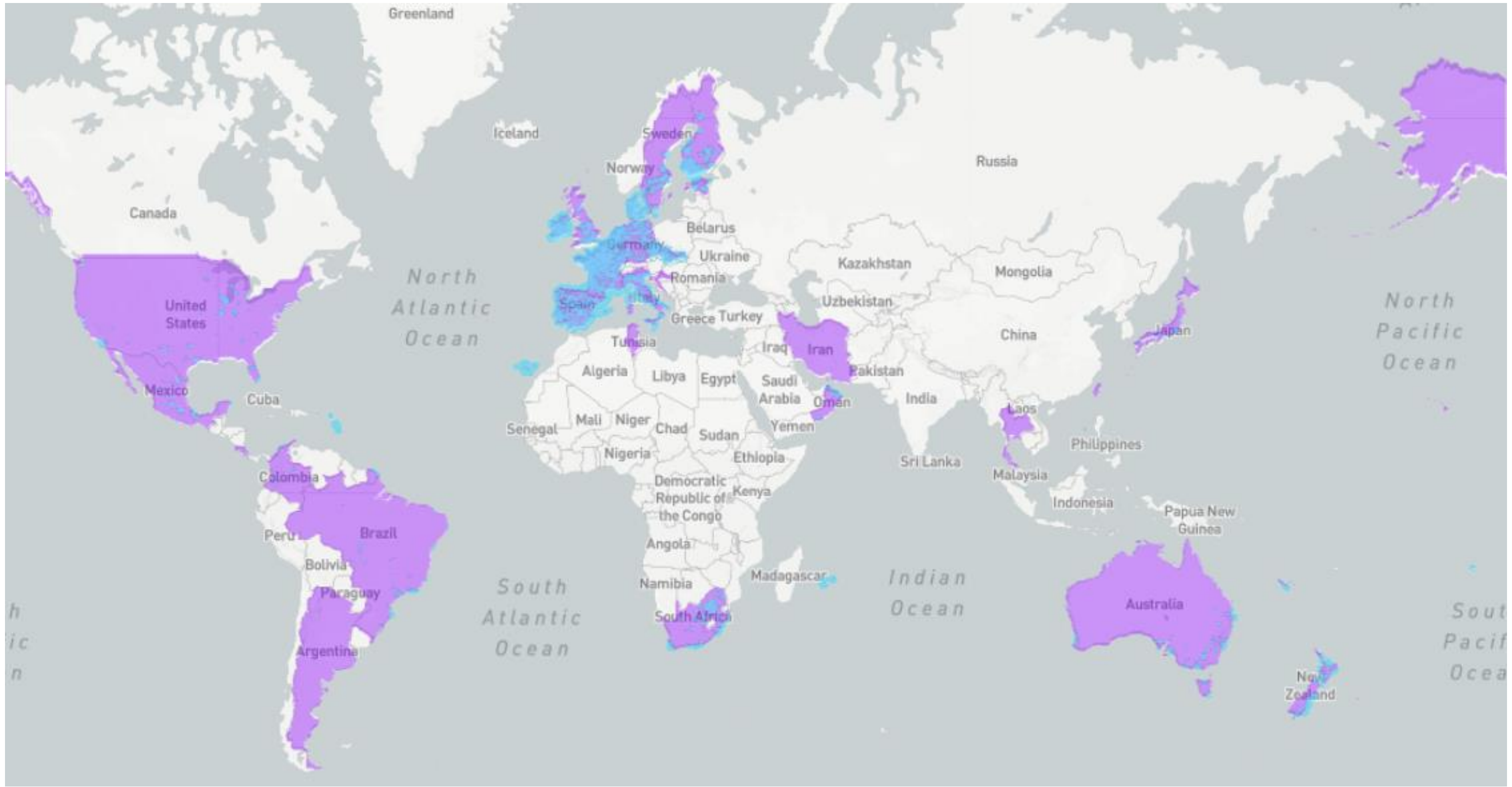
SIGFOX

Radio Technology – Object Initiated Communication (EU)



SIGFOX

Coverage



Currently present in over **30 countries**, they aim to cover 100% of the globe within the next few years.

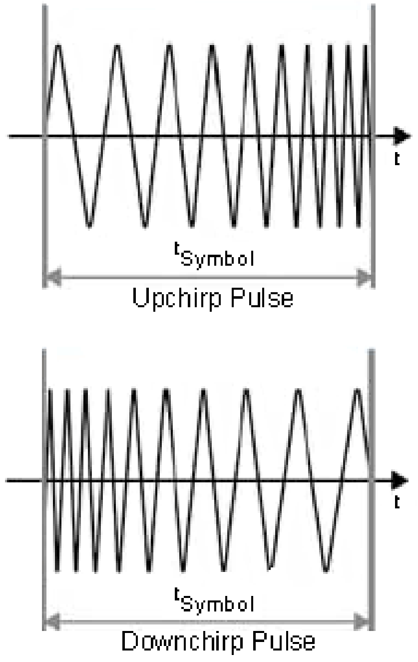
LoRaWAN

They provide LoRa-enabled Communication
Let’s you deploy IoT networks

LoRa & LoRaWAN

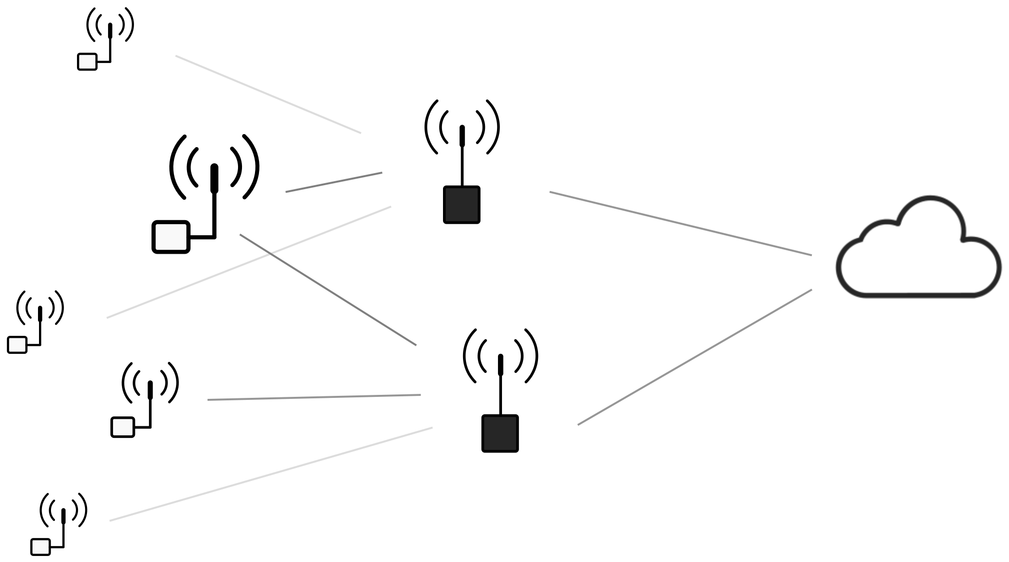
LoRa

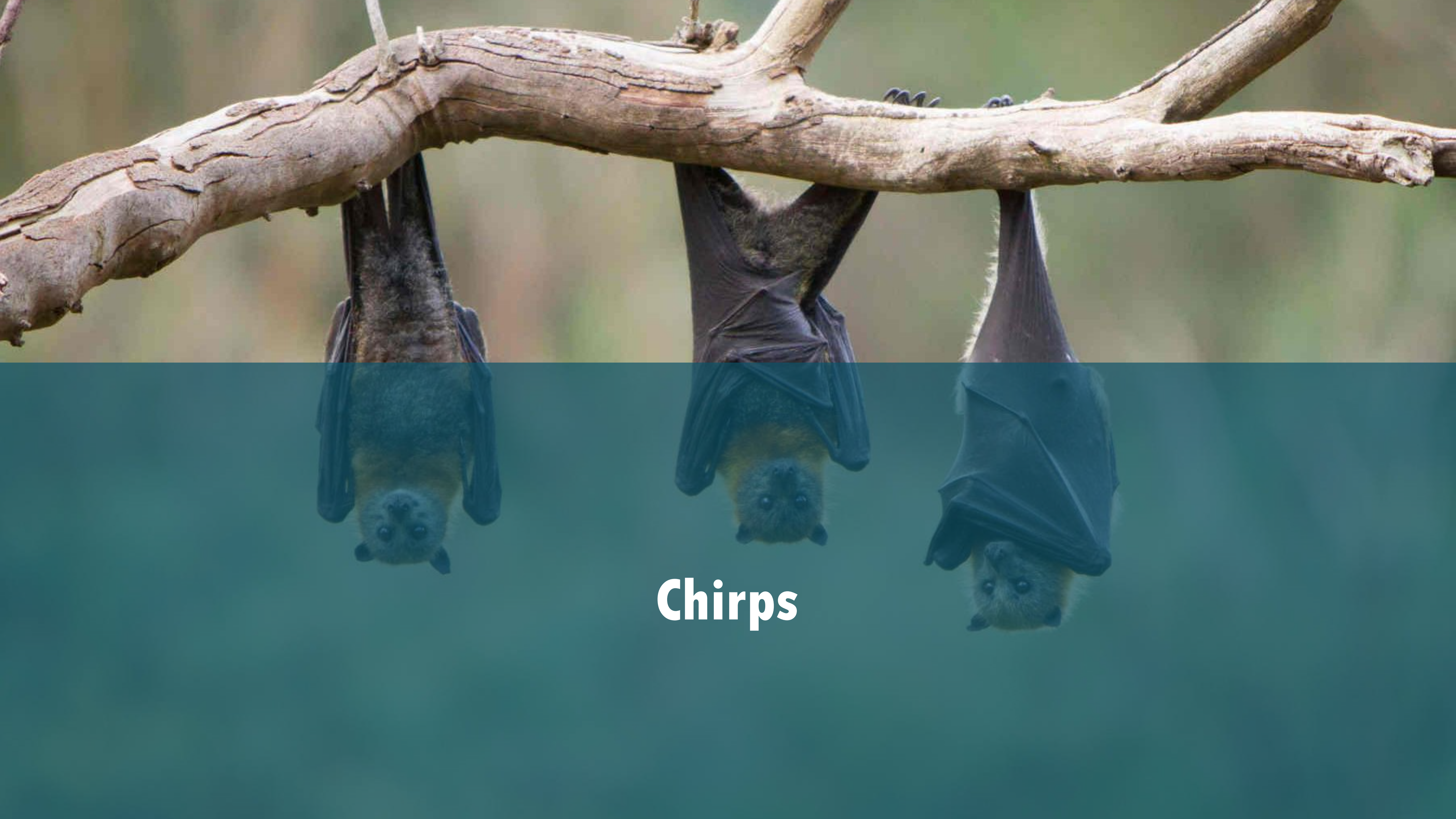
= PHY
Radio modulation patented by Semtech
Based on Chirp Spread Spectrum (CSS)



LoRaWAN

= MAC + System Architecture





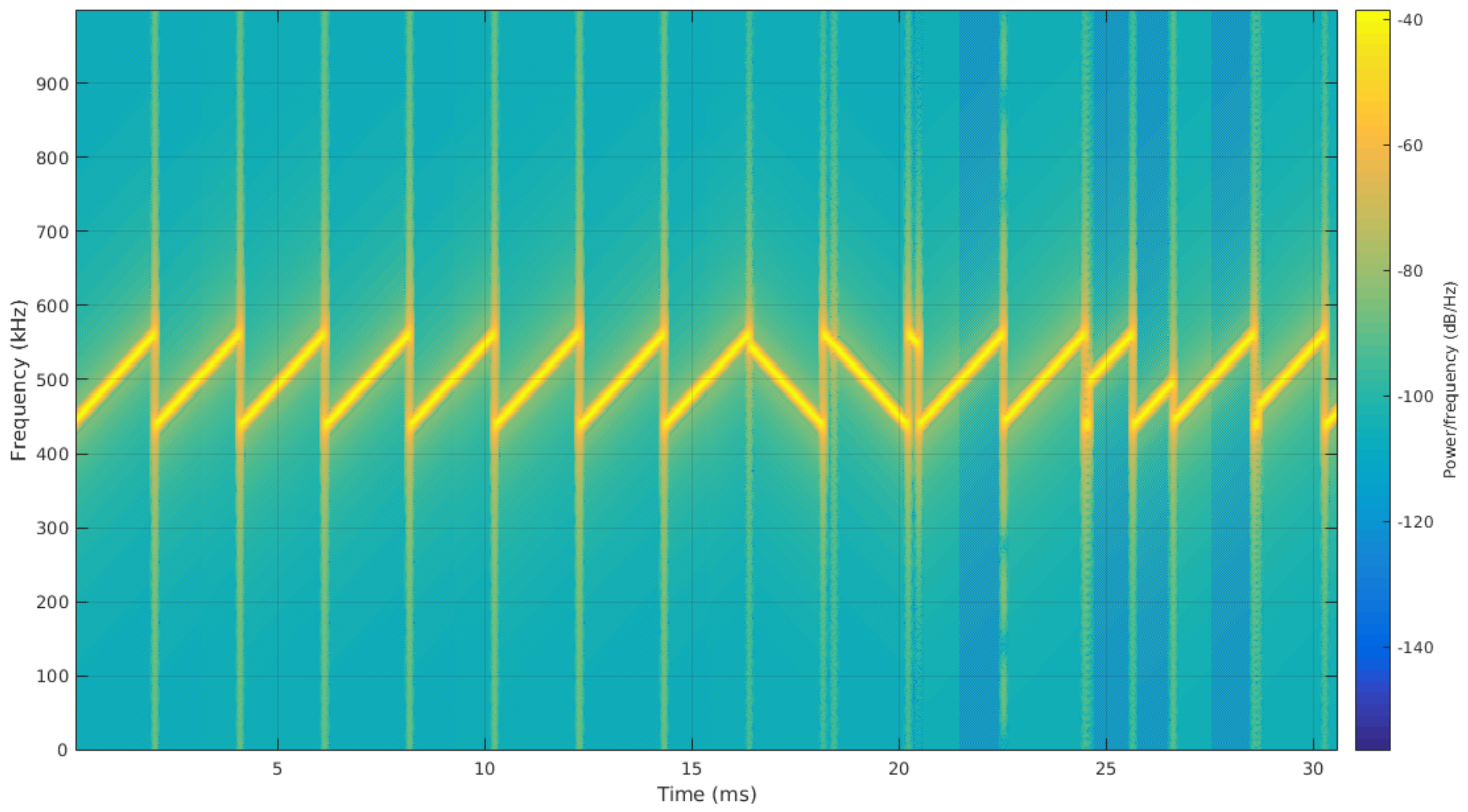
Chirps

LoRa

A Robust Modulation Technique

BW

125, 250, 500 Hz



Preamble

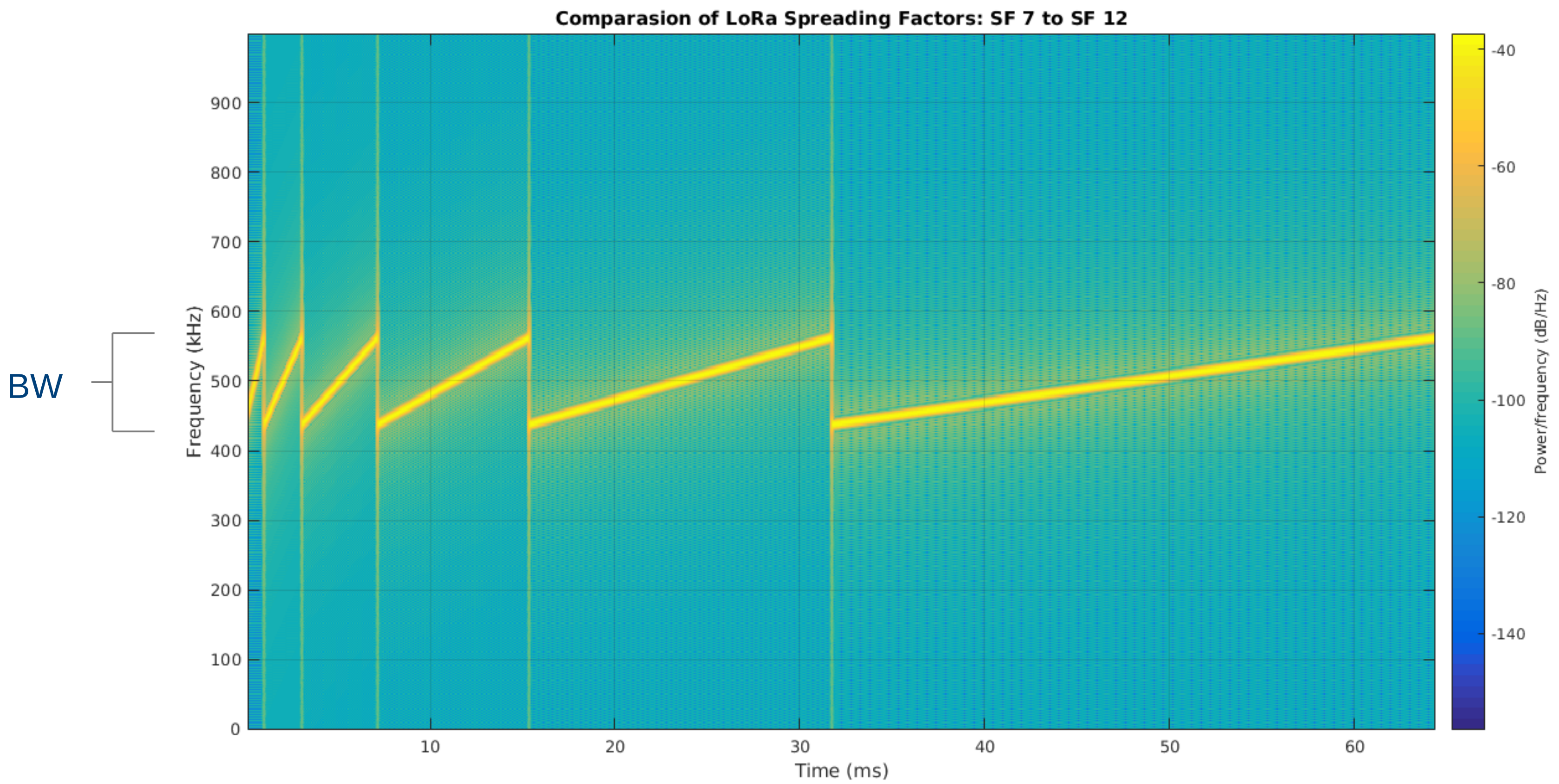
LoRa Signal Detection

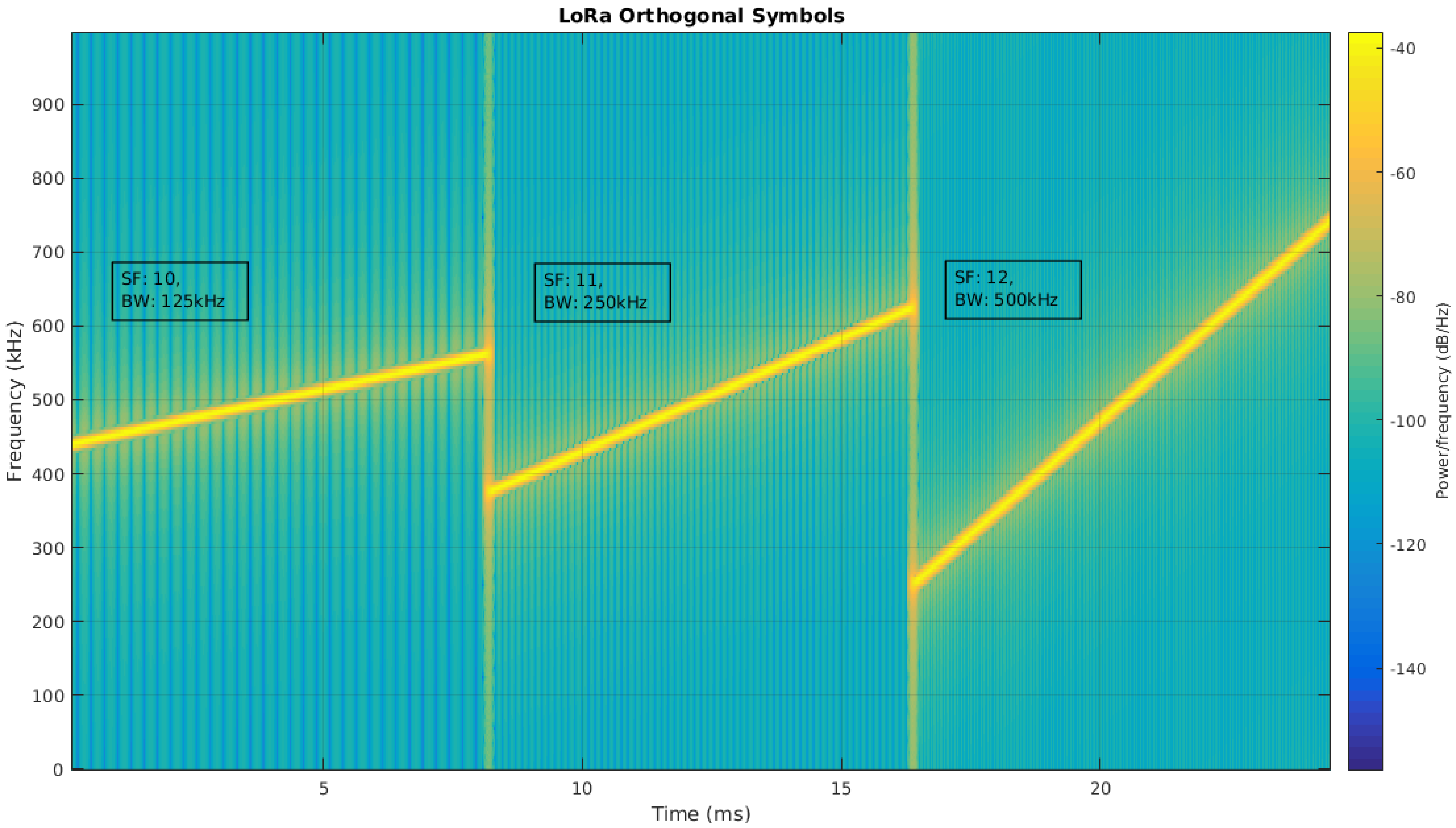
Sync

Time sync.
Detect starting of payload

Symbols

Payload


Comparasion of LoRa Spreading Factors: SF 7 to SF 12
BW
Frequency (kHz)
0
100
200
300
400
500
600
700
800
900
Time (ms)
10
20
30
40
50
60
Power/frequency (dB/Hz)
-40
-60
-80
-100
-120
-140



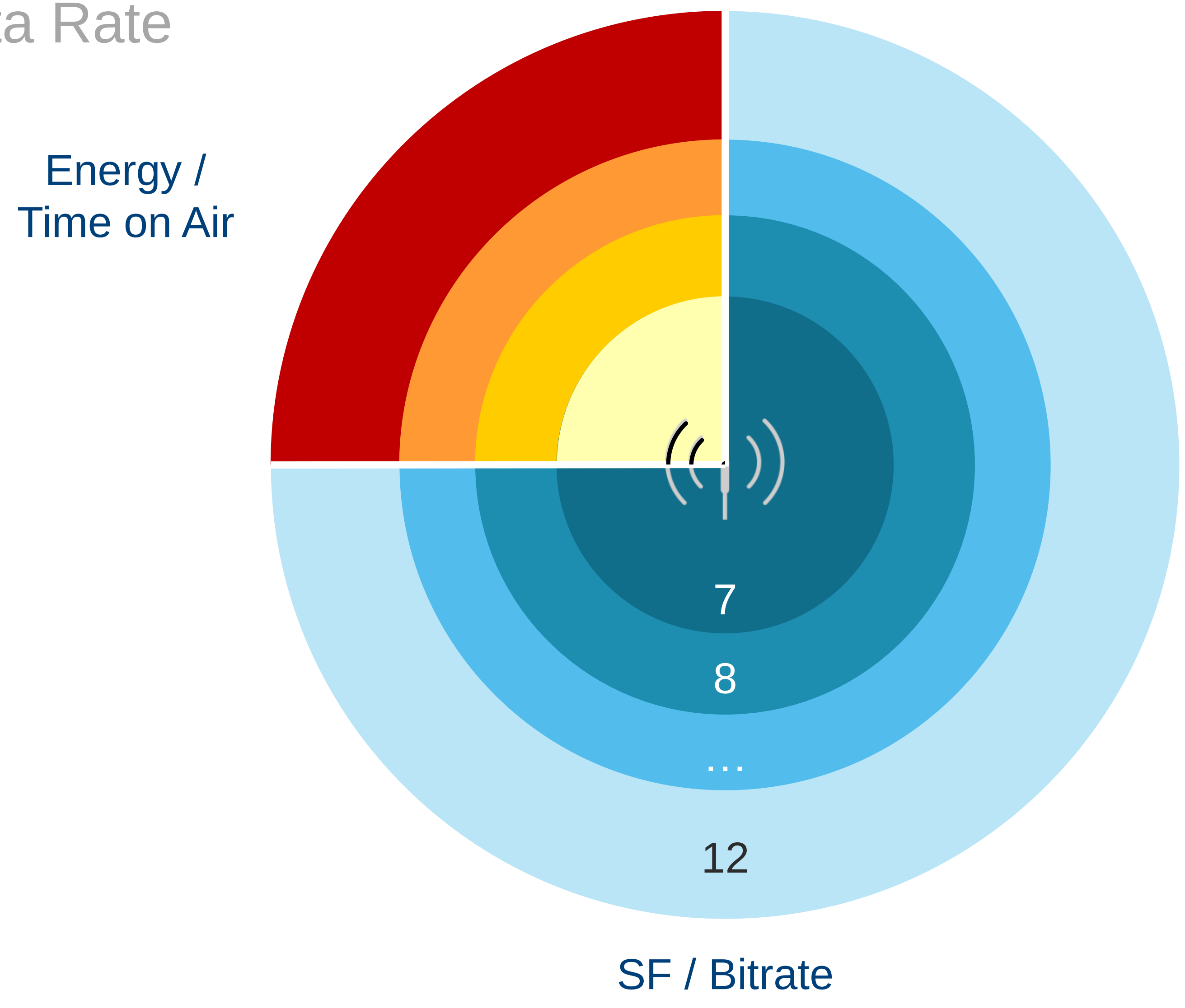
LoRa Orthogonal Symbols
SF: 10,
BW: 125kHz
SF: 11,
BW: 250kHz
SF: 12,
BW: 500kHz
Frequency (kHz)
0
100
200
300
400
500
600
700
800
900
Time (ms)
5
10
15
20
Power/frequency (dB/Hz)
-40
-60
-80
-100
-120
-140

LoRaWAN

Adapts to its surroundings

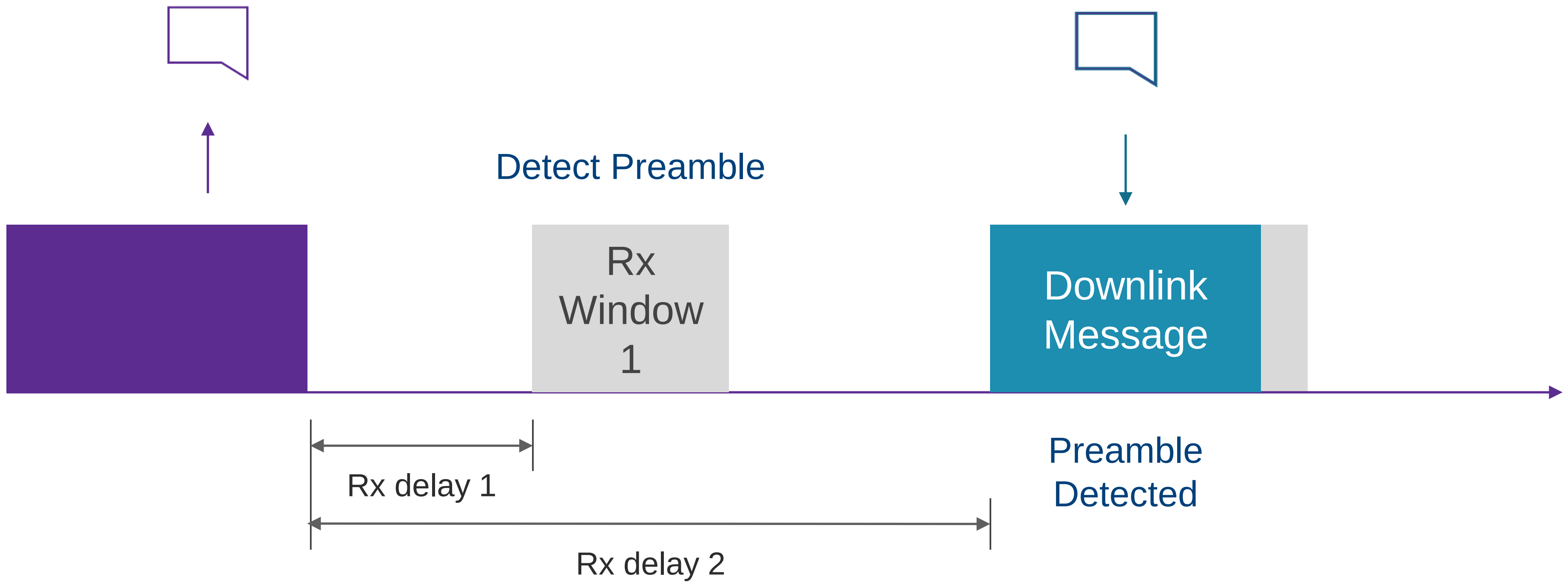
LoRaWAN

Adaptive Data Rate



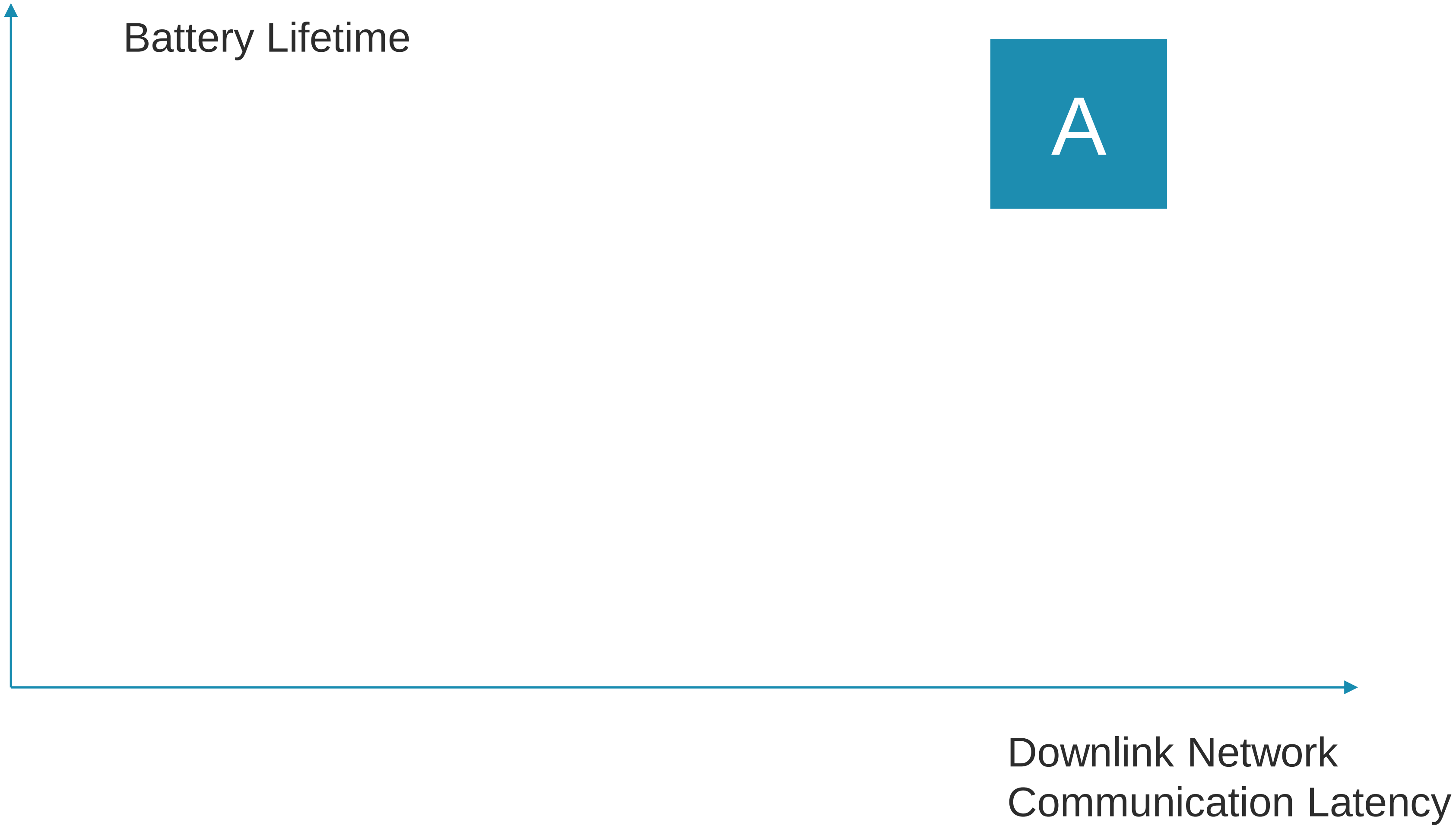
LoRaWAN Class A

Device Classes



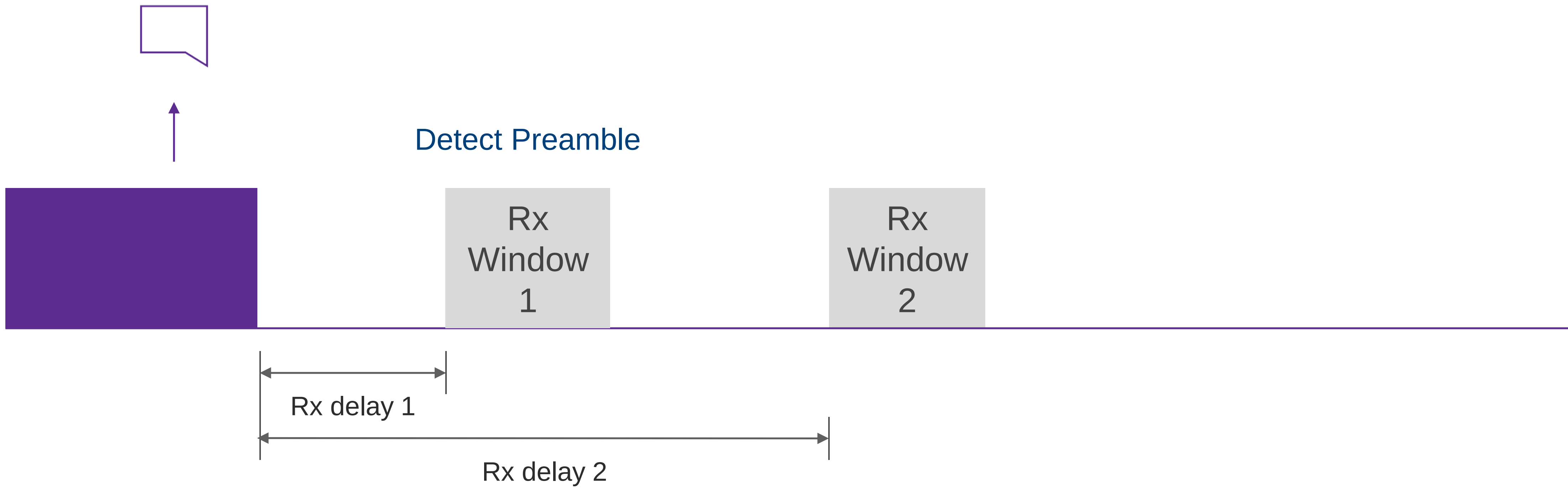
LoRaWAN

Device Classes



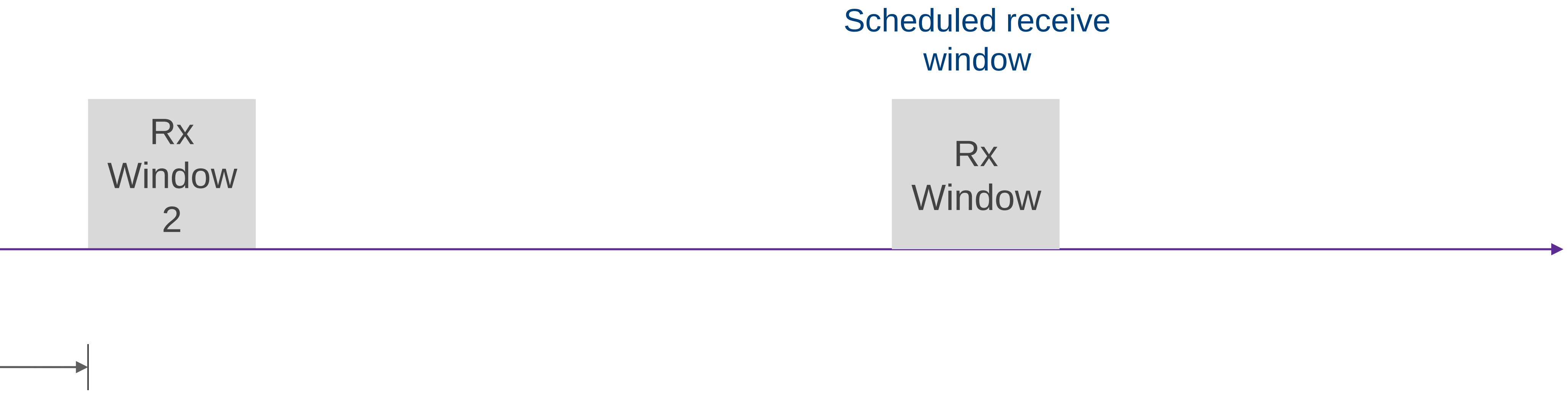
LoRaWAN Class B

Device Classes



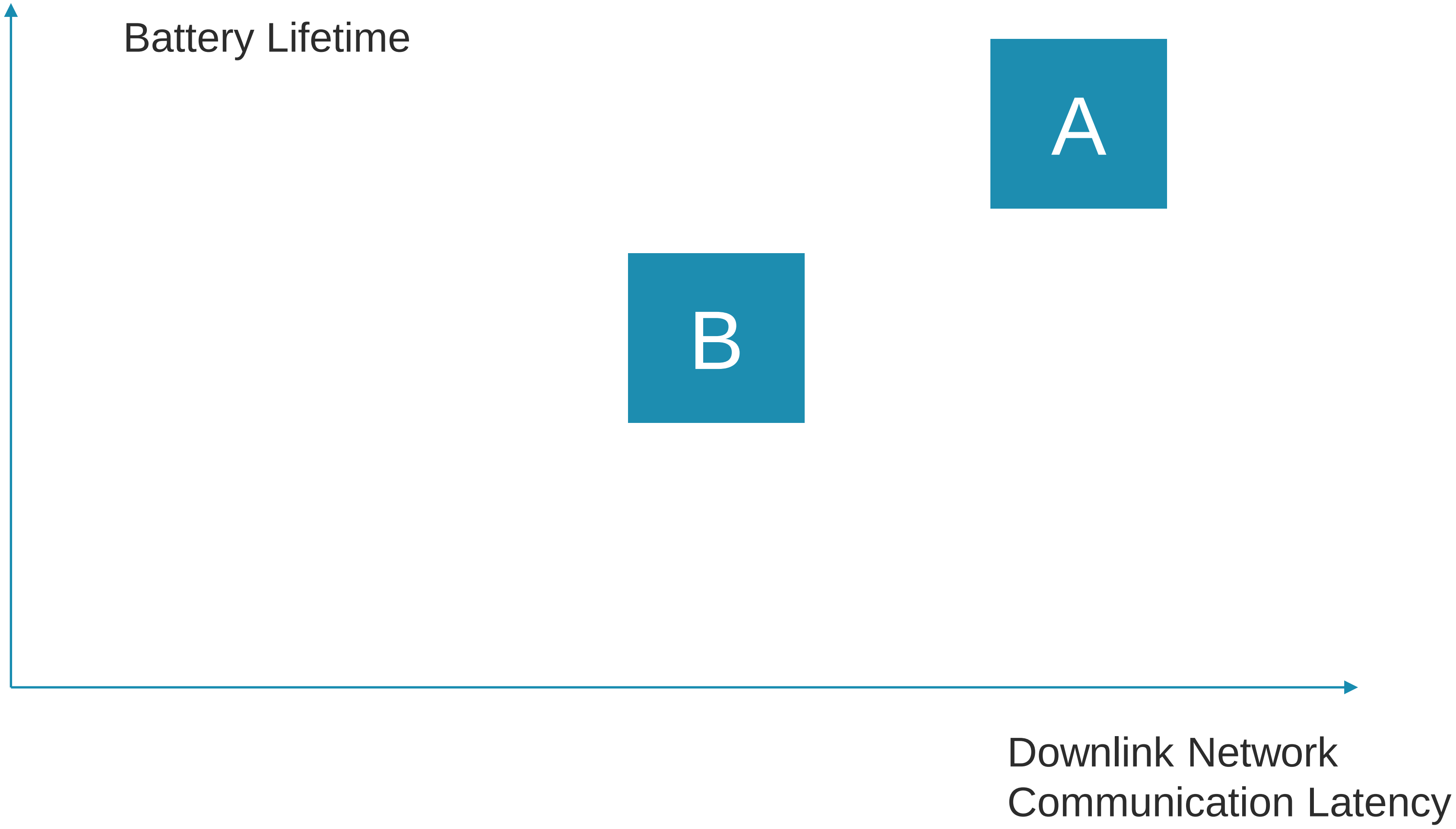
LoRaWAN Class B

Device Classes



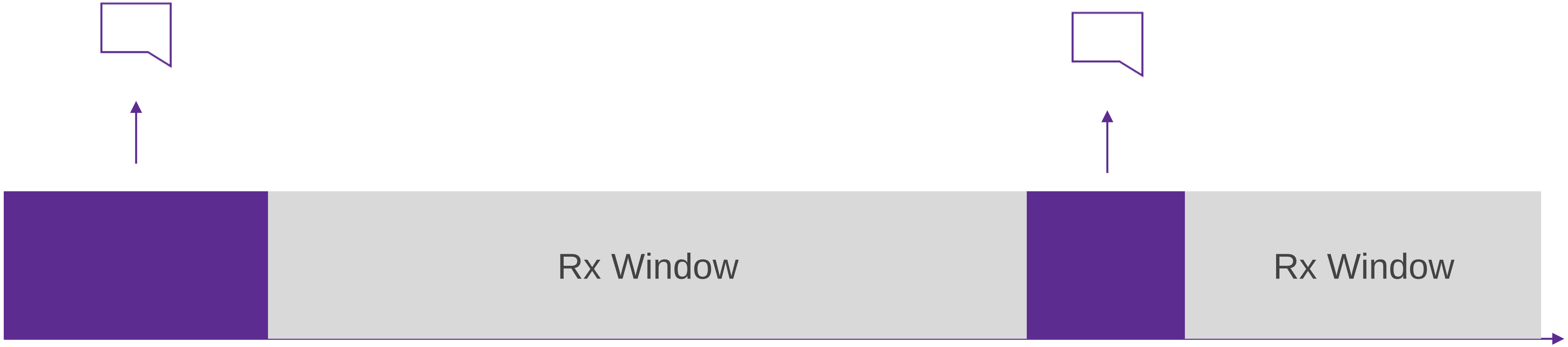
LoRaWAN

Device Classes



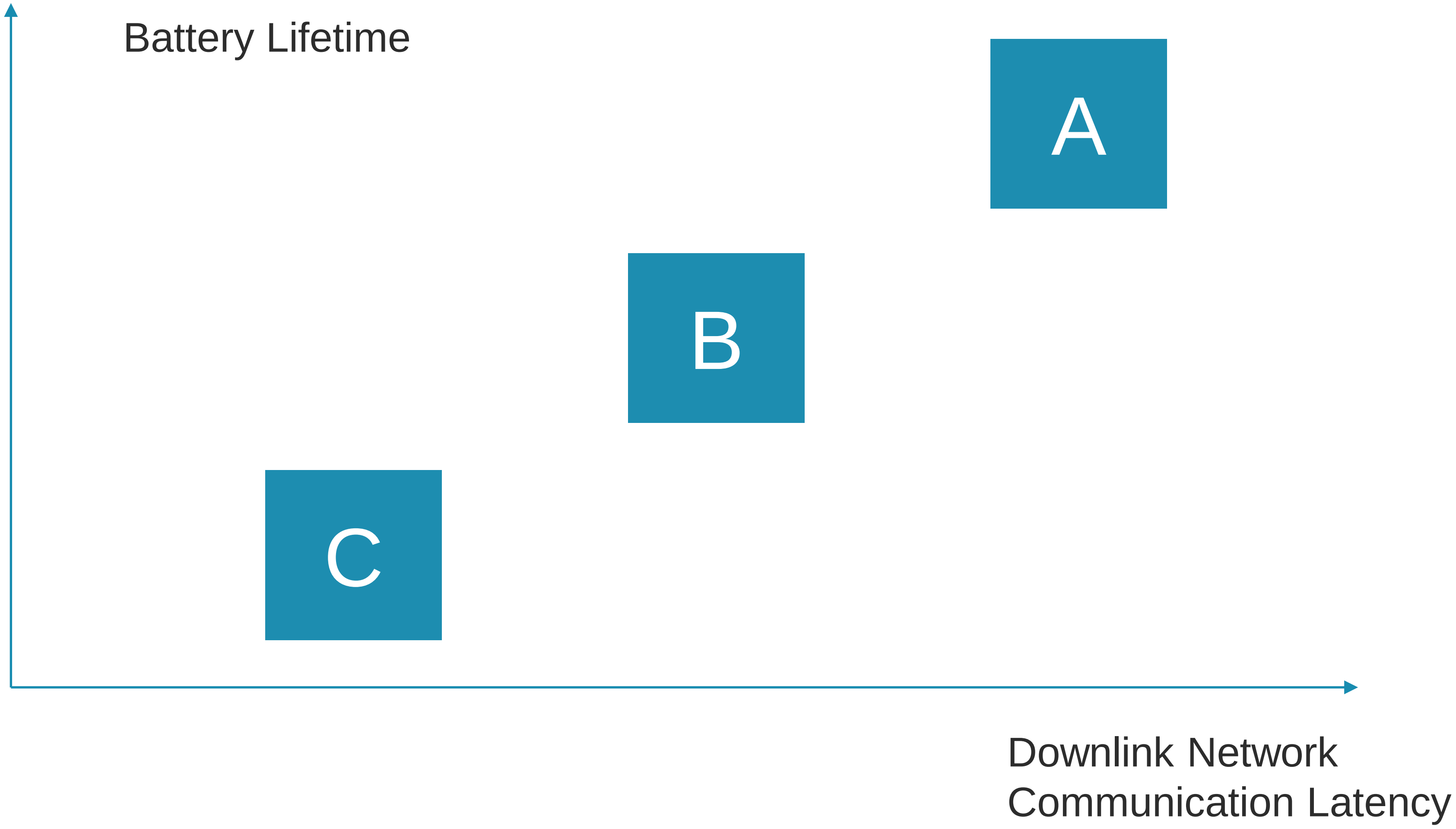
LoRaWAN Class C

Device Classes



LoRaWAN

Device Classes



LoRaWAN

Deploy your own network!

LoRaWAN

Deployment Strategies

Private Networks

Commercial Networks

Crowdsourced Networks

LoRaWAN

Crowdsourced Networks gain traction

THE THINGS
NETWORK


Ville de
Trois-Rivières
Drummondville
Ottawa
Sherbrooke
Barrie
Kingston
Vermont
New Hampshire
Rochester
Buffalo
Albany
Nashua
Oneonta
Boston
Brockton
Scranton
Connecticut
Yonkers
Bridgeport
Pennsylvania
Allentown
Philadelphia

What about cellular?

Low Power Wide Area Networks (LPWAN) – 3GPP (members) propose ‘central RAN’

3rd Generation Partnership Project: Global initiative for broadband mobile, succeeded in globally harmonizing cellular standards.

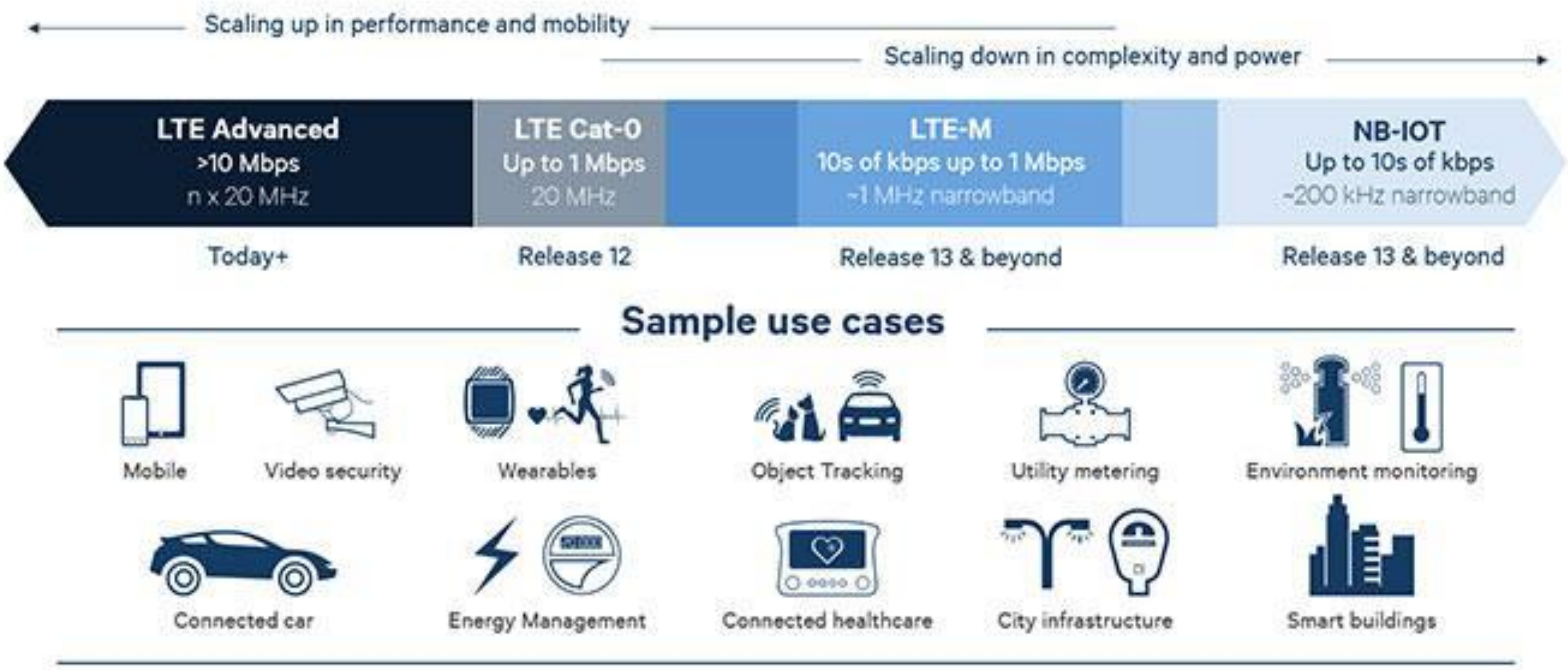
Vision: one central all-encompassing Radio Access Network (RAN) (for technical & commercial reasons)

http://www.3gpp.org

https://www.youtube.com/watch?v=2nsEAw_SirQ

A GLOBAL INITIATIVE

3GPP-LTE not longer only about higher speed



3GPP-LTE is considering different UE (User Equipment) categories

LTE UE Category	Release	Downlink	Uplink	BW	Rx Path	Duplex	Tx Power	Module Cost	Standard Ready	Network Ready
Cat 4	Rel.8	150 Mbps	50 Mbps	20 MHz	2	FD	23 dbm	$35	Now	Available
Cat 1	Rel.8	10 Mbps	5 Mbps	20 MHz	2	FD	23 dbm	$30	Now	1Q16
Cat 0	Rel.12	1 Mbps	1 Mbps	20 MHz	1	HD	23 dbm	$15	Now	4Q16
Cat M	Rel.13	200 Kbps	200 Kbps	1.4 MHz	1	HD	20 dbm	$10	1Q16	1Q17
NB-IoT	Rel.13	50 Kbps	50 Kbps	200 KHz	1	HD	TBD	$5	2Q16	2Q17

target


ONE SIZE DOES NOT FIT ALL.
KEEP TRYING...
AND EVENTUALLY YOU WILL FIND THE
PERFECT FIT.