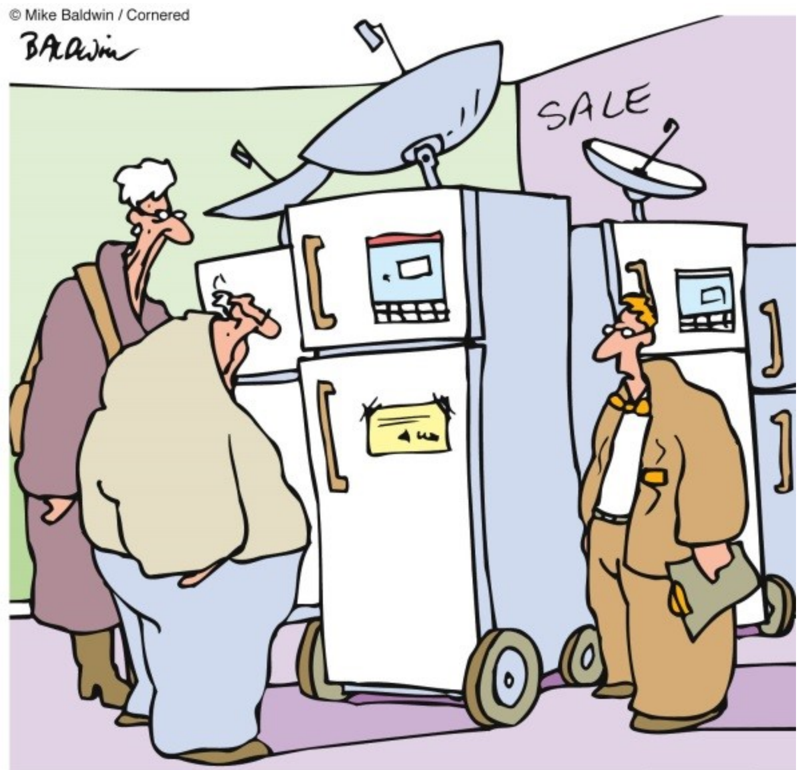


"Yes, it's self-defrosting. It also does a daily inventory, searches for the best deal and runs over to the store for you."

Internet Rzeczy
Komunikacja radiowa

prof. dr hab. inż. Katarzyna Kosek-Szott

Ewolucja Sieci 2023/2024

Lecture Scope

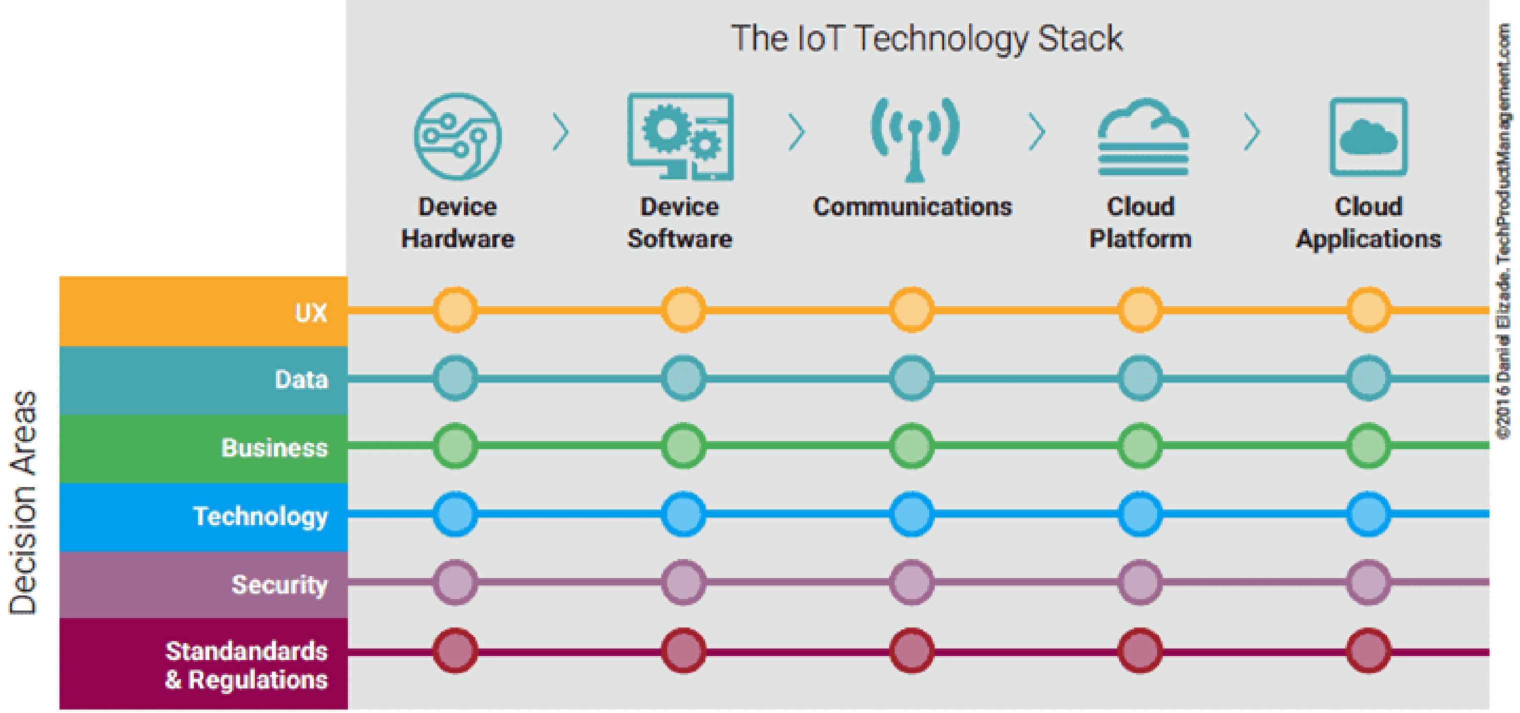
- IoT technology stack
  - How many experts are needed to tackle IoT problems?
- Indoor vs outdoor IoT problems
  - The devil is in the detail…
- Most important PHY/MAC mechanisms
  - How to serve thousands of IoT devices?
- Comparison of IoT radio technologies
  - Short range communications
  - Long range communications

IoT Technology Stack

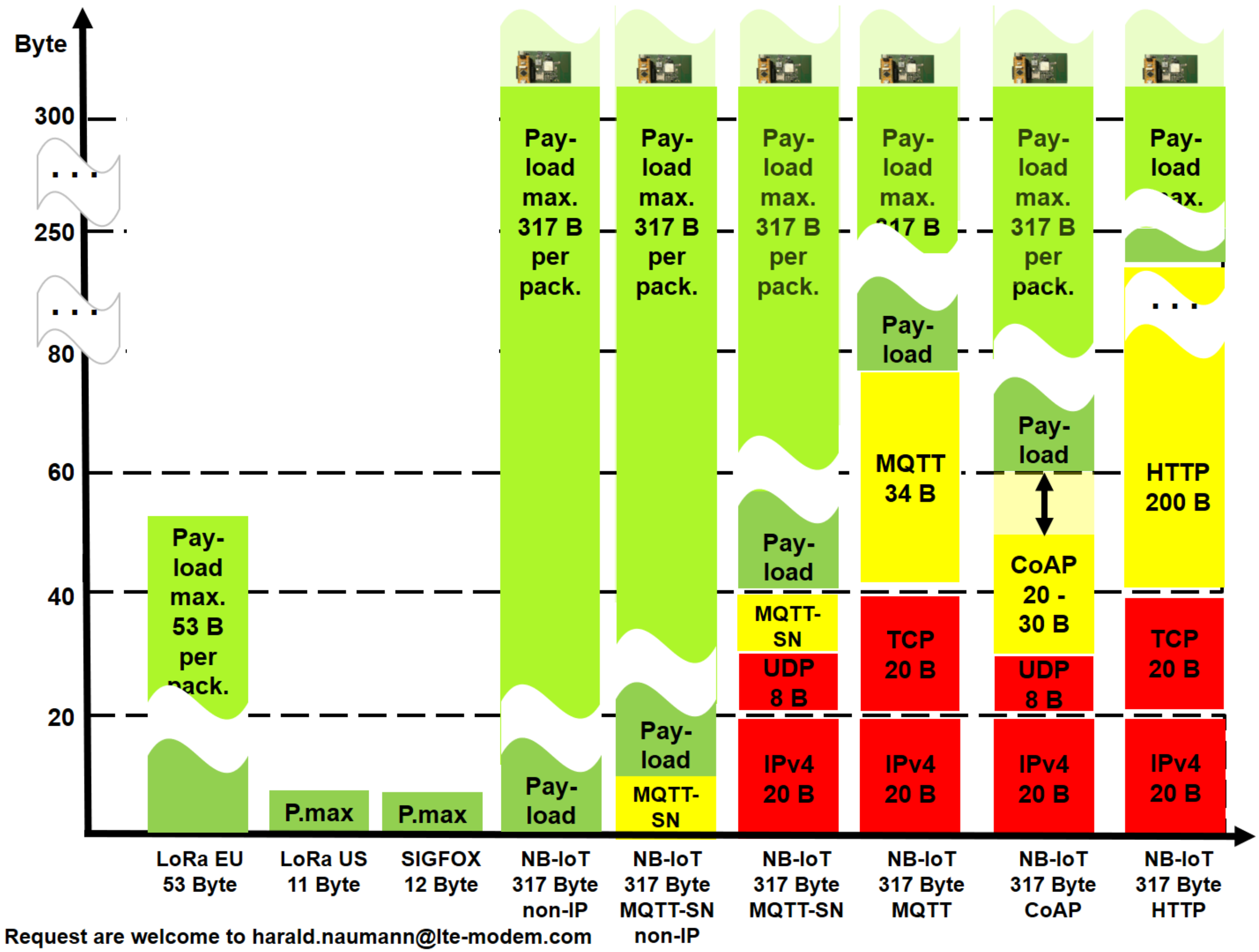
- **Hardware** (sensors and actuators)
- **Software** (communication with the cloud, collecting data, device integration, real-time data analysis)
- **Communication** (exchanging information)
  - Physical connectivity (e.g., cellular, Ethernet LAN, WiFi)
  - Higher layer communication (e.g., MQTT, CoAP)
- **Platform + Applications** (data gathering, managing, processing, analysis, and presentation to the user)
  - On-premise or cloud-based

Is it easy to create a successful IoT system/application?

- [The 6 Complexities of Building a Managed IoT Platform]
  - „Why underestimating complexity causes 75% of self-initiated IoT projects to fail"
- [A Simple IoT Decision Framework for Product Managers]



IoT System: Let’s decide!



https://forums.quectel.com/t/out-of-lwm2m-mqtt-which-is-the-best-suitable-protocol-for-the-assert-tracking/701/14

IoT System: Let’s decide!

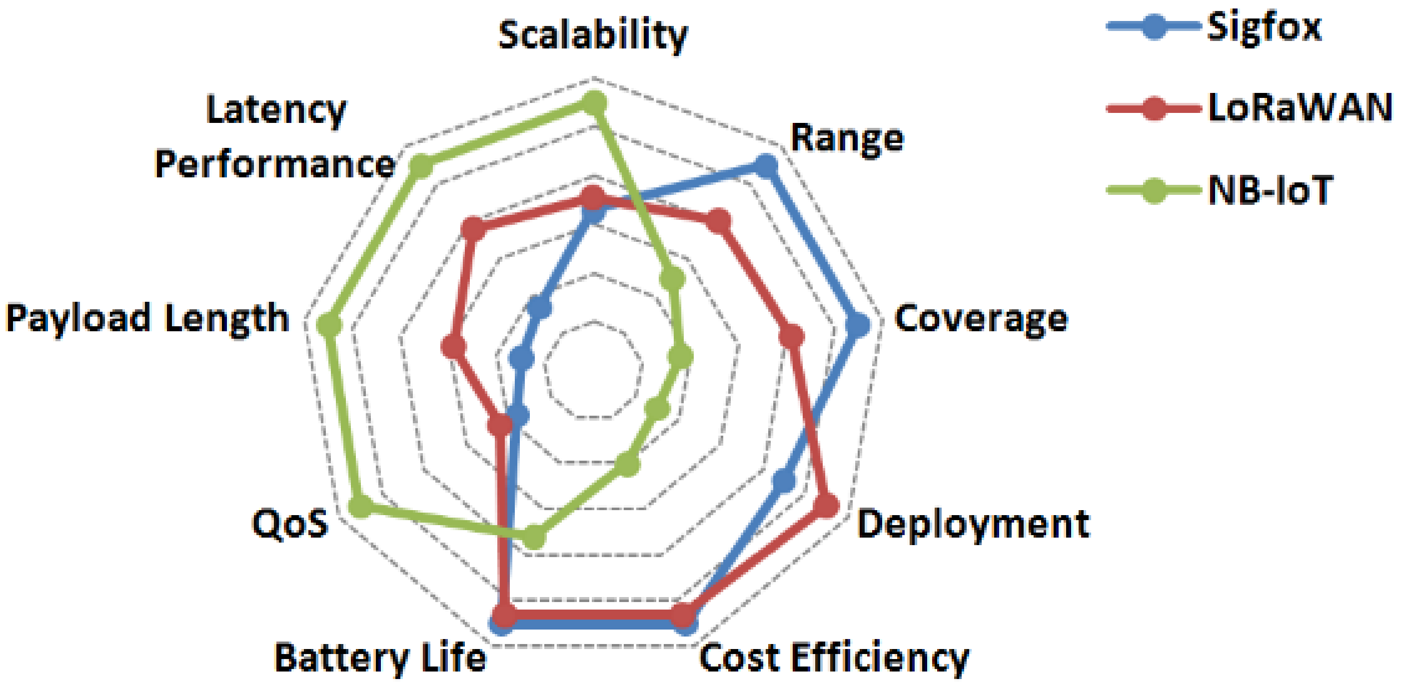


Fig. 5. Respective advantages of Sigfox, NB-IoT, and LoRaWAN

Mekki, Kais, et al. "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)*. IEEE, 2018.

IoT System
How many experts are needed?

- **Hardware** designers
- Embedded **firmware** developers
- **Wireless + wired communications** experts
- **Backend** developers
- **Frontend** developers
- **App** developers
- **Automation and systems integration** engineers
- **Data scientists**
- **UX experts**
  - Rowland, Claire, et al. *Designing connected products: UX for the consumer Internet of Things*. " O'Reilly Media, Inc.", 2015.

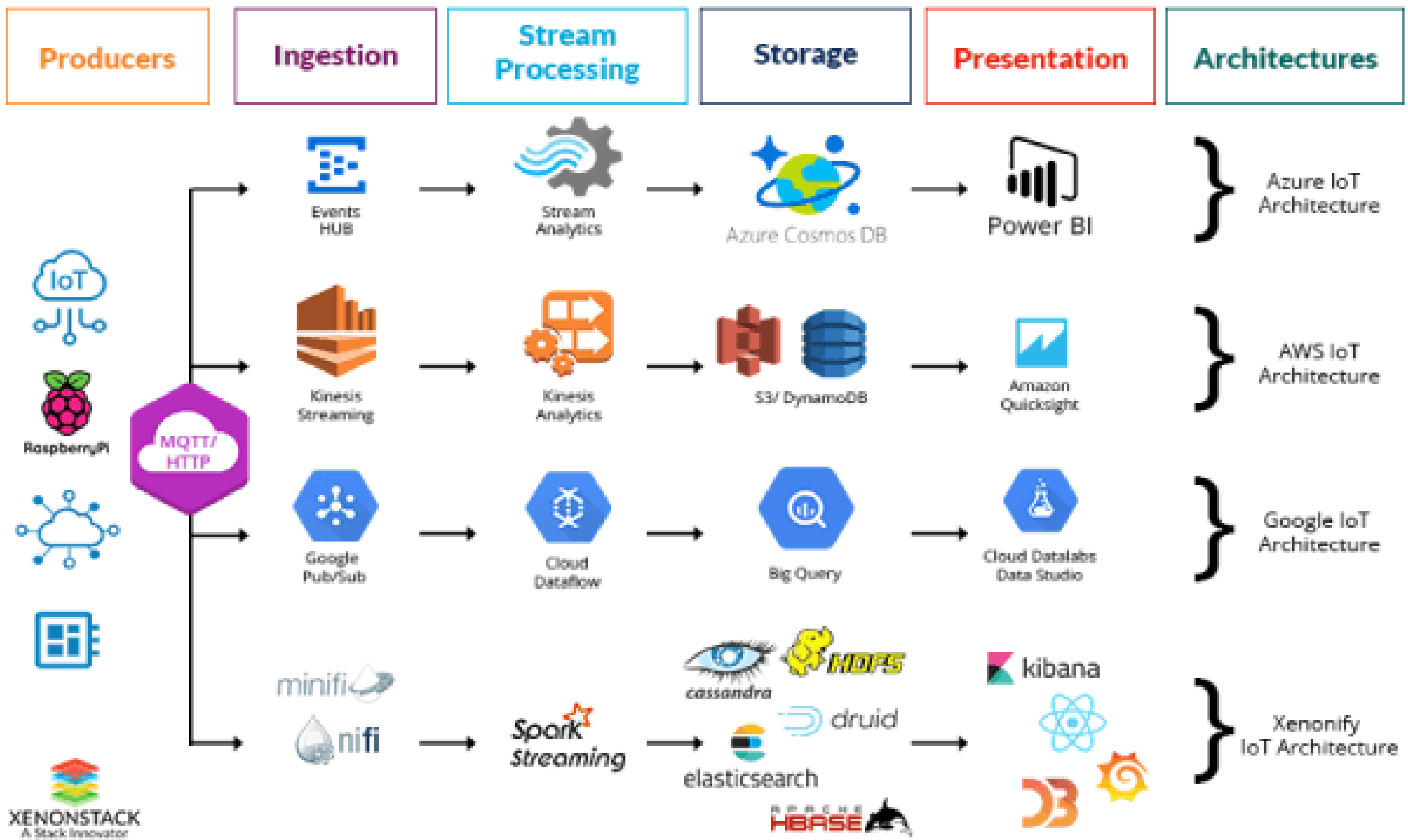
https://www.thingsquare.com/blog/articles/developer-profiles-for-successful-iot-projects/

IoT System
What skills are needed?

- Developer Handbook

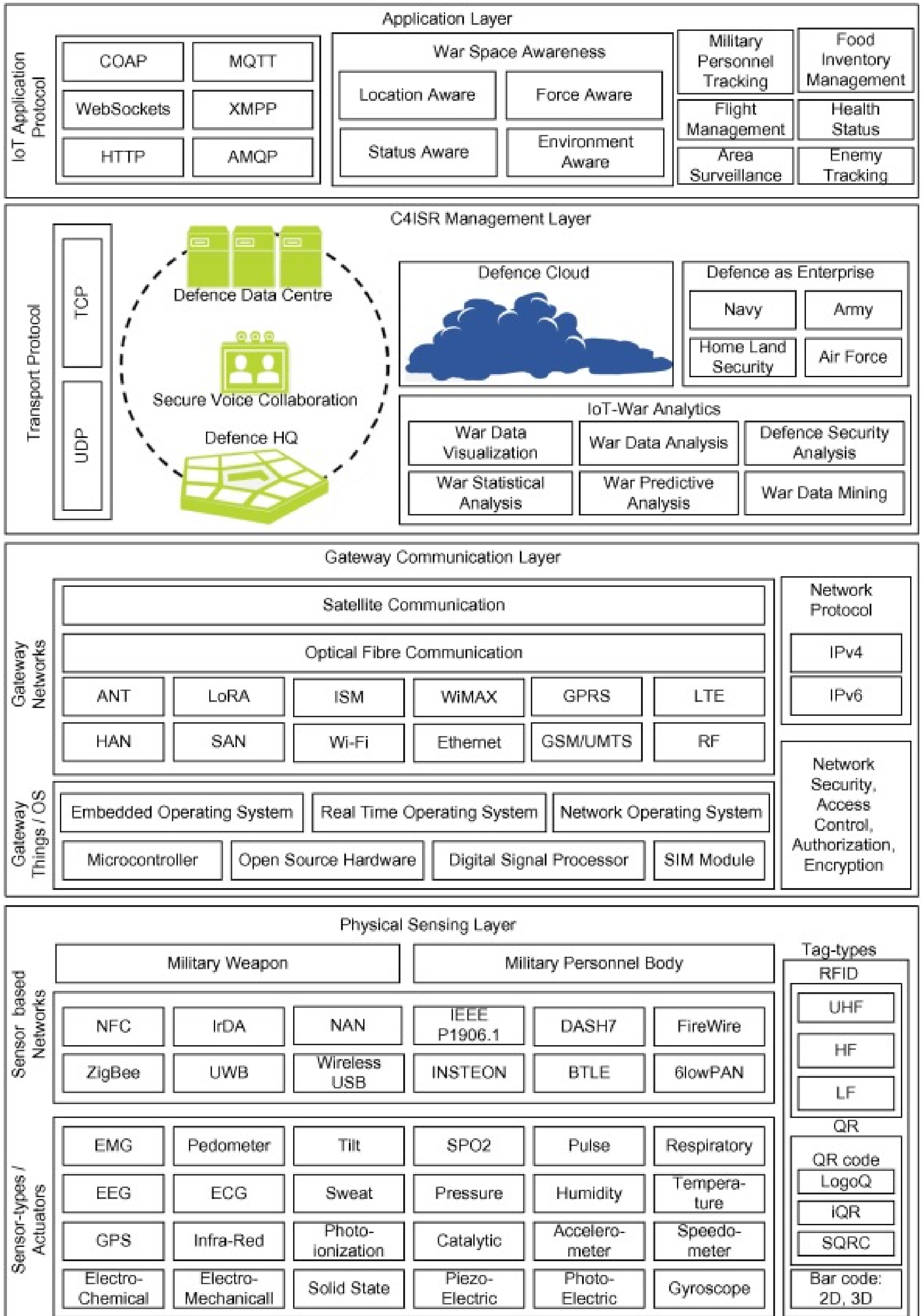
Section 1	Section 2	Section 3
1. DevOps	21. Swift	41. Objective-C
2. IoT	22. Golang	42. Qt
3. Open Source Security	23. C++	43. LabVIEW
4. Linux	24. Ruby	44. Bootstrap
5. Networking	25. Java	45. Elixir
6. Cloud-Native	26. Scala	46. Erlang
7. Kubernetes	27. Groovy	47. Lua
8. ARM	28. Clojure	48. Vala
9. Assembly(x86)	29. WebAssembly	49. Haskell
10. Machine Learning	30. CUDA	50. PHP
11. Python Guide	31. Julia	51. Robotics
12. SQL	32. R	52. WSL
13. HMTL/CSS	33. MATLAB	53. 3D Graphics & Design
14. React	34. Bash/Shell/PowerShell	54. Game Development
15. Angular	35. C#	55. Blockchain
		56. Working Remote
		57. Audio & Video Editing
		58. Podcasting
		59. Agile Development
		60. RISC-V

IoT System
What skills are needed?



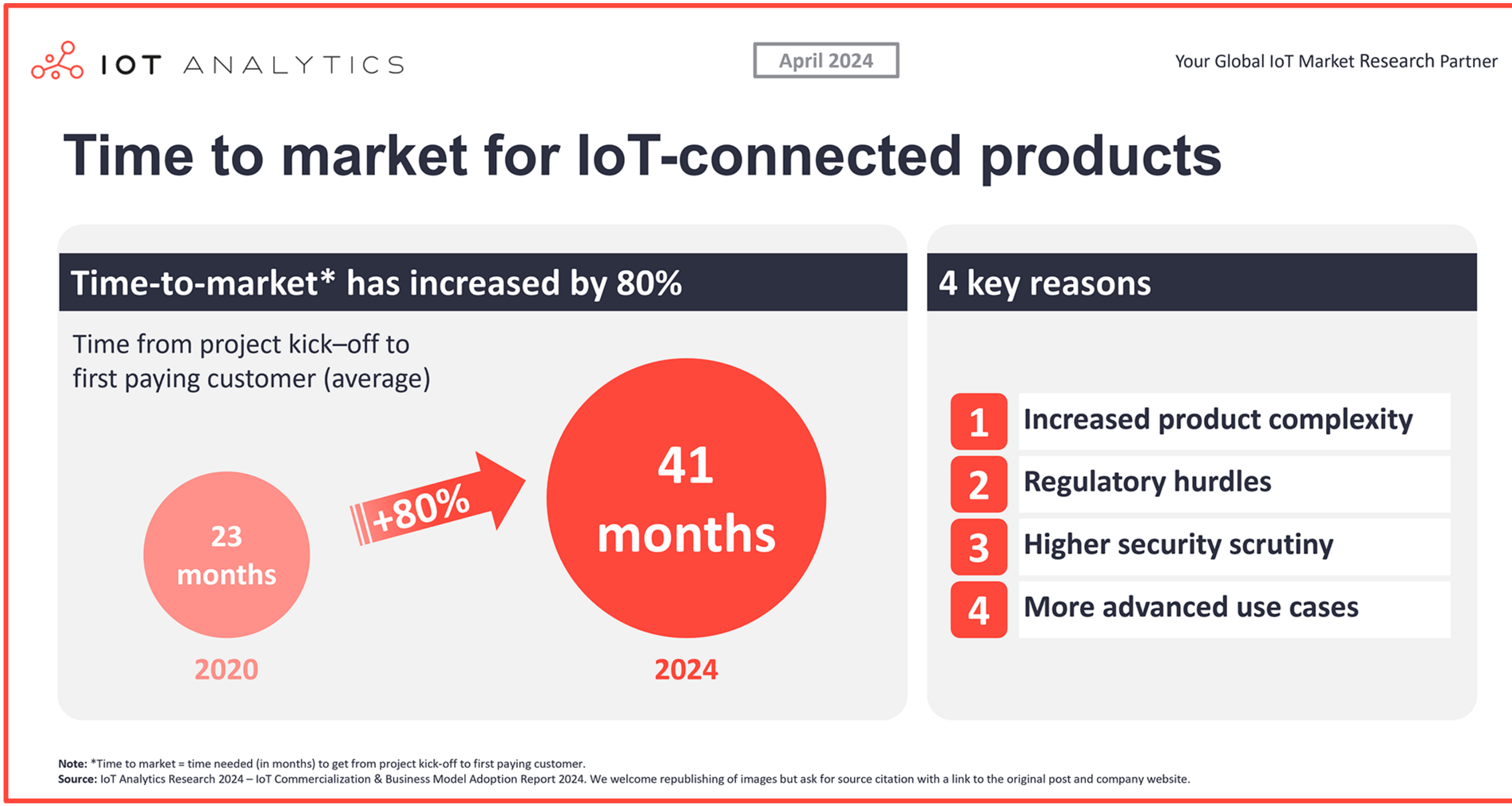
https://www.postscapes.com/internet-of-things-protocols/

IoTNetWar architectural framework



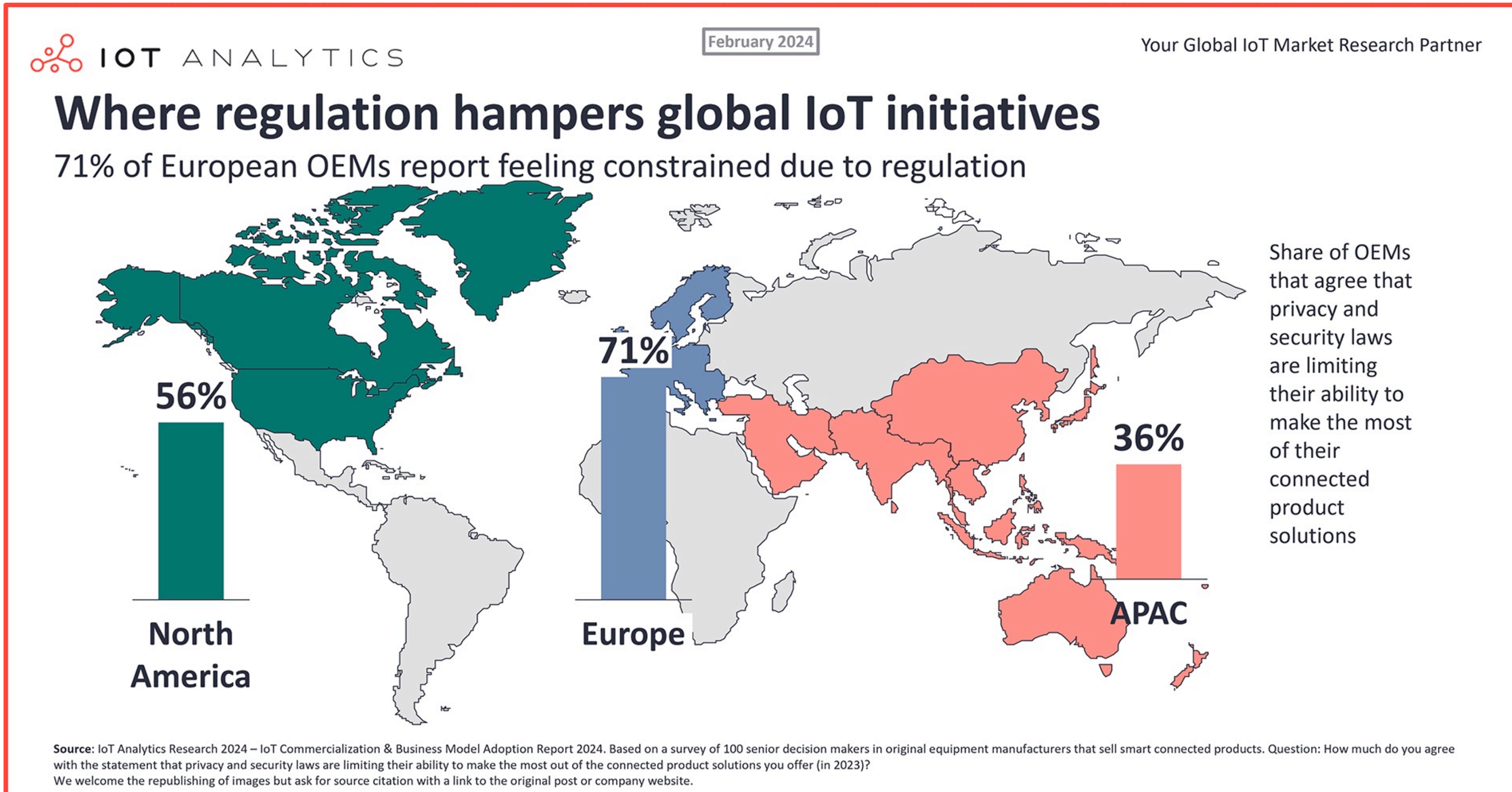
Ray, Partha Pratim. "A survey on Internet of Things architectures." *Journal of King Saud University-Computer and Information Sciences* 30.3 (2018): 291-319.

Time-to-market



https://iot-analytics.com/

Major IoT obstacle - security



https://iot-analytics.com/

Indoor IoT

- Challenges
  - High power consumption
  - Various protocols
    - WPAN (ZigBee, Z-Wave, Bluetooth, …)
    - WLAN (802.11a/b/g/n/ac/ax/be/ad/ay/ah…)
  - Lack of interoperability between technologies

P. Gallo, K. Kosek-Szott, S. Szott, I. Tinnirello, SDN@home: A Method for Controlling Future Wireless Home Networks, IEEE Communications Magazine, May 2016.

Outdoor IoT

- Requirements
  - Low device cost & power (extended battery life), enhanced coverage & scalability, non/sub-ms latency
- Key challenges
  - Millions of devices
    - Each needs only a fraction of bandwidth
  - Heavy signaling and data overheads
    - Connection setup, mobility, QoS handling

THE DEVIL IS IN THE DETAIL…

ETSI Documents (Networks)

- EN 300 328
  - ***Wideband transmission systems***
  - *Data transmission equipment operating in the* ***2,4 GHz*** *ISM band and using wide band modulation techniques*
  - Examples: IEEE 802.11™, Bluetooth® wireless technologies, Zigbee™
- EN 301 893
  - ***Broadband Radio Access Networks*** *(BRAN)*
  - ***5 GHz*** *high performance Radio LAN (RLAN)*
  - Examples: Wireless LAN, Cellular Networks (LAA)
- …

ETSI Documents (Equipment)

- EN 300 220, EN 300 330, EN 300 440
  - ***Short Range Devices*** *(SRD) operating in the frequency range* ***25 MHz to 1 000 MHz***
  - *…9 kHz to 25 MHz*
  - *…1 GHz to 40 GHz*
- EN 302 567
  - Multiple-Gigabit/s radio equipment operating in the **60 GHz band**
- …

Test Item	EN 300 328 V1.7.1(2006-10)	EN 300 328 V1.8.1(2012-07)
Equipment Types	FHSS and DSSS	FHSS, other Wide Band modulation, adaptive and non-adaptive equipment.
RF output Power	100mW maximum e.i.r.p	100mW mean e.i.r.p (need to consider beam forming gain)
Power Spectral Density (non-FHSS only)	10dBm/MHz maximum e.i.r.p spectral density	10dBm/MHz, mean e.i.r.p. spectral density
Duty Cycle, TX-Sequence, TX-Gap	Not defined	Duty cycle shall be equal to or less than the maximum value declared. - For FHSS : max TX-sequence time ≤ 5 ms, min TX-Gap time ≥ 5 ms - For non-FHSS: TX-sequence time = Min. TX- Gap time = M (Note: 3.5mS < M < 10mS)
Dwell time, Minimum Frequency Occupation and Hopping Sequence (FHSS only)	Frequency Hopping requirements: Dwell time < 0.4s Hopping channel, Hopping sequence	Dwell time, Minimum Frequency Occupation and hopping sequence Hopping frequency separation: new limits;
Medium access protocol	A medium access protocol shall be implemented	Medium Utilization factor only for Non-adaptive equipment with and EIRP > 10mW; Limit: ≤ 10%
Adaptivity	No requirement	Only for adaptive equipment with e.i.r.p > 10 mW
Occupied Bandwidth	No requirement	99% OBW shall fall within the used band. FHSS and Non-AFH equipment (e.i.r.p > 10 dBm): Occupied Channel Bandwidth ≤5 MHz Non-FHSS and non-AFH equipment (e.i.r.p > 10 dBm): Occupied Channel Bandwidth < 20MHz

How to serve thousands of IoT devices?

MOST IMPORTANT PHY/MAC MECHANISMS

FDMA
OFDMA

TDD

FHSS

Scheduled access (CFP)
Distributed access (CP)
Super-frames (CFP+CP)

TDMA

FDD

DSSS

Fast association
Restricted access window (podział na mniejsze grupy)

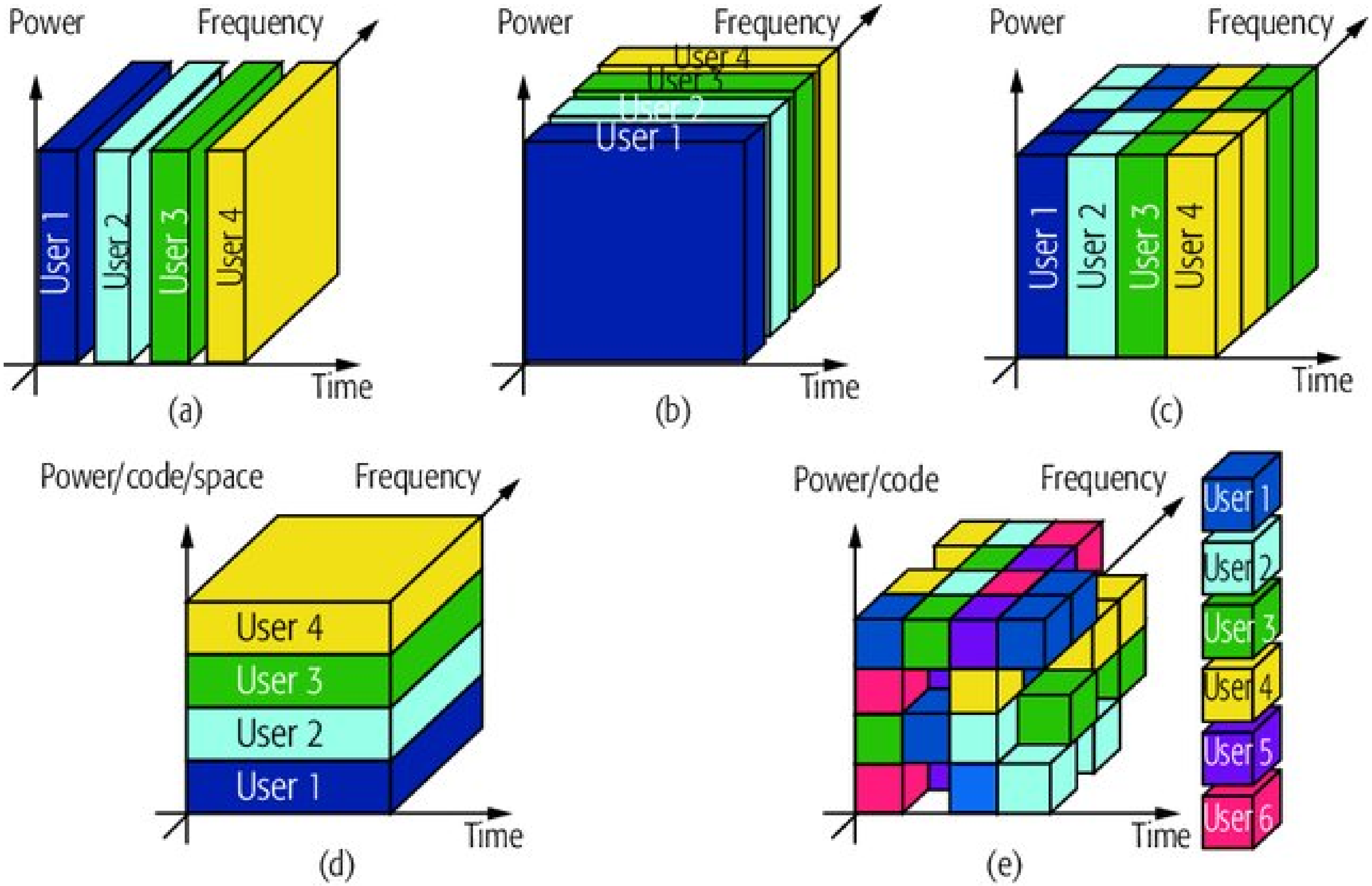
CDMA
SDMA
NOMA

SDD

Chirp SS

Half-duplex
Full-duplex

Multiple Access Types



Chen, Yan, et al. "Toward the standardization of non-orthogonal multiple access for next generation wireless networks." *IEEE Communications Magazine* 56.3 (2018): 19-27.

Code-Division Multiple Access (CDMA)

CODES

$c_A = (\,1\;\;1\;\;1\;\;1\;\;1\;\;1\;\;1\;\;1\,)^T$

$c_B = (\,1\;-1\;\;1\;-1\;\;1\;-1\;\;1\;-1\,)^T$

$c_C = (\,1\;\;1\;\;1\;\;1\;-1\;-1\;-1\;-1\,)^T$

Transmitter (Tx) 0: $-C_U$ 1: C_U

Receiver (Rx) $s_U(d) = c_U^T \cdot d$

A: 0, B: 1, C: 0 $d = -c_A + c_B - c_C$

Channel: $d = (-1\;-3\;-1\;-3\;1\;-1\;1\;-1)^T$

Rx:

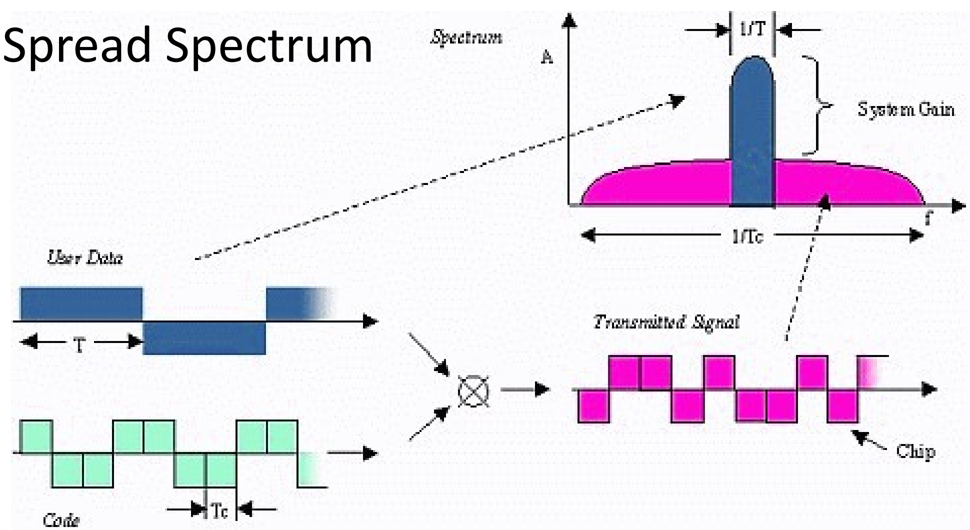
$s_A(d) = -8$ 0

$s_B(d) = 8$ 1

$s_C(d) = -8$ 0

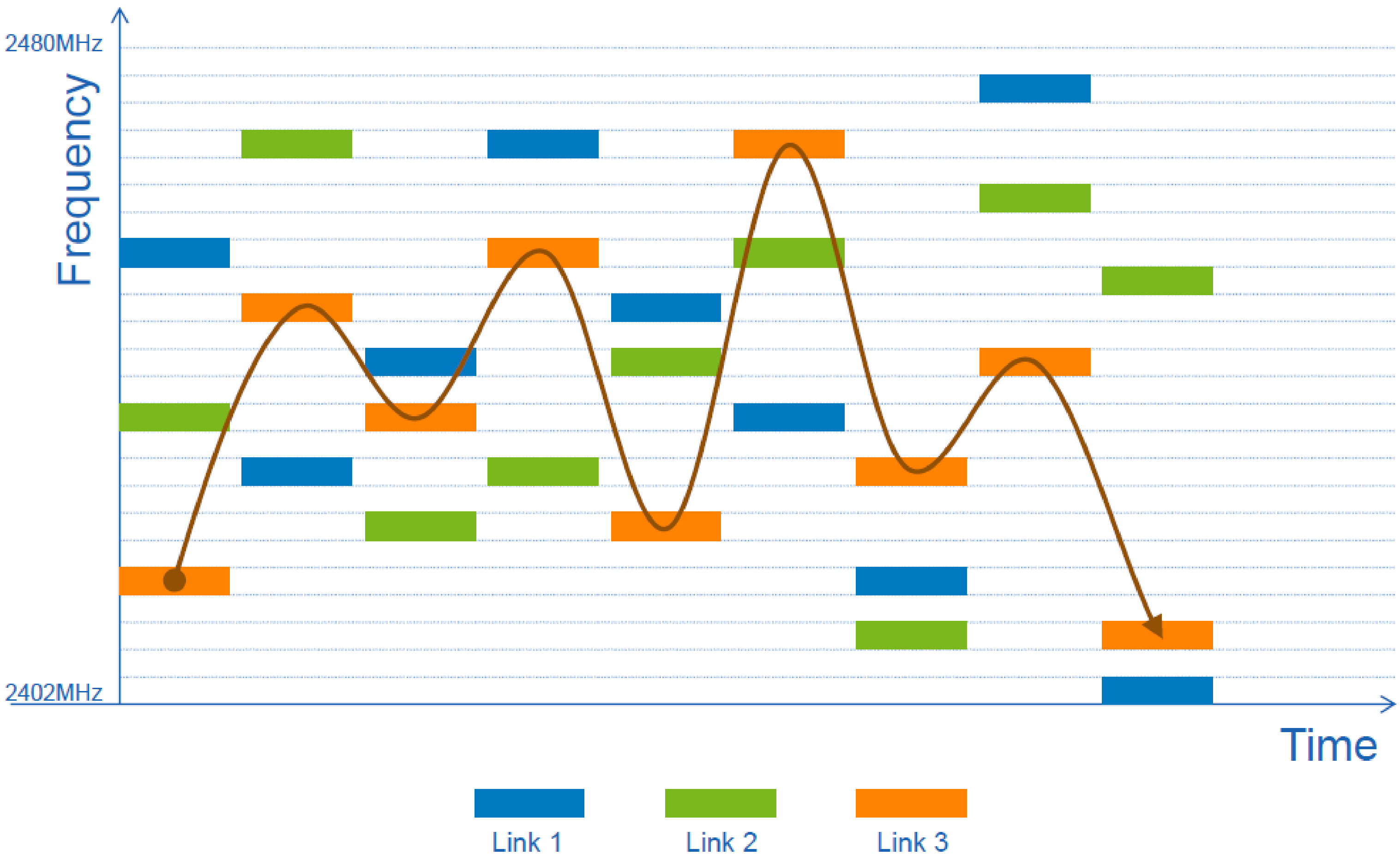
https://www.researchgate.net/publication/24009326_Quantum_multiplexing_with_optical_coherent_states/figures?lo=1

Direct Sequence Spread Spectrum



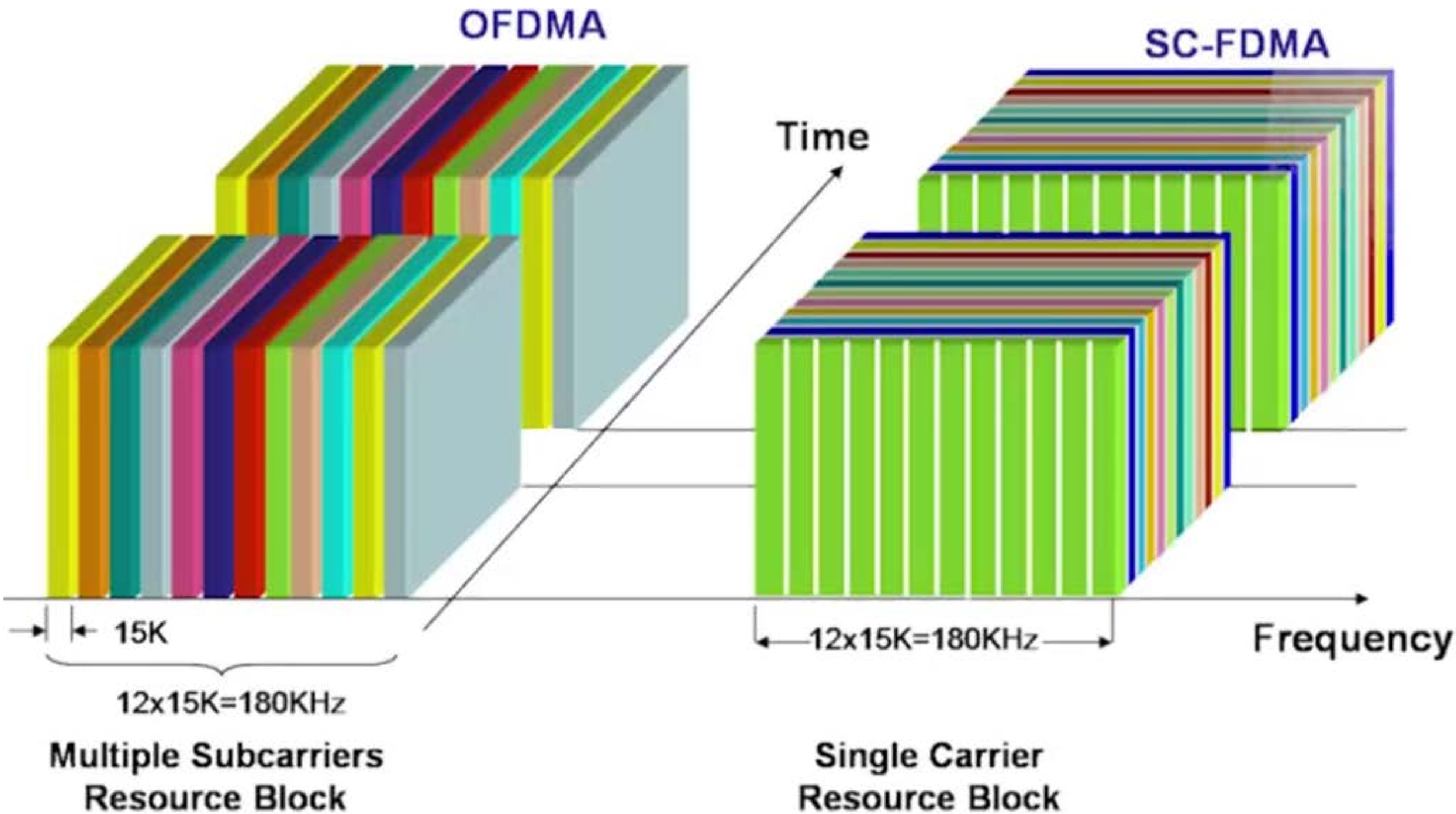
http://www.telecomabc.com/d/dsss.html

Frequency Hopping (FHSS)



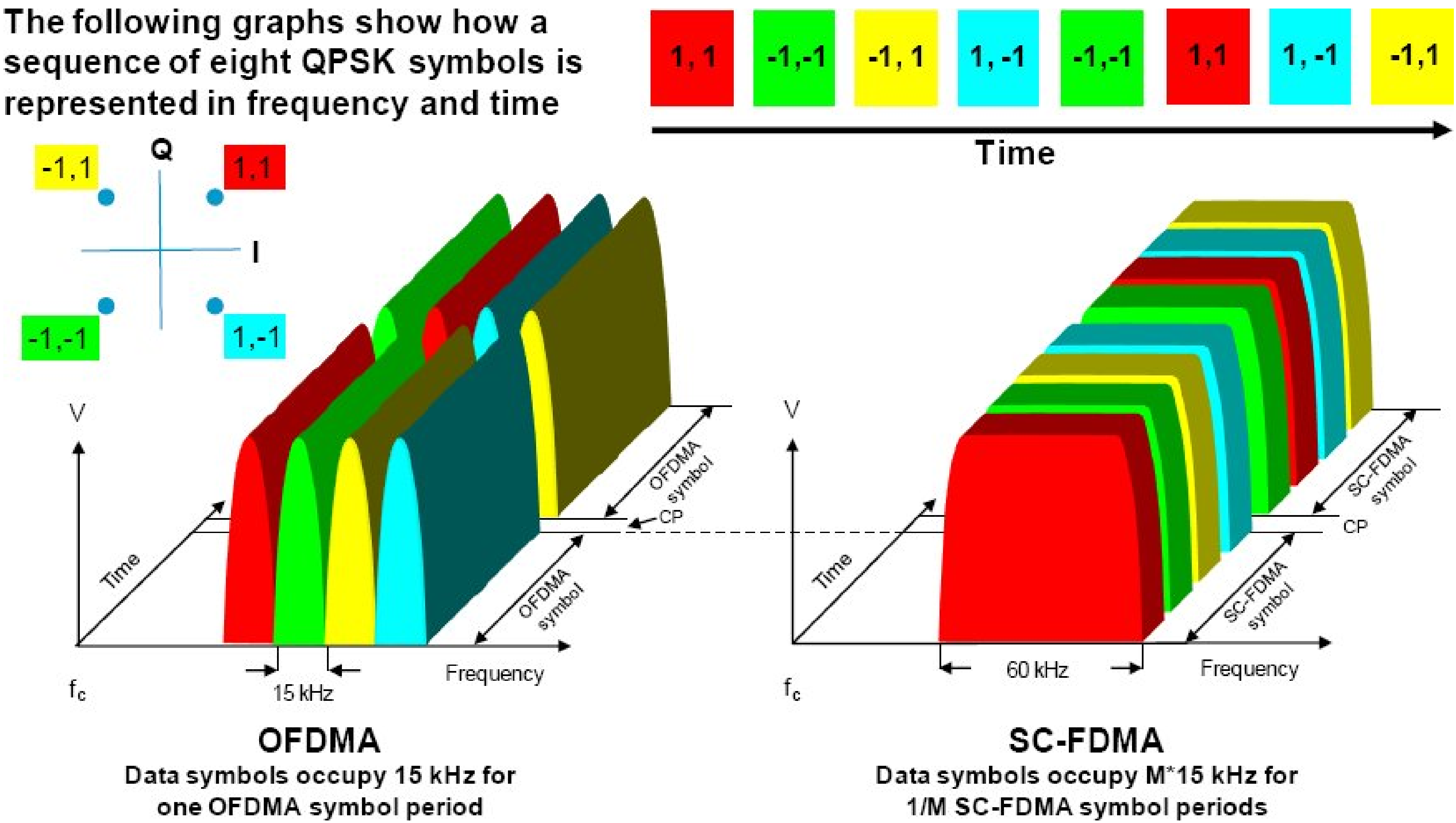
https://microchipdeveloper.com/

OFDMA/SC-FDMA



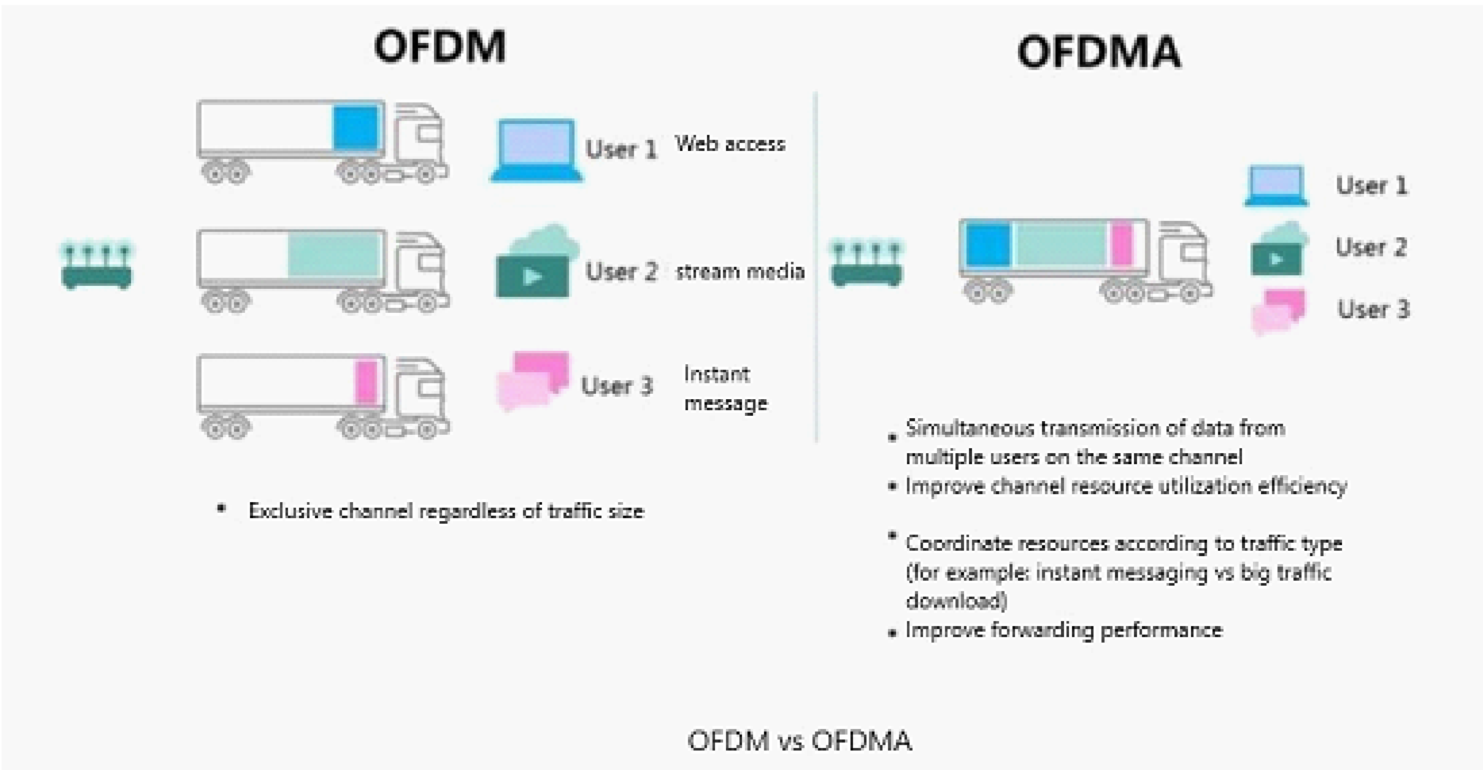
Source: https://www.gta.ufrj.br/ensino/eel879/trabalhos_vf_2014_2/rafaelreis/ofdma_scfdma.html

OFDMA/SC-FDMA



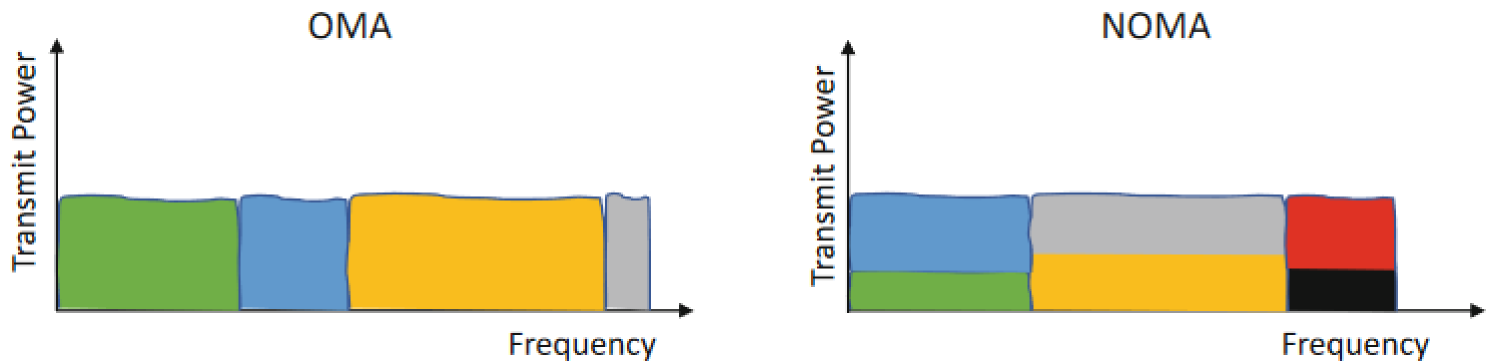
https://blog.3g4g.co.uk/2009/02/ofdm-and-sc-fdma.html

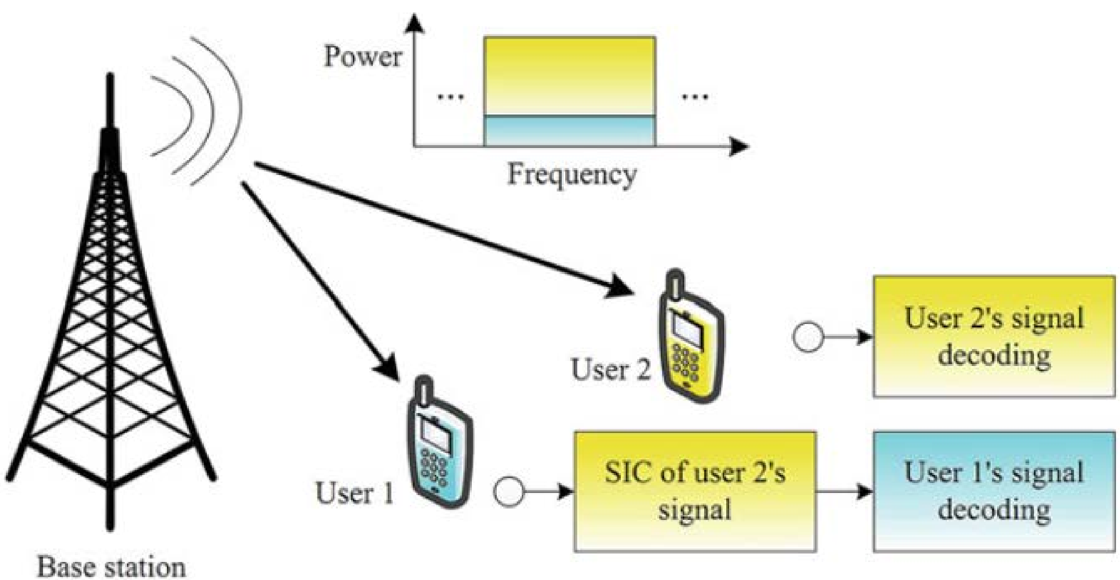
OFDM vs OFDMA



https://forum.huawei.com/enterprise/en/wifi-6-key-technologies-ofdma/thread/577958-869

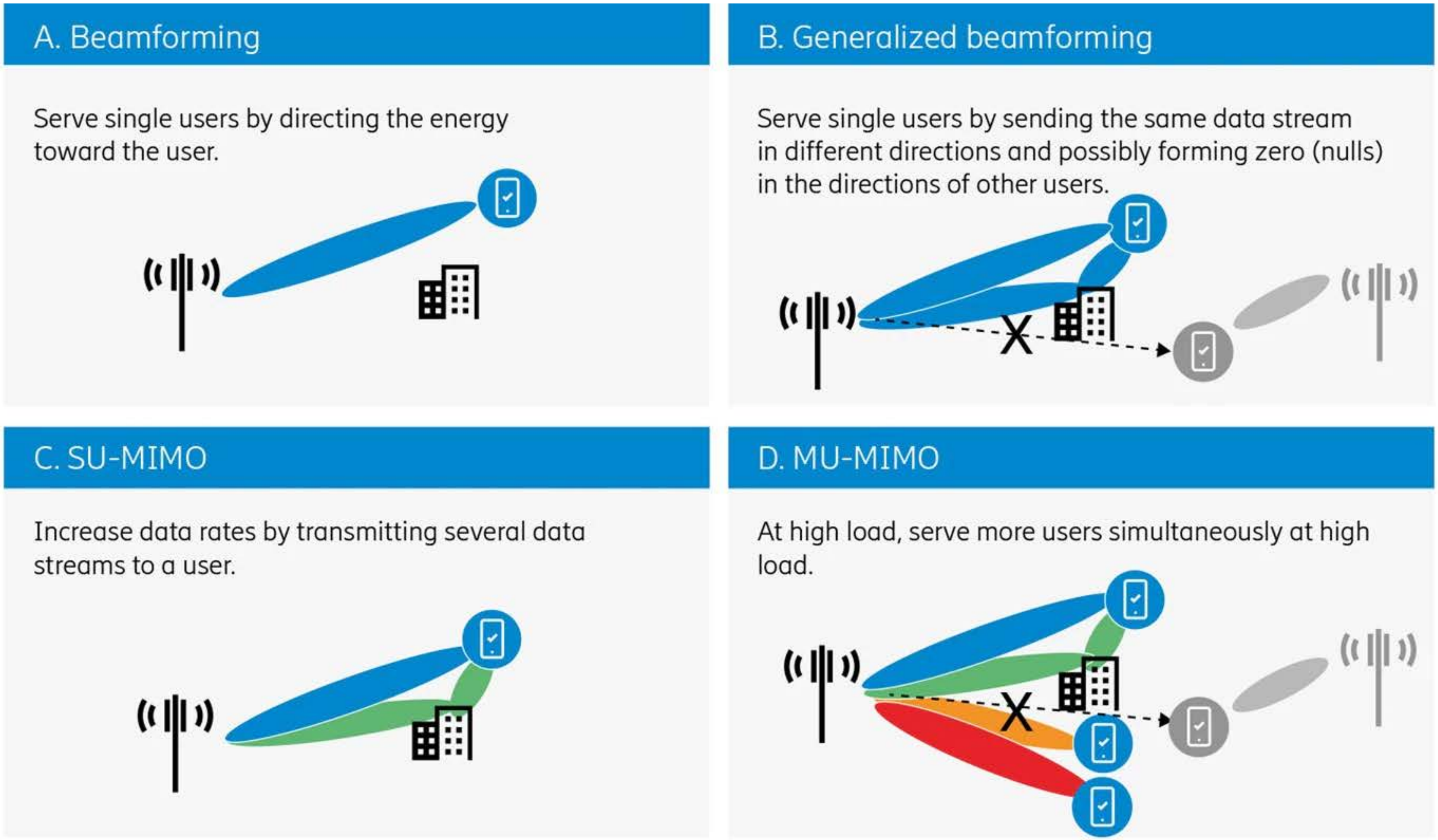
Non-orthogonal multiple access (NOMA)





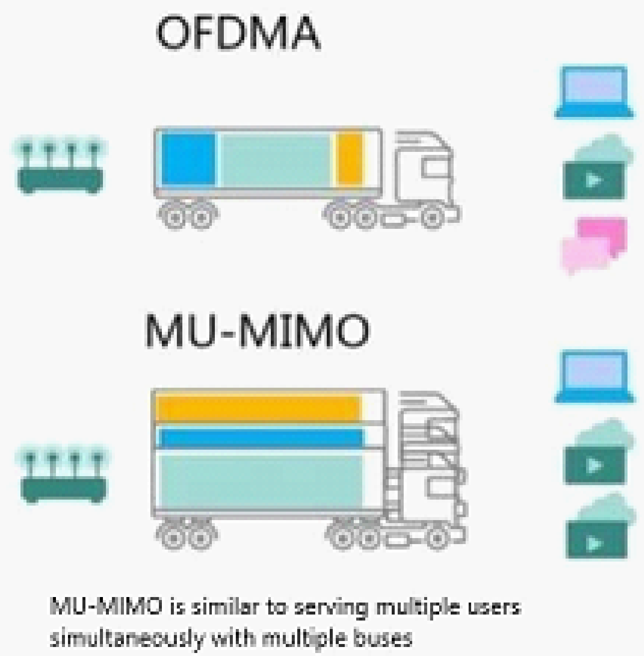
Source: Vaezi, Mojtaba, Zhiguo Ding, and H. Vincent Poor, eds. *Multiple access techniques for 5G wireless networks and beyond*. Cham: Springer, 2019.

Space/Spatial Division Duplex (SDD)



https://www.ericsson.com/en/reports-and-papers/white-papers/advanced-antenna-systems-for-5g-networks

OFDMA vs MU-MIMO



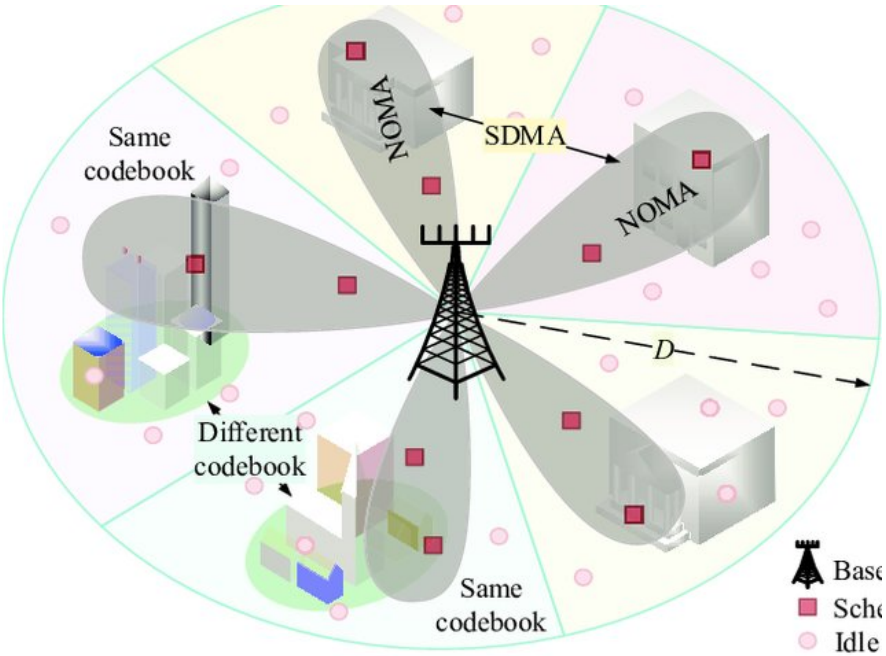
- OFDMA improves performance and efficiency
- OFDMA reduces latency
- Suitable for low bandwidth applications

- MU-MIMO boost capacity
- MU-MIMO provides high-speed connectivity for each user
- Suitable for high bandwidth applications

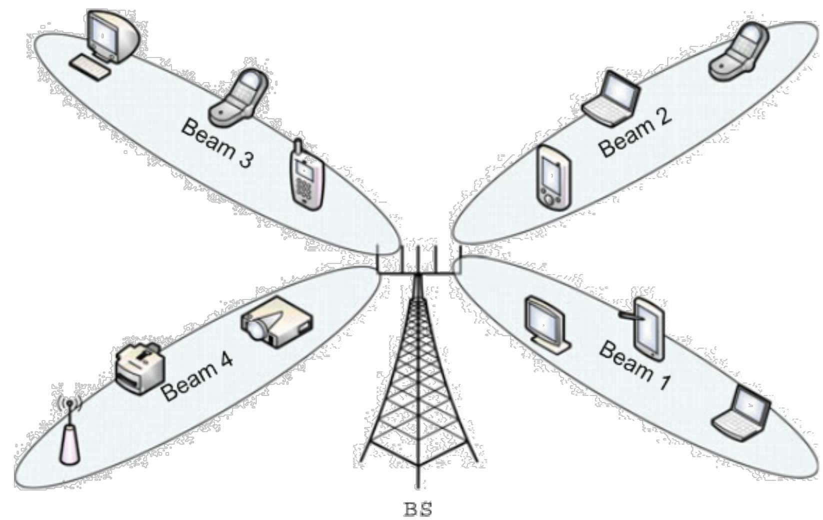
Use OFDMA and MU-MIMO depending on the type of application being served

https://forum.huawei.com/enterprise/en/wifi-6-key-technologies-ofdma/thread/577958-869

Space-division multiple access (SDMA)



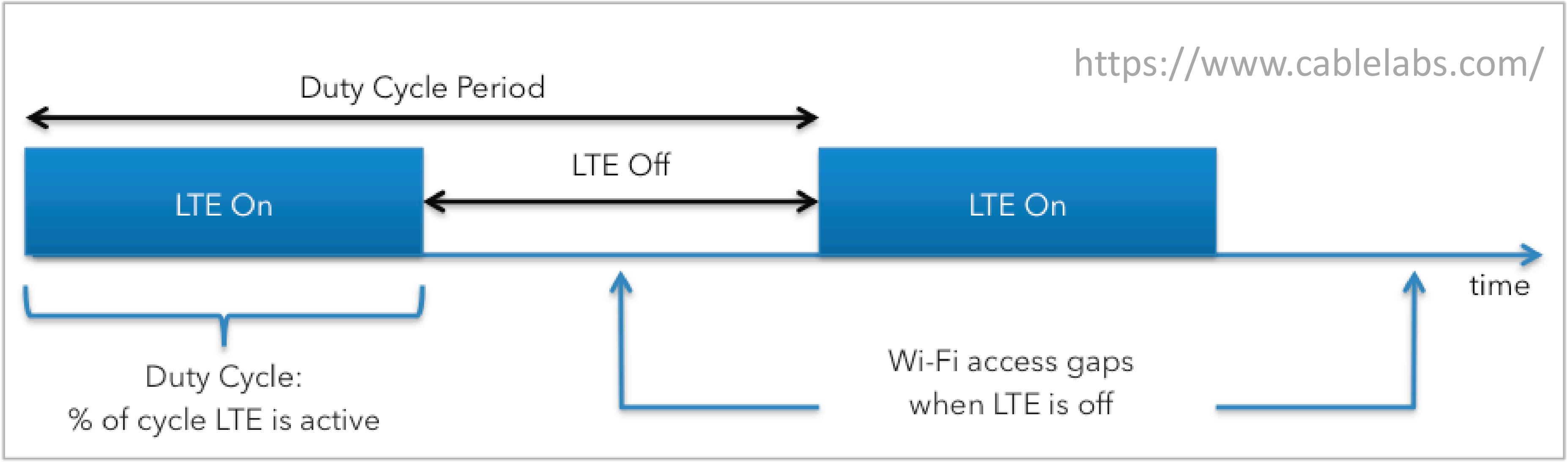
Yang, Qian, et al. "Outage performance of NOMA in downlink SDMA systems with limited feedback." *2017 IEEE International Conference on Communications (ICC)*. IEEE, 2017.



A multiuser NOMA communication system with 4 clusters

Vaezi, Mojtaba, Zhiguo Ding, and H. Vincent Poor, eds. *Multiple access techniques for 5G wireless networks and beyond*. Cham: Springer, 2019.

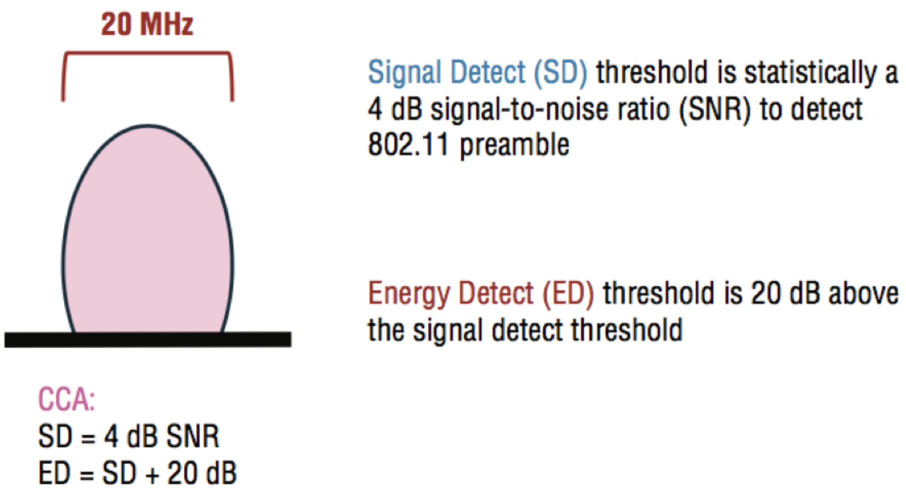
Duty Cycle (TDD)



- Do not sense the channel before transmission
- Turn transmisison on/off for some time

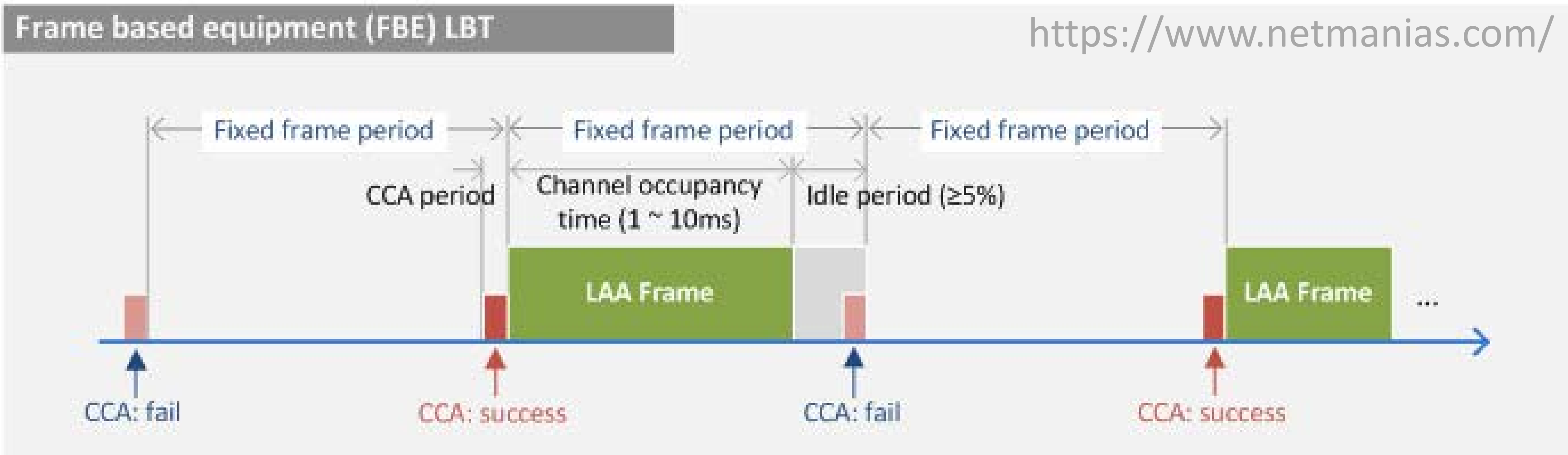
Listen Before Talk (LBT)

- Before using the channel, equipment first applies Clear Channel Assessment (CCA)
  - Channel is considered occupied if the energy level in the channel exceeds some threshold
  - If the channel is clear, equipment starts transmitting



https://www.extremenetworks.com

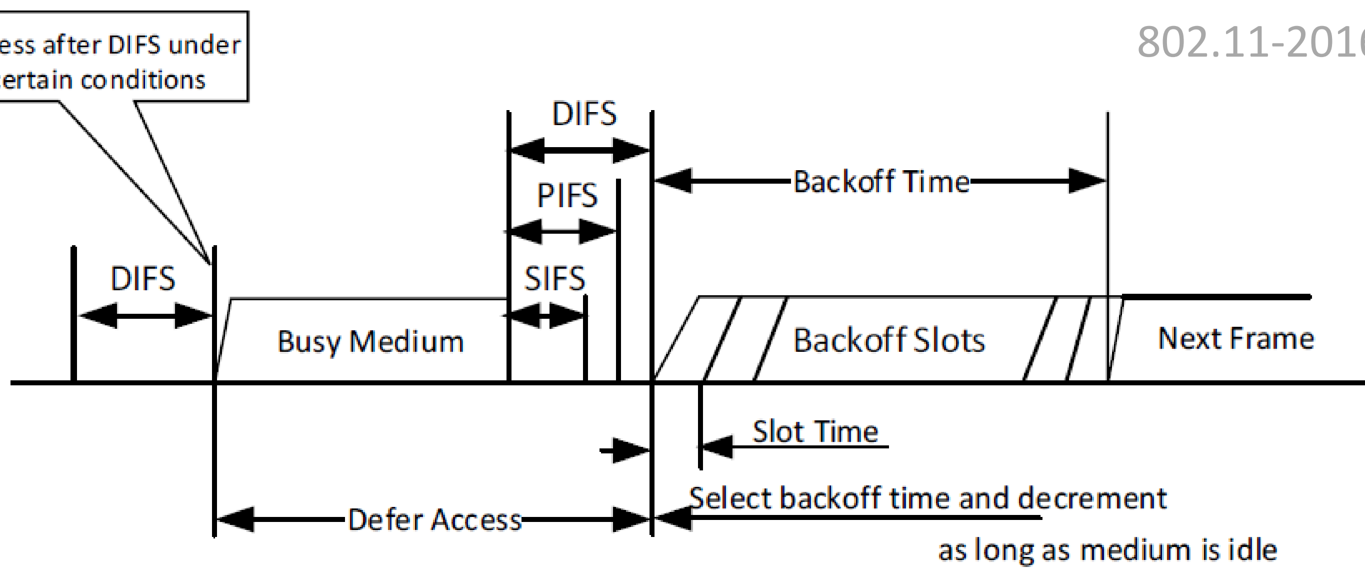
Frame-based Equipment



- Transmissions on fixed timing, with fixed frame period
- At the end of idle frame – clear channel assessment (CCA)
  - Busy channel: skip frame and perform CCA in the next frame period
  - Empty channel: transmission at the beginning of the next frame

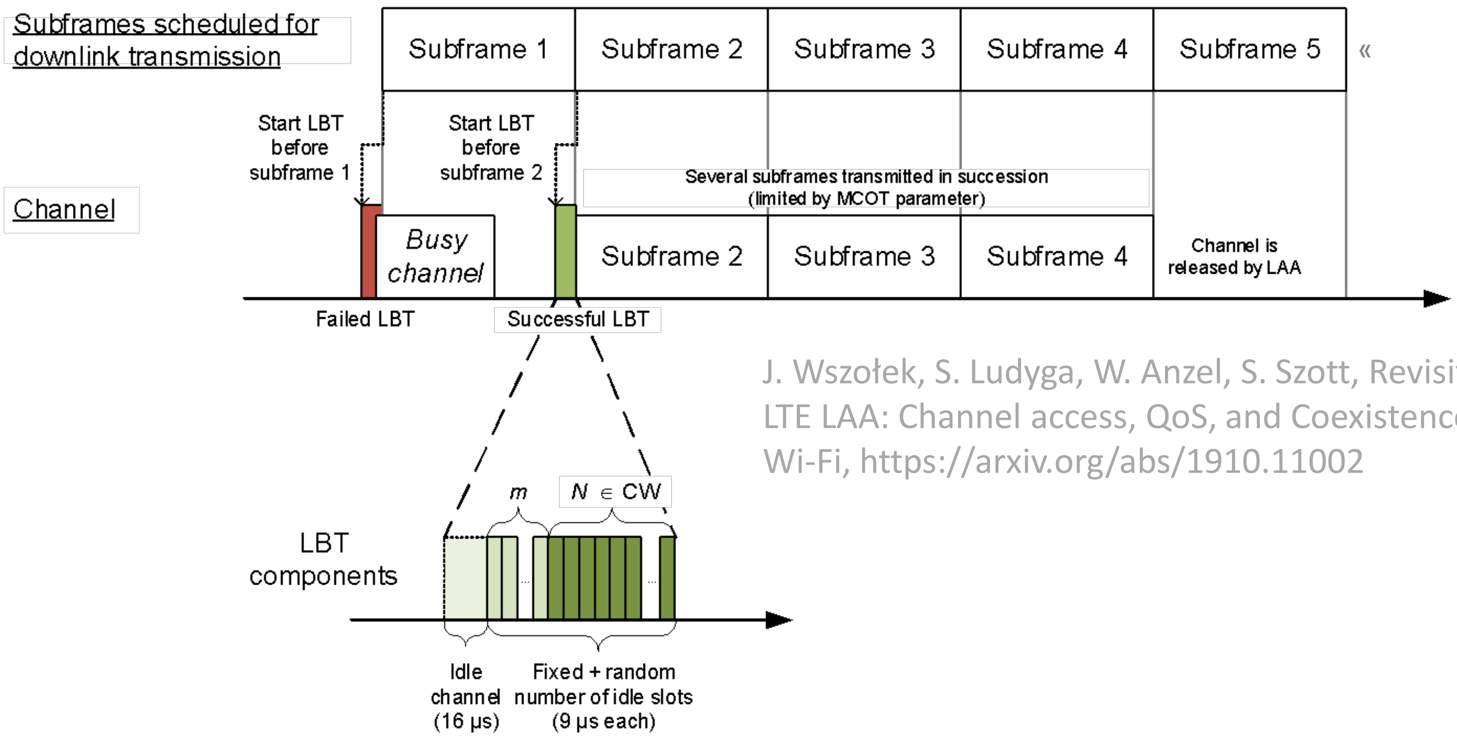
Random Backoff

- Device selects a random number *N* in {0, ..., CW}, CW: contention window
  - Backoff Time = Random() x aSlotTime
- CCA performed for each observation slot, results either in decrementing *N* by 1 or freezing the backoff procedure
- Once *N* reaches 0, a transmission may commence



802.11-2016

Load-based Equipment



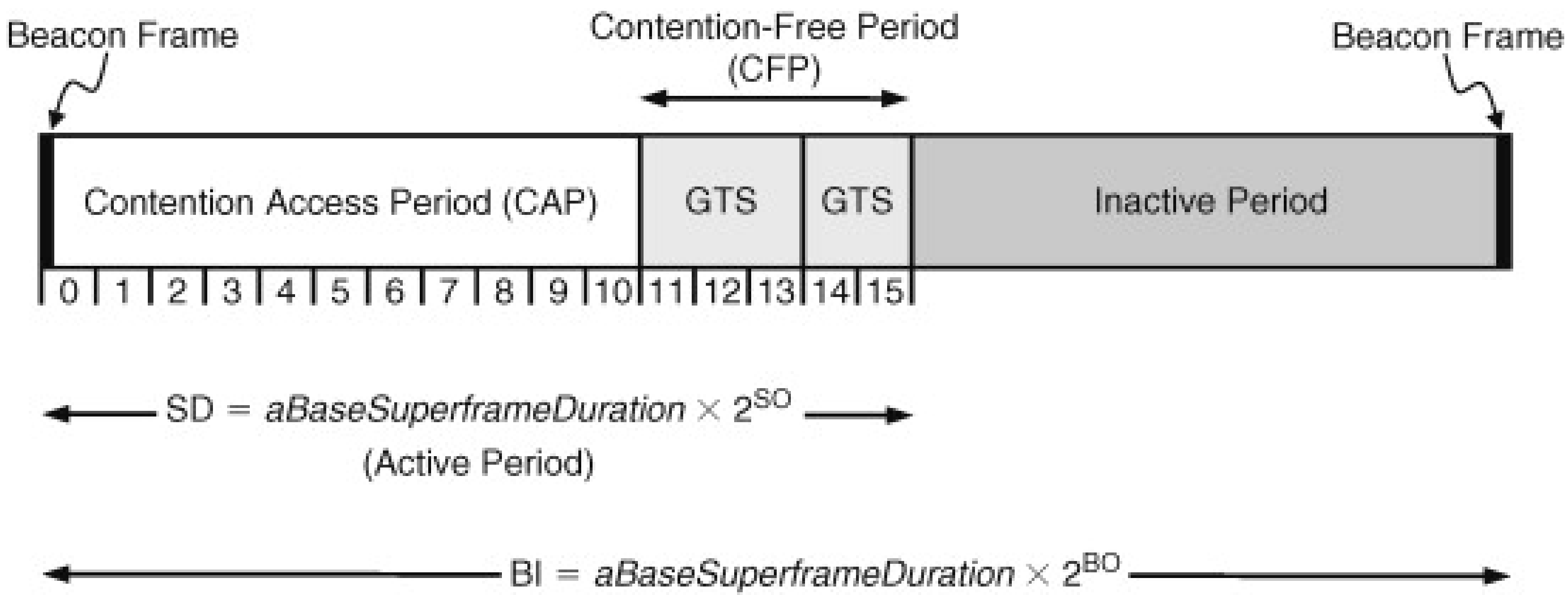
J. Wszołek, S. Ludyga, W. Anzel, S. Szott, Revisiting LTE LAA: Channel access, QoS, and Coexistence with Wi-Fi, https://arxiv.org/abs/1910.11002

- Perform CCA whenever needed to send frames
  - Busy channel: calculate backoff and wait for the medium to become idle again
  - Empty channel: immediate transmission

Super Frames

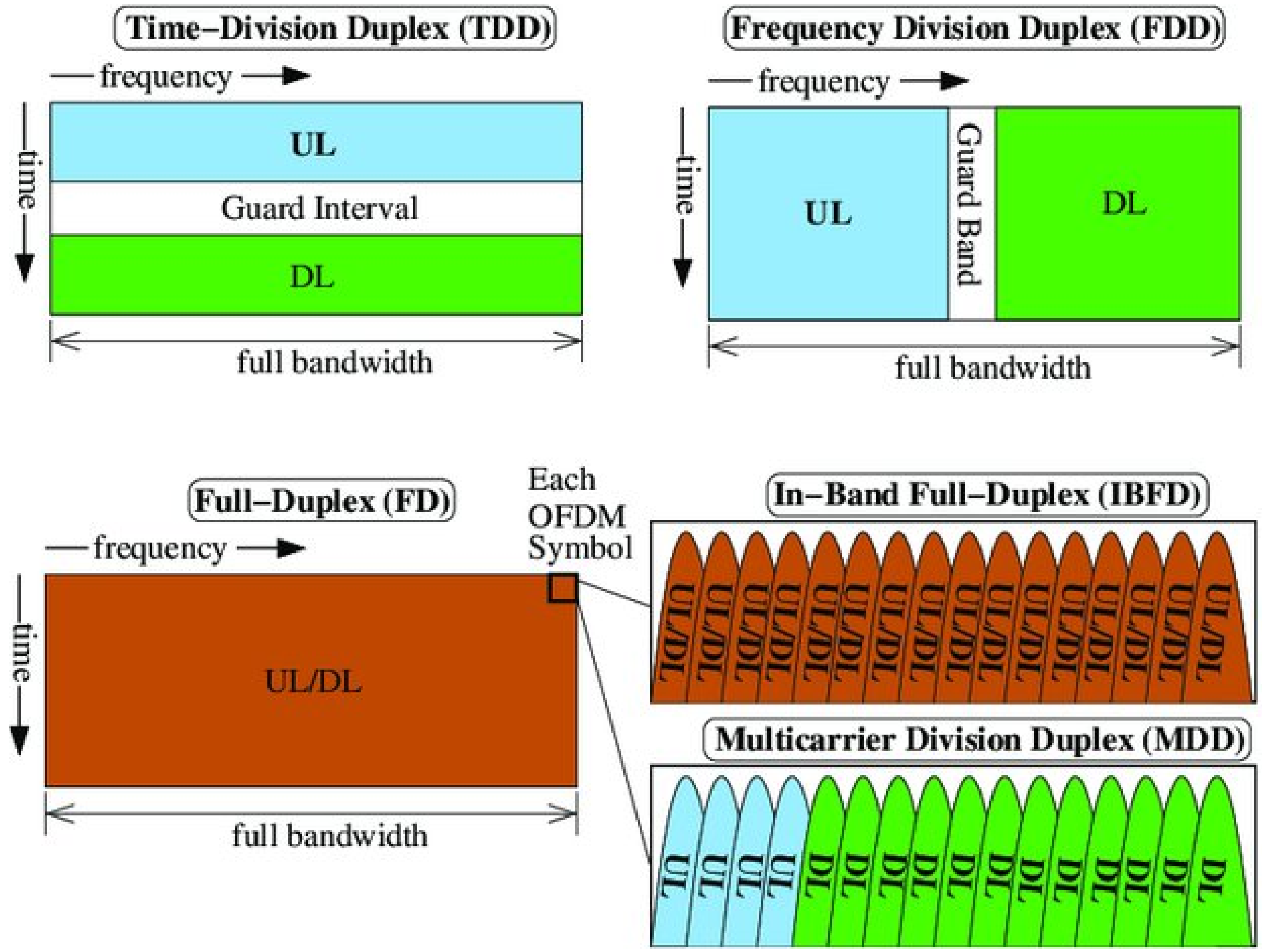
CSMA/CA is mandatory in CAP
- Access is not guaranteed

CSMA/CA is not allowed within CFP
- Access is guaranteed
- Good for low-latency applications



https://www.sciencedirect.com/topics/computer-science/guaranteed-time-slot

Full-duplex: TDD/FDD/IBFD/MDD



Xu, Chao, et al. "Sixty years of coherent versus non-coherent tradeoffs and the road from 5G to wireless futures." *IEEE Access* 7 (2019): 178246-178299.

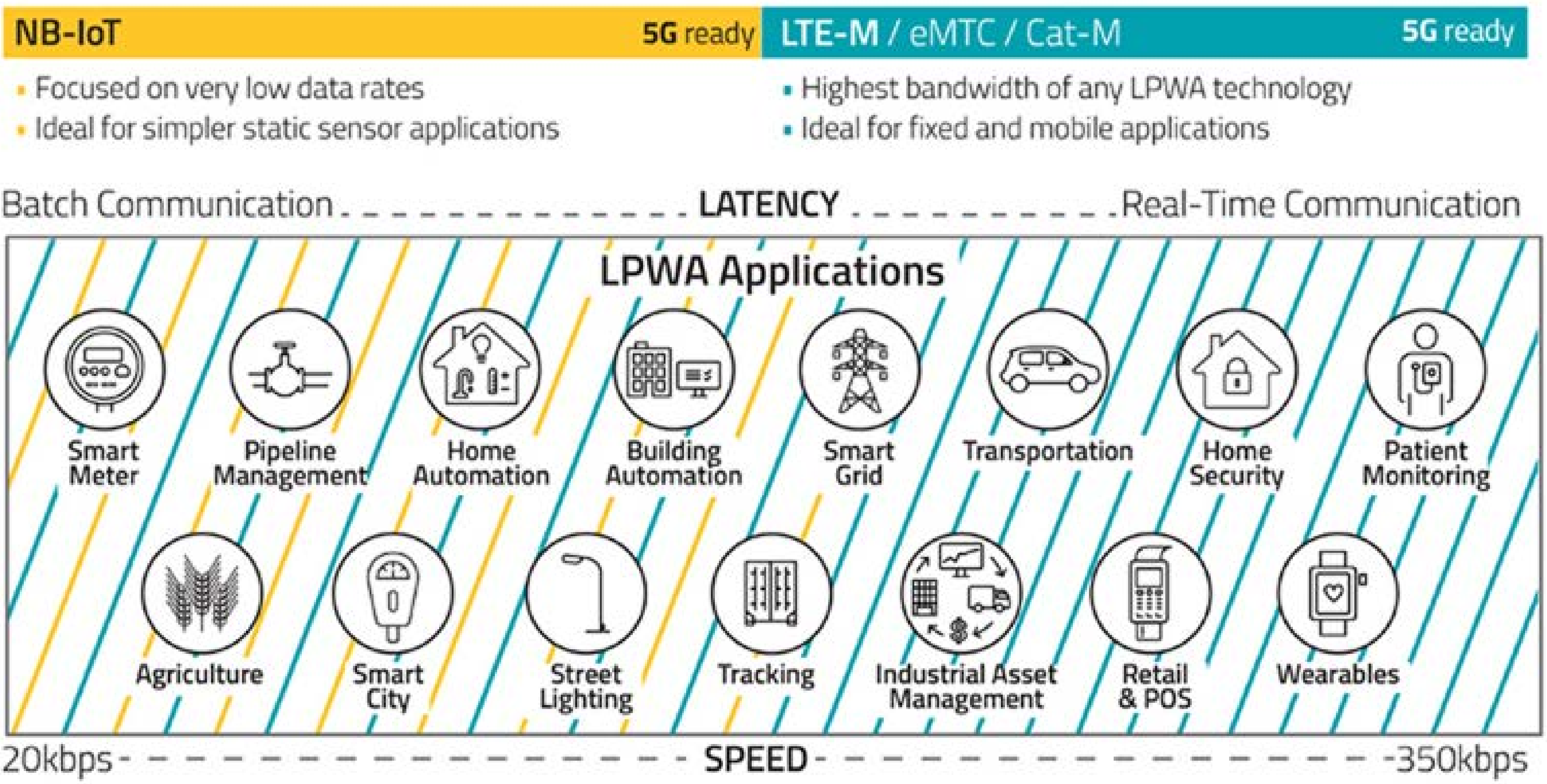
Short Range Communications Comparison

Type	Range [m]	Data rate [Mb/s]	No. of devices	Latency [ms]	Channel Access method	Power consumption	Frequency band
BLE	100	2	No limit	6	FHSS, duty cycle	Low	2.4 GHz
6LoWPAN	200	0.2	100	1000-2000	CSMA/CA, time slotting, duty cycle	Low	< 1 GHz, 2.4 GHz
Wi-Fi	10 – 1000	347 (11ah) – 7000 (11ad)	8191 (11ah)	Even <1	CSMA/CA, partially scheduled access (e.g., OFDMA in 802.11ax)	High to low	<1GHz, 2.4 GHz, 5 GHz, 60 GHz

Long Range Communications Comparison

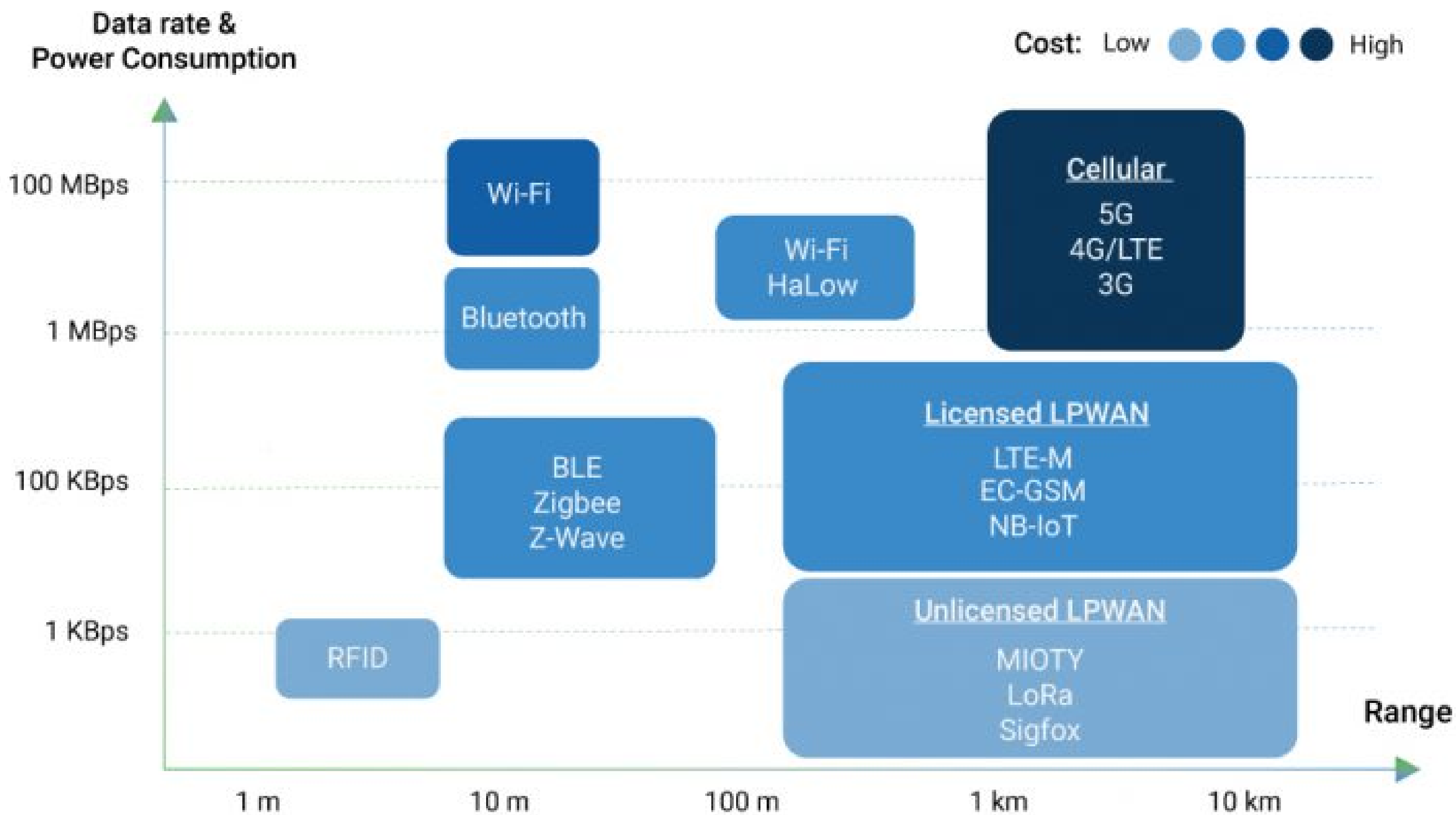
Type	Range [km]	Data rate [Mb/s]	No. of devices	Lat. [s]	MAC	Power consumption	Freq. band
LoRaWAN	15	0.05	1 M (UL), 100 K (DL)	1-10	Duty cycle, channel hopping	Medium	433/780/ 868/915 MHz
SigFox	50	0.1	1 M	1-30	Duty cycle, channel hopping	Medium	868/902 MHz
NB-IoT	15	0.25	> 50 K	2-10	SC-FDMA (UL), OFDMA (DL)	High	Licensed, mostly <1 GHz
LTE-M	15	1	> 50 K	2-10	SC-FDMA (UL), OFDMA (DL)	High	Licensed, mostly <1 GHz

NB-IoT vs LTE-M



Source: https://www.sierrawireless.com/iot-blog/iot-blog/2018/04/lte-m-vs-nb-iot/

Wireless IoT Technologies



https://industrytoday.com/best-uses-of-wireless-iot-communication-technology/

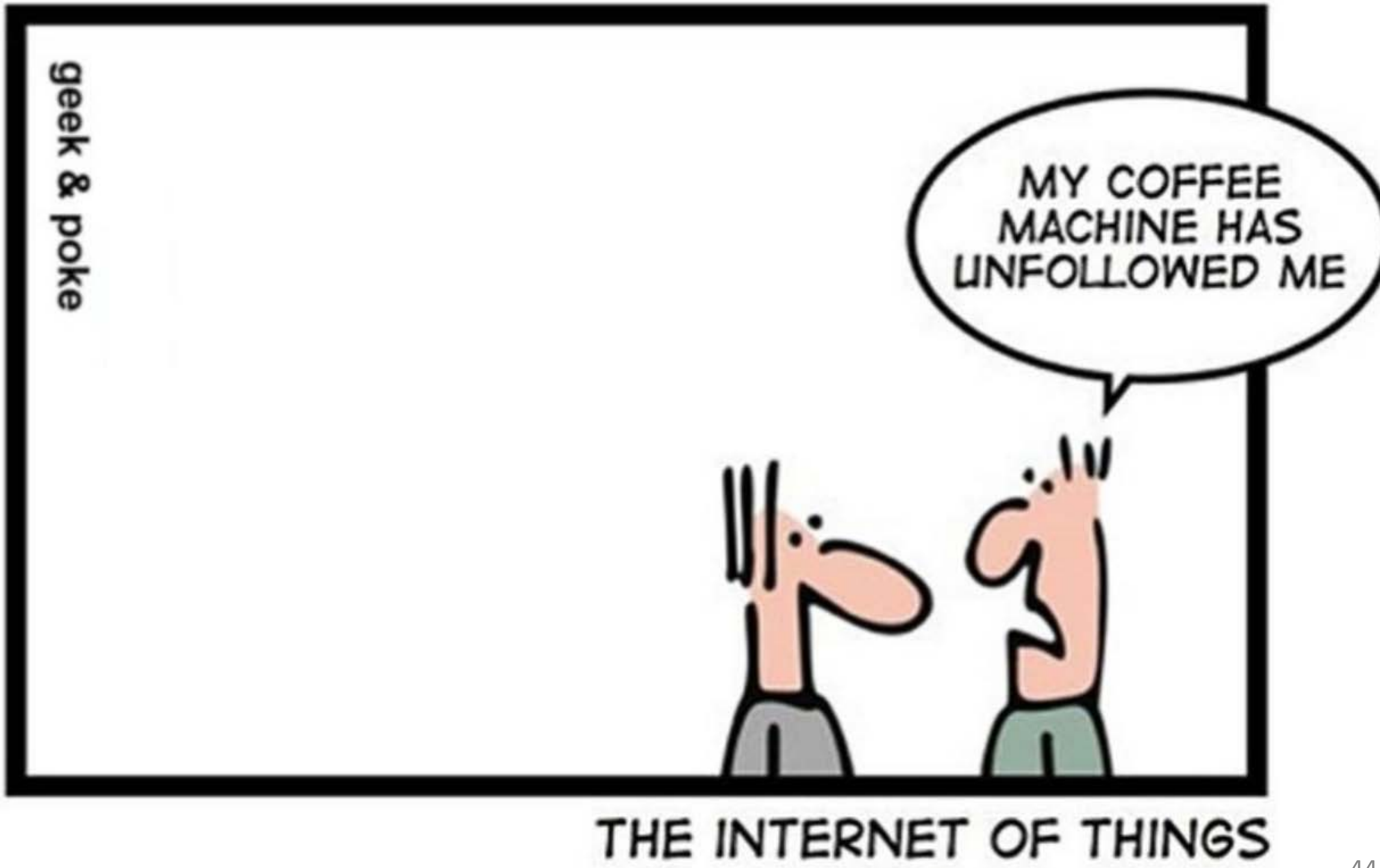
Wireless IoT Technologies

Key IoT Verticals	LPWAN (Star)	Cellular (Star)	Zigbee (Mostly Mesh)	BLE (Star & Mesh)	Wi-Fi (Star & Mesh)	RFID (Point-to-point)
Industrial IoT	●	○	○			
Smart Meter	●					
Smart City	●					
Smart Building	●		○	○		
Smart Home			●	●	●	
Wearables	○			●		
Connected Car					○	
Connected Health		●		●		
Smart Retail		○		●	○	●
Logistics & Asset Tracking	○	●				●
Smart Agriculture	●					

● Highly applicable ○ Moderately applicable

https://industrytoday.com/best-uses-of-wireless-iot-communication-technology/

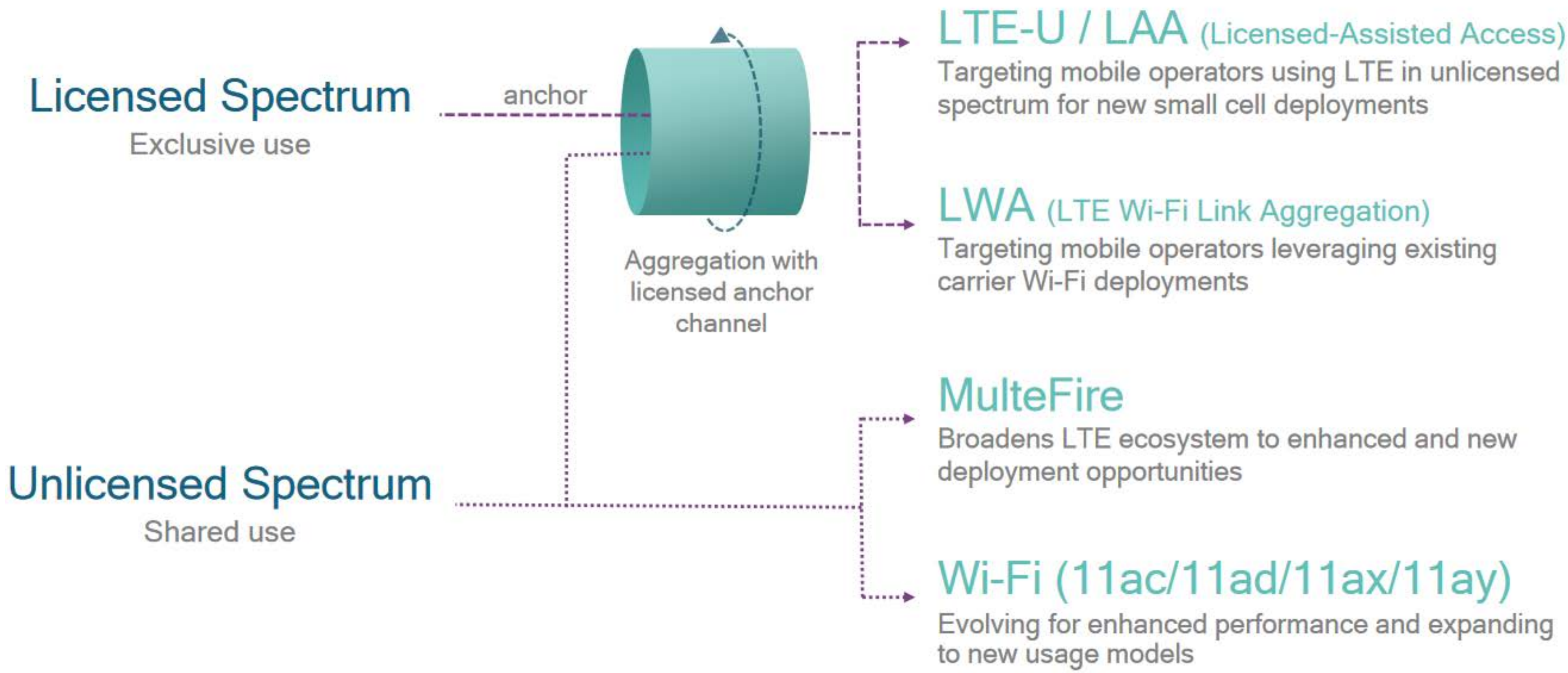
Questions?


geek & poke
MY COFFEE MACHINE HAS UNFOLLOWED ME
THE INTERNET OF THINGS

- Dodatkowe informacje do wykładu

SHORT RANGE COMMUNICATIONS

Unlicensed Band Co-Existence



IEEE 802.11a/b/g/n/ah/af

https://www.qualcomm.com/

IEEE 802.11 (WiFi)

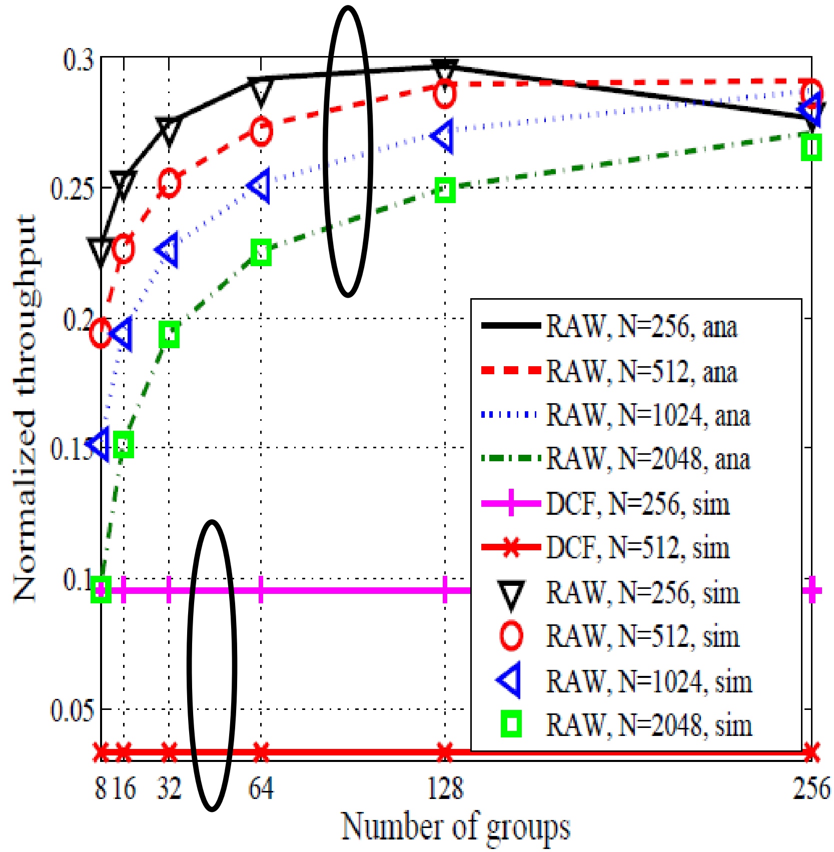
- Unlicensed band (**<1 GHz, 2.4 GHz, 5 GHz, 60 GHz**)
  - **1 MHz** (802.11ah) - **2.16 GHz** (802.11ad) channel widths
- Max data rates: **347 Mb/s** (11ah) - **7 Gb/s** (11ad)
- Range: **10 m** (11ad) - **1 km** (11ah)
- Topology
  - Infrastructure, ad-hoc, mesh
  - Star, tree (802.11h)
- **PHY**
  - **OFDM**, BPSK, QPSK, QAM, OFDMA, MIMO, MU-MIMO, beamforming
- **MAC**: **CSMA/CA, random backoff, CCA, scheduled channel access**
- Power consumption: high (legacy) – low (802.11ah)
- Security: WPA2 Personal/Enterprise: Preshared Key/802.1X + AES (802.11i) oraz WPA3 Personal/Enterprise: Simultaneous Authentication of Equals/ WPA3-Commercial National Security Agency

IEEE 802.11ah > 8000 STAs

- Short MAC headers (36 B -> 14 B), short beacons
- **Bi-directional TXOP**
  - UL/DL transmissions
- Sectorization: **beamforming**
- **Relay access points**
- Station types
  - **TIM** (periodically receive information from AP)
  - **non-TIM** (use TWT, manage to keep a long sleep mode)
- Target wake time (TWT)
  - AP schedules channel access for STAs
- **Fast association mechanism**
- **Restricted access window** (**RAW**)
  - Channel access only for a group of stations

Restricted Access Window

- Goal: reducing the contention
  - Stations divided into groups
  - Channel splitted into slots
  - Each slot is assigned to a group
- TDMA vs CSMA/CA

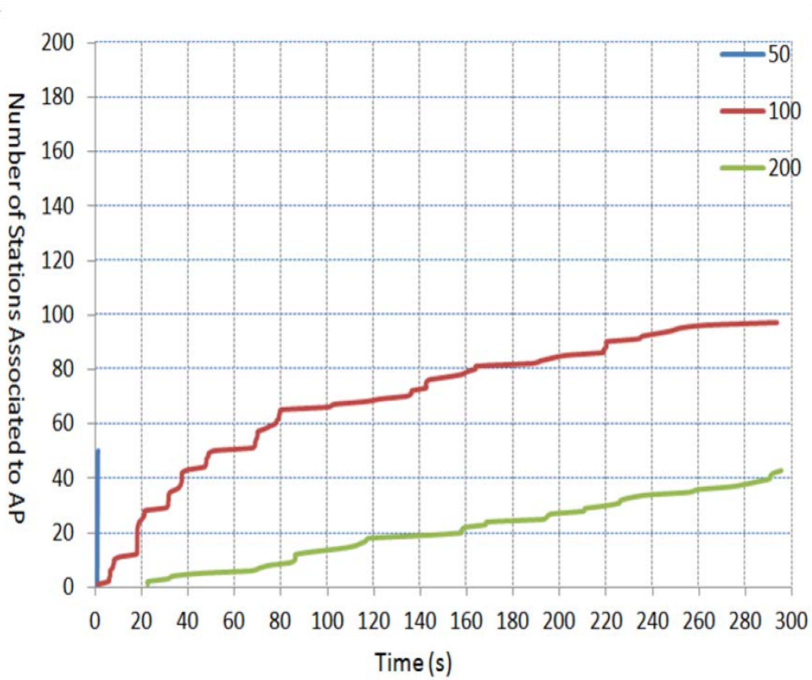


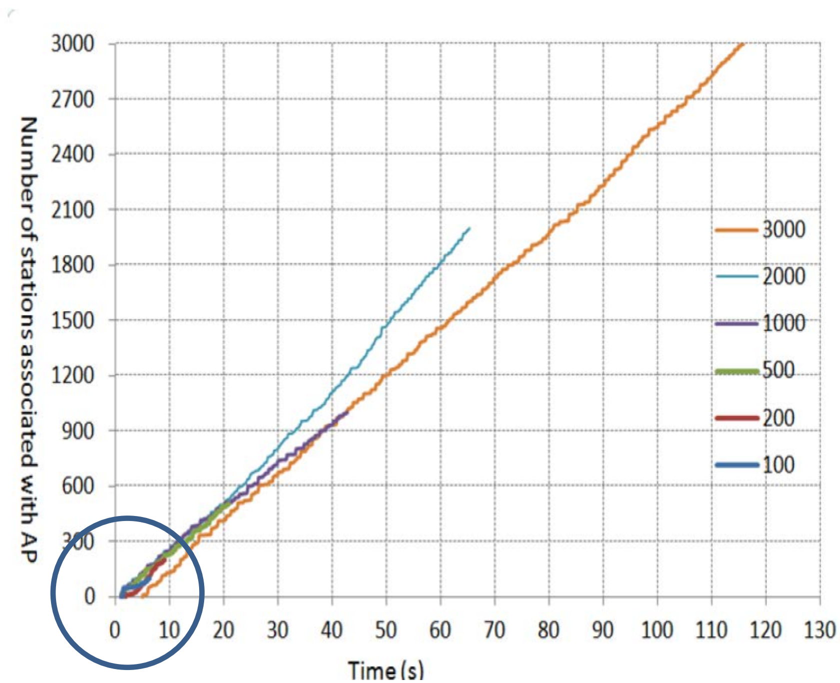
E. Khorov et al. A survey on IEEE 802.11ah: an Enabling Networking Technology for Smart Cities, Computer Communications, Volume 58, March 2015, pp. 53–69

Fast Station Association

- RAW does not eliminate contention at network initialization
- Example
  - 5000 STAs try to associate with the AP
  - Result: collisions, long association time
- Solution
  - Association of a fraction of STAs in each beacon interval

Time of Association, w/o FSA vs w/ FSA

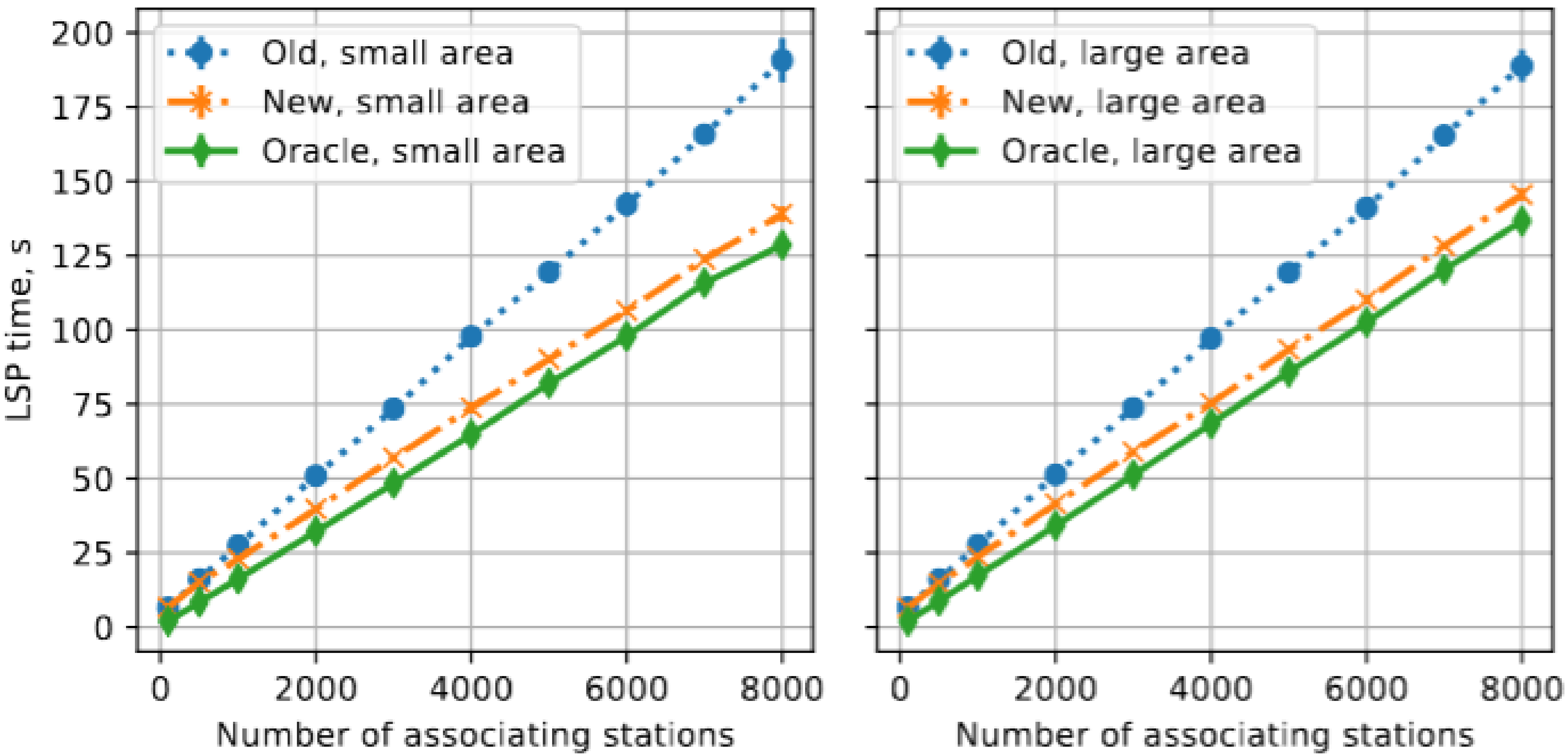




Less than 10 sec!

Supporting Authentication/Association for Large Number of Stations, doc.: IEEE 802.11-12/0112r4

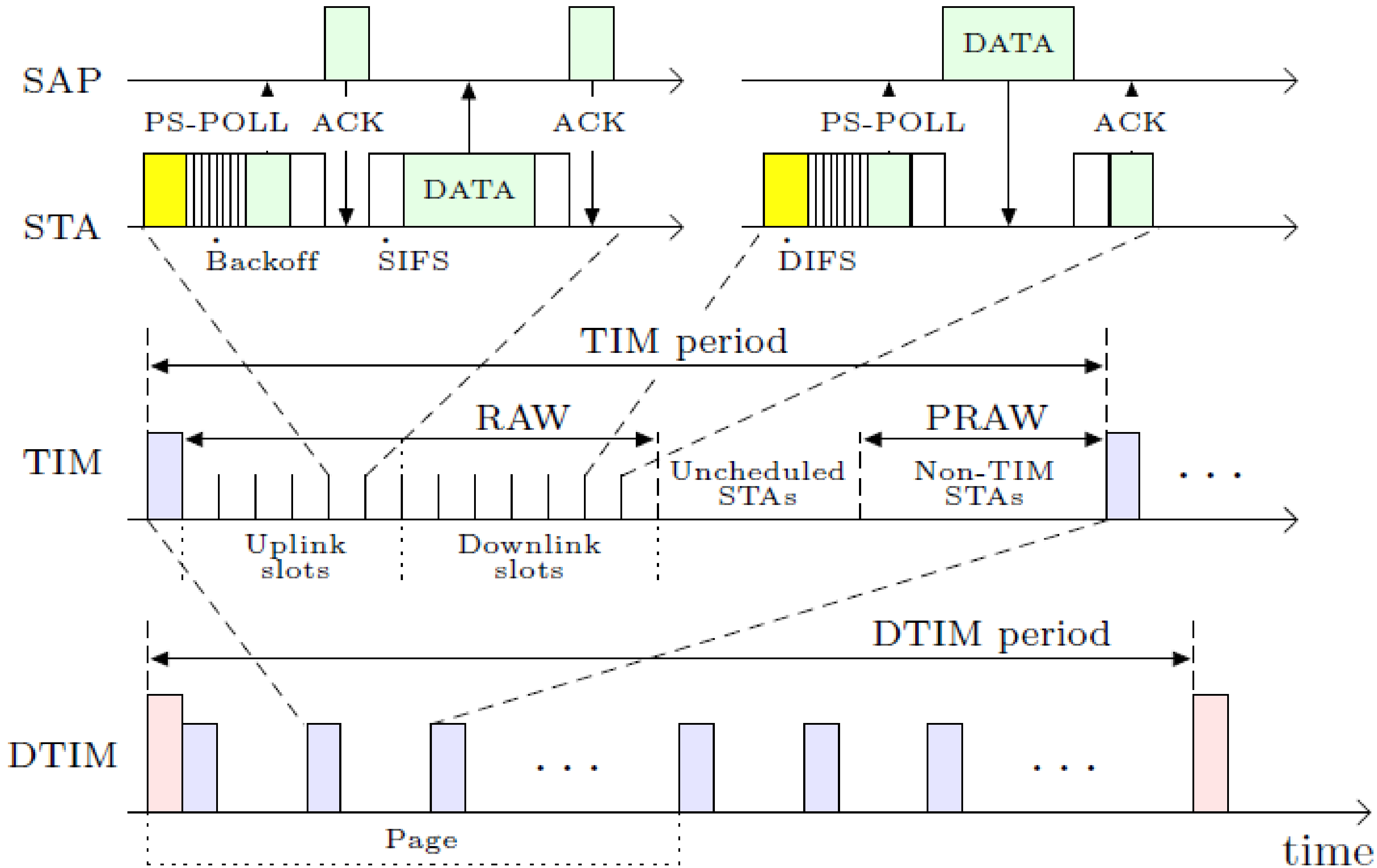
OLD vs NEW



Old: Bankov, D., Khorov, E., Lyakhov, A., Stepanova, E., Tian, L., & Famaey, J. (2018). *What Is the Fastest Way to Connect Stations to a Wi-Fi HaLow Network?*. *Sensors*, *18*(9), 2744.
New: Super Fast Link Set-up in Wi-Fi HaLow Networks

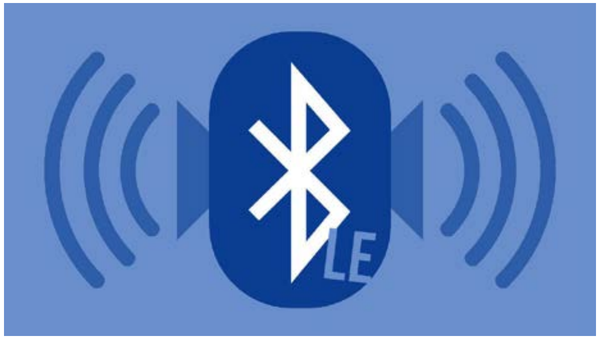
IEEE 802.11ah

Delivery TIM (DTIM)



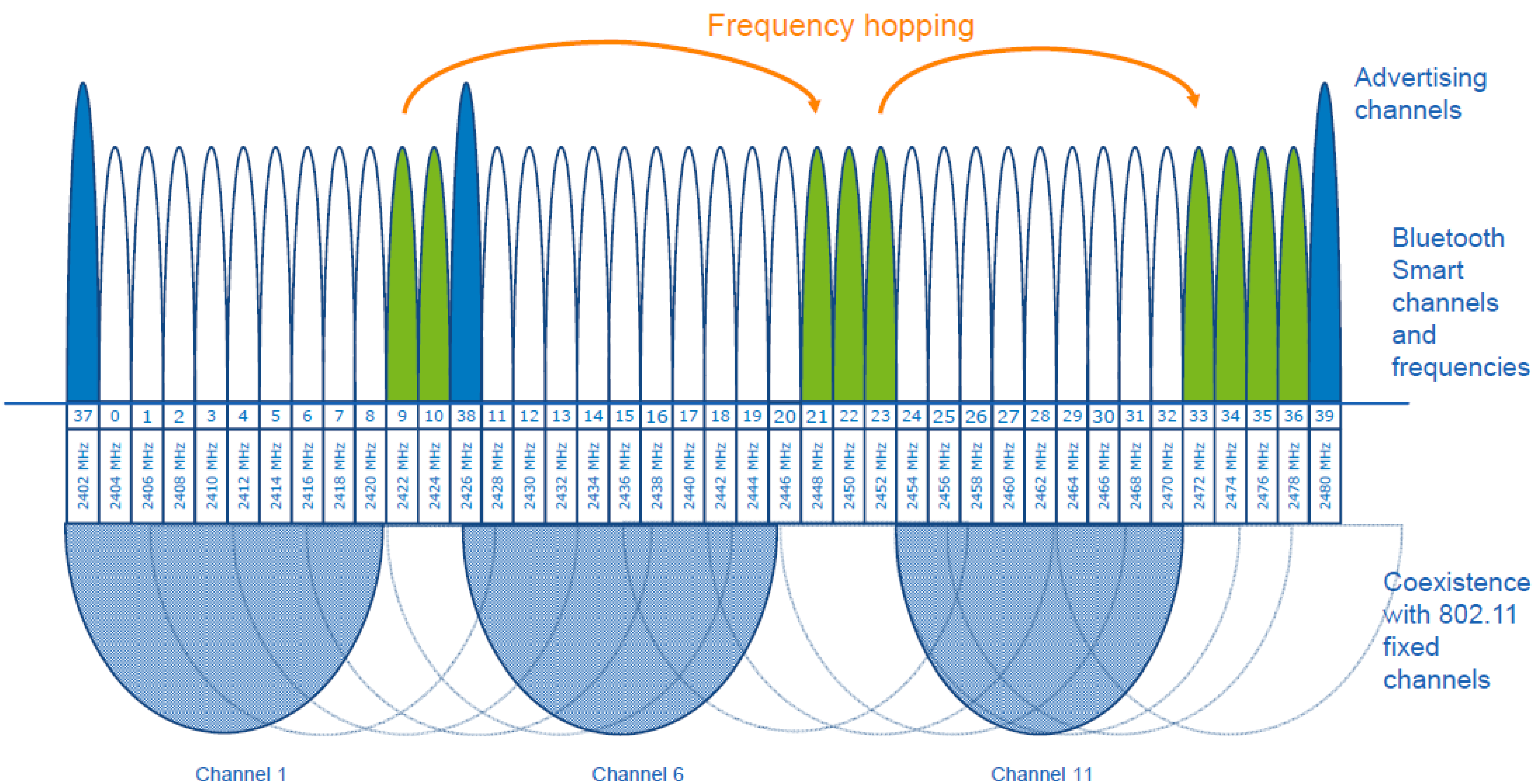
Source: M. Shafiq et al. Multiple Access Control for Cognitive Radio-Based IEEE 802.11ah Networks, MDPI Sensors, 2018

Bluetooth Low Energy/ Bluetooth Smart



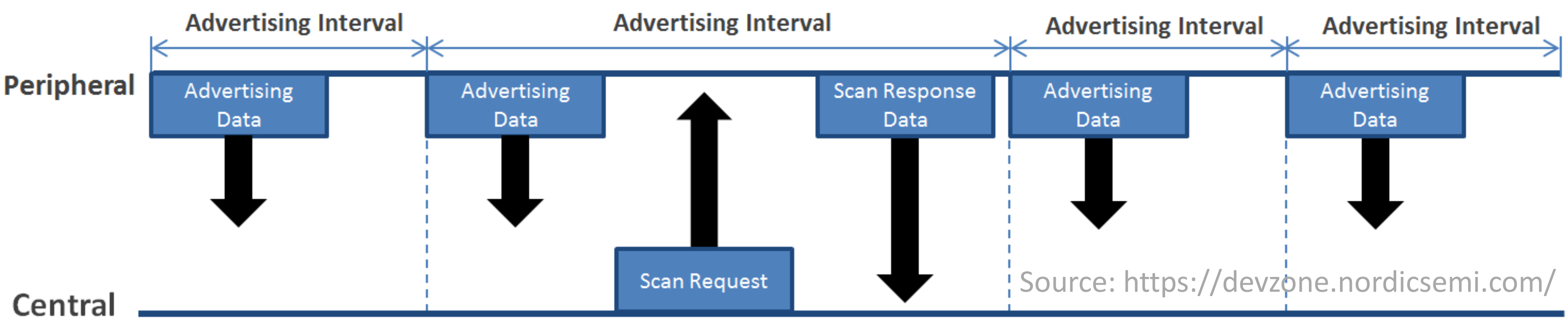
- Unlicensed band (**2.4 GHz**)
  - **37 x 2 MHz data channels**
  - **3 x 2 MHz advertising channels**
- Max data rate: **2 Mb/s**
- Range: **100 m**
- Topology: WPAN, P2P, broadcast, mesh
- **PHY: FHSS (narrowband interference reduction), GFSK**
- **MAC: TDMA, FDMA, low duty cycle (<5 ms)**
- Power consumption: low
- Security: 128-bit AES encryption
- **Applications**: PC peripherals, remotes, healthcare, beaconing
- Availability: high (~90% of smartphones)
- **Not backward compatible with Bluetooth**
- **Bluetooth LE audio available from 2020**

Bluetooth-LE



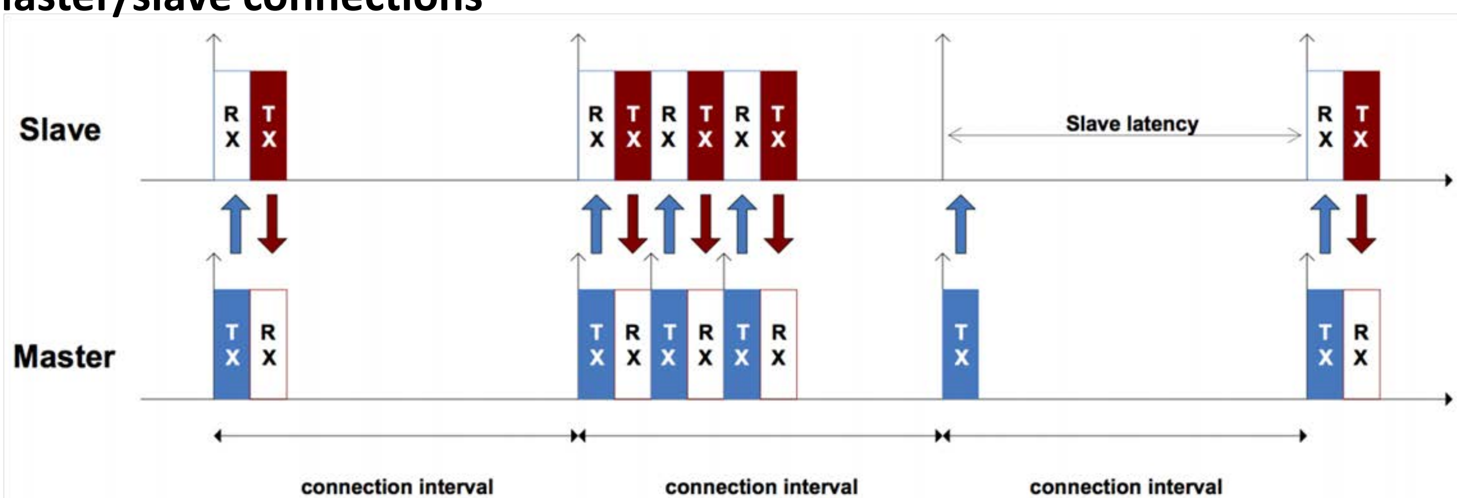
Bluetooth-LE

Broadcasting



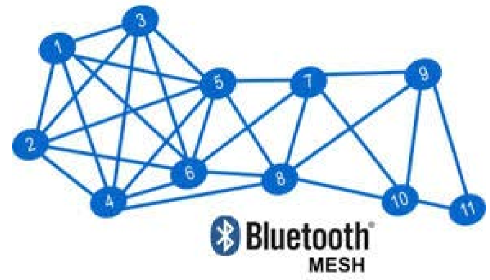
Source: https://devzone.nordicsemi.com/

Master/slave connections



Source: https://microchipdeveloper.com/

Bluetooth MESH



- Unlicensed band (**2.4 GHz**)
- Operates on Bluetooth Low Energy
- Power consumption: low, need to wake up once every four days
- Capacity: up to **32,000 nodes**
- Applications
  - Building automation, sensor network, asset tracking, IoT solutions with thousands of devices
  - NOT for audio streaming

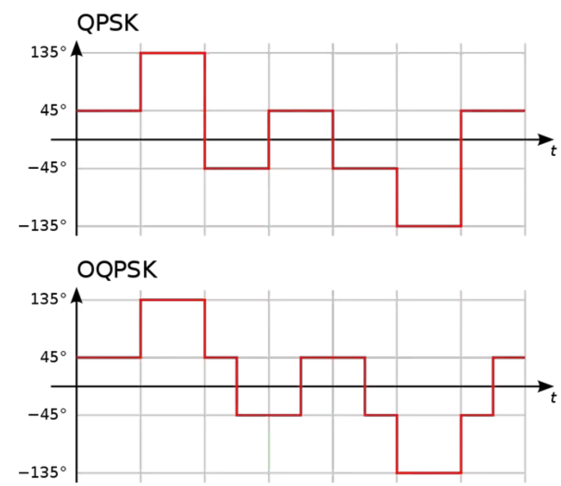
SILVAIR

Krakowski start-up, https://silvair.com, platforma dla inteligentnego oświetlenia oparta na Bluetooth Mesh

ZigBee (802.15.4-based)

ZigBee®
Control your world

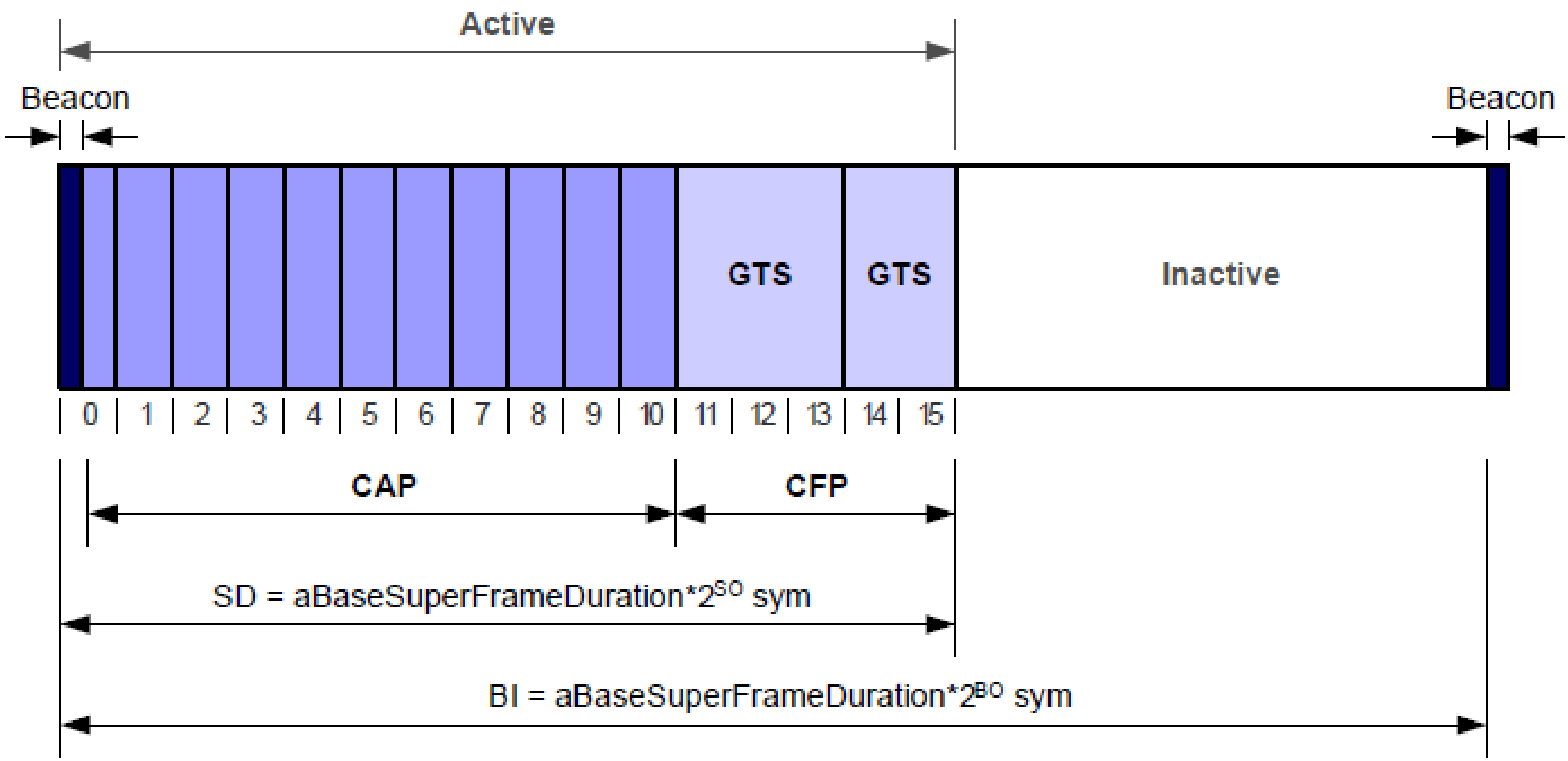
- Unlicensed band (**<1 GHz, 2.4 GHz**)
  - **1 x 600 kHz channel (868-868.6 MHz)**
  - **10 x 2 MHz channels (902-928 MHz)**
  - **15 x 5 MHz channels (2.4 GHz)**
- Max data rate: **250 kb/s** (2.4 GHz)
- Range: **20 m**
- Topology: star, mesh, tree
- **PHY**: **DSSS**, BPSK (<1 GHz), OQPSK (2.4 GHz)
- **MAC: CSMA/CA, slotted CSMA/CA, duty cycle**
- Security: AES-128 encryption
- Power consumption: medium
- Application: home automation, smart metering, monitoring



ZigBee

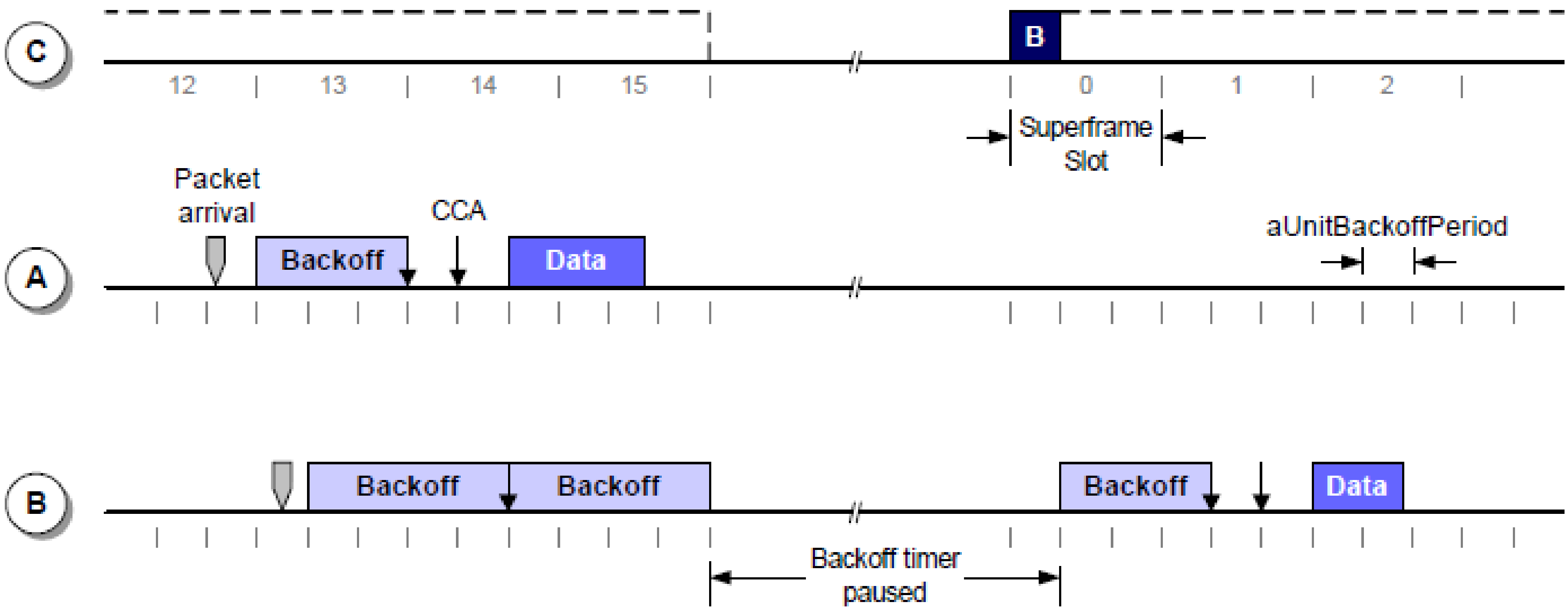
- Device types
  - Coordinator (only 1), routers, end devices
- Network types
  - Beacon-enabled
    - Power saving, duty cycle (15.36 ms to 251.66 s @2.4 GHz)
    - Slotted CSMA/CA – superframe structure present
  - Non-beacon-enabled
    - Unslotted CSMA/CA – without superframe structure
- Ad hoc On-Demand Distance Vector (AODV) Routing (RFC 3561)

ZigBee



Source: Mario Di Francesco, The IEEE 802.15.4 Standard and the ZigBee Specifications, Aalto University, 2012

ZigBee



Source: Mario Di Francesco, The IEEE 802.15.4 Standard and the ZigBee Specifications, Aalto University, 2012

6TiSCH

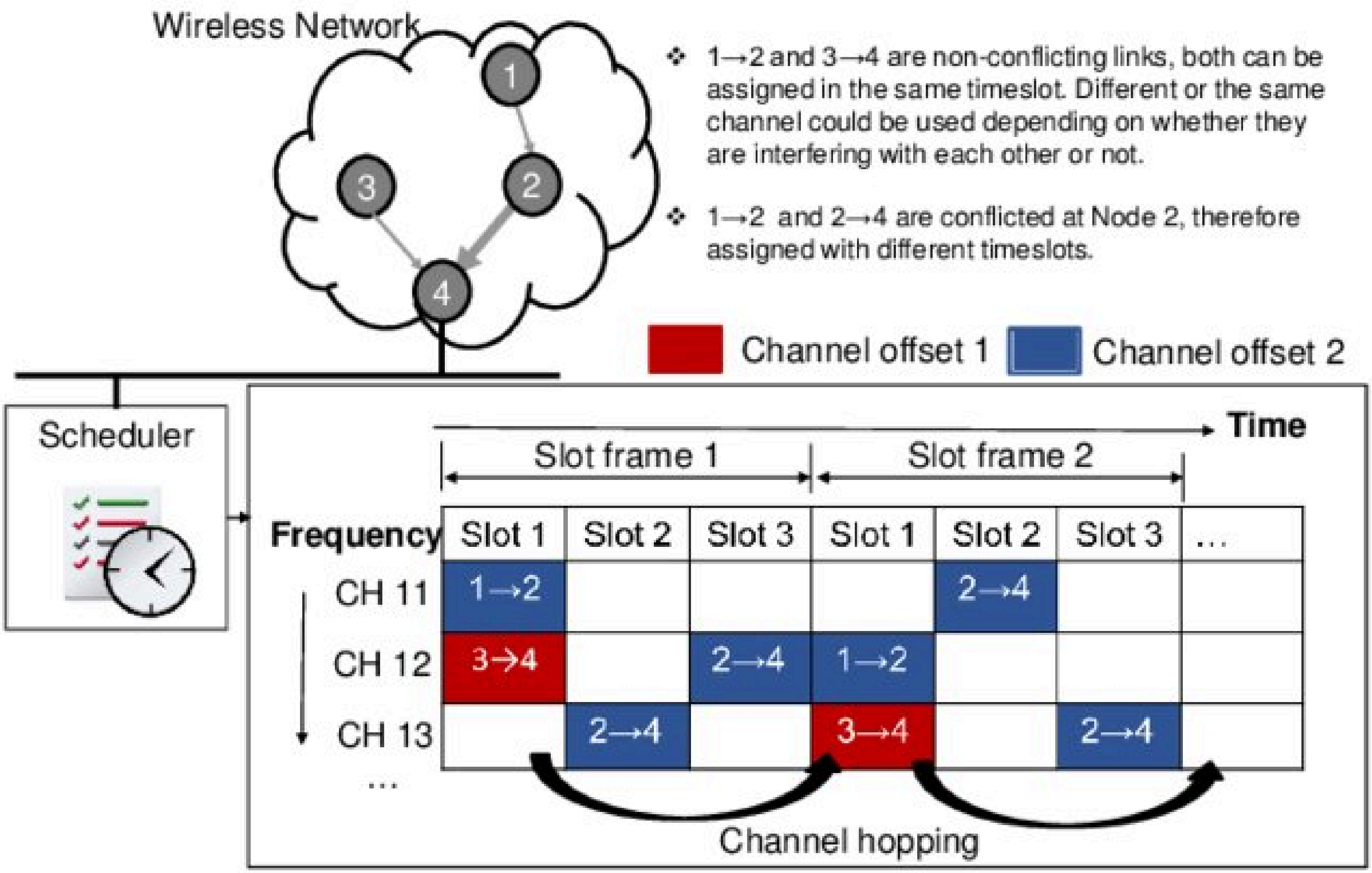
- Timeslotted Channel Hopping (TSCH) added to IEEE 802.15.4 (2012)
  - Industrial automation
  - Process control
- IPv6 over TSCH (6TiSH)
  - Adoption of IPv6 in industrial standards

6TiSCH Protocol Stack

```
+--------+--------+
| Applis |  CoJP  |
+--------+--------+-------------+-----+
| CoAP / OSCORE   |  6LoWPAN ND | RPL |
+-----------------+-------------+-----+
|       UDP       |       ICMPv6      |
+-----------------+-------------------+
|                IPv6                 |
+-------------------------------------+---------------------+
|     6LoWPAN HC   /   6LoRH HC       | Scheduling Functions |
+-------------------------------------+---------------------+
|     6top (to be IEEE Std 802.15.12) inc. 6top protocol     |
+-----------------------------------------------------------+
|                IEEE Std 802.15.4 TSCH                      |
+-----------------------------------------------------------+
```

https://datatracker.ietf.org/doc/draft-ietf-6tisch-architecture/19/?include_text=1 (December 17, 2018)

Deterministic 6TiSCH Schedule



Y. Jin, U. Raza and M. Sooriyabandara, "BOOST: Bringing Opportunistic ROuting and Effortless-Scheduling to TSCH MAC"Globecom 2018

6LoWPAN

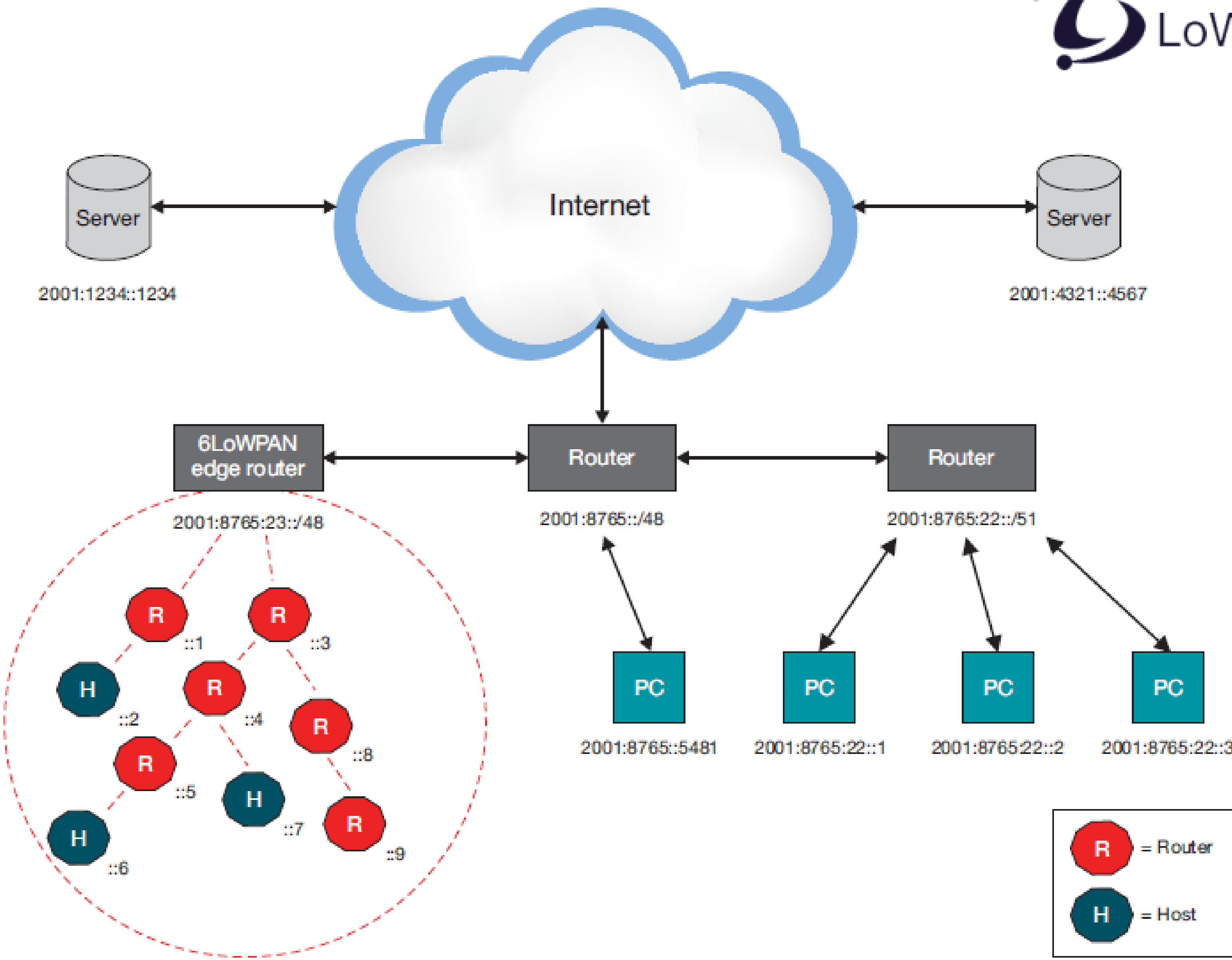
- Unlicensed band (**< 1 GHz, 2.4 GHz**)
- Data rates: **256 kb/s**
- Range: **200 m**
- Topology: star/mesh, ad-hoc configuration
- **PHY: like IEEE 802.15.4**
- **MAC: like IEEE 802.15.4**
- Security: AES-128
- Power consumption: low
- Applicaiton: monitoring, automation, security

6LoWPAN

Simplified OSI model	Wi-Fi® stack example	6LoWPAN stack example
5. Application layer	HTTP	HTTP, COAP, MQTT, Websocket, etc.
4. Transport Layer	TCP	UDP, TCP (Security TLS/DTLS)
3. Network Layer	Internet Protocol (IP)	IPv6, RPL
2. Data Link Layer	Wi-Fi	6LoWPAN IEEE 802.15.4 MAC
1. Physical Layer		IEEE 802.15.4

Source: Jonas Olsson, 6LoWPAN demystified, Texas Instruments, October 2014

IPv6 network with a 6LoWPAN mesh network



Source: Jonas Olsson, 6LoWPAN demystified, Texas Instruments, October 2014

6LoWPAN

- IPv4 limitations
  - 32-bit addresses
  - 4,294,967,296 unique addresses
- IPv6 advantages
  - 128-bit addresses
  - $3.4*10^{38}$ unique addresses
    - $50*10^{9}$ IoT devices by 2020
  - Minimum MTU 1280 B
- 802.15.4 constraints
  - 127 B packets, limited memory, multi-hop connections

6LoWPAN

- Header compression
  - 40-byte IPv6 and 8-byte UDP headers way too big
  - Within 6LoWPAN network: 2 B IPv6_H + 4 B UDP_H
- Fragmentation and reassembly
  - 1280 B (IPv6) -> 127 B (802.15.4)
  - Additional information in the header for reassembly
- Network auto-configuration
  - Neighbor discovery protocol
  - 128-bit address = 64-bit network prefix + 64-bit interface ID (IID)
  - IID typically from MAC address

MulteFire Evolution

- MulteFire 1.0
  - Based on LAA/eLAA
  - 5 GHz Band
  - Goal: new application scenarios
- MulteFire 1.1
  - Based on eMTC/NB-IoT
    - Which currently used licensed bands…
  - Band: 2.4 GHz (eMTC), 800/900 MHz (NB-IoT)
  - Goal: IoT support in unlicensed bands

Short Range Communications Comparison

Type	Range [m]	Data rate [Mb/s]	No. of devices	Latency [ms]	Channel Access method	Power consumption	Frequency band
BLE	100	2	No limit	6	FHSS, duty cycle	Low	2.4 GHz
6LoWPAN	200	0.2	100	1000-2000	CSMA/CA, time slotting, duty cycle	Low	< 1 GHz, 2.4 GHz
Wi-Fi	10 – 1000	347 (11ah) – 7000 (11ad)	8191 (11ah)	Even <1	CSMA/CA, partially scheduled access (e.g., OFDMA in 802.11ax)	High to low	<1GHz, 2.4 GHz, 5 GHz, 60 GHz

LoRa™

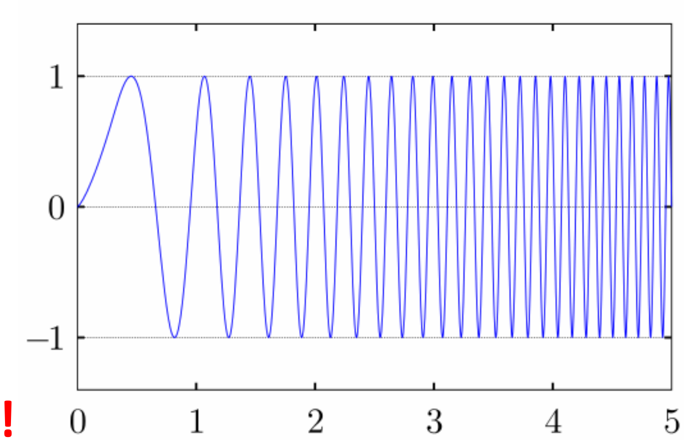
sigfox

Lte™

LONG RANGE COMMUNICATIONS

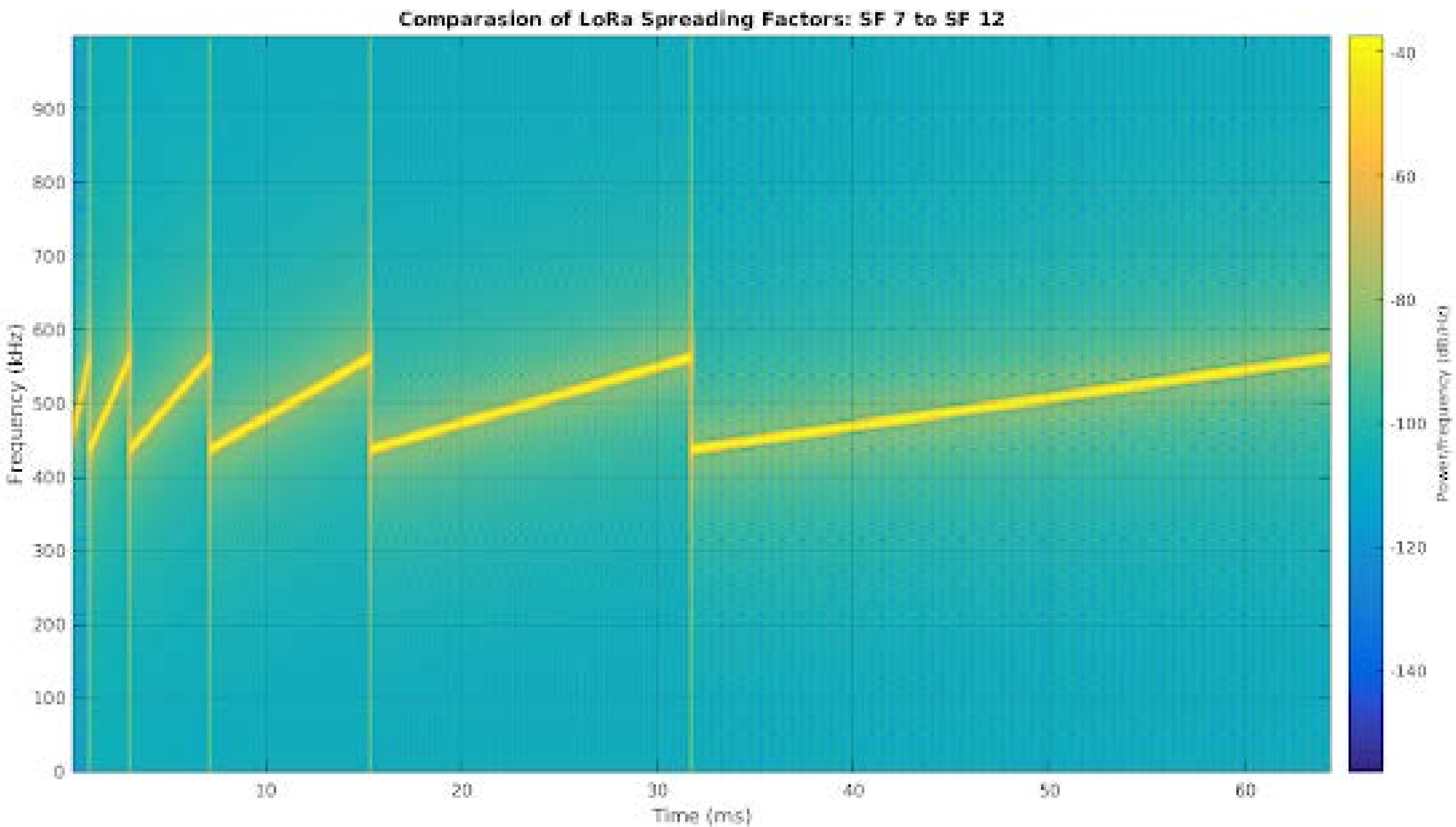
LoRaWAN

- Unlicensed band (**433/868/780/915 MHz)**
  - **6 channels of 125 kHz**
  - **1 channel of 250 kHz**
- **Max data rate: 50 kbit/s**
- Range: **15 km**
- **Packet capacity: 12 bytes (!)**
- Topology: star on star, star (cellular WAN)
- **PHY: LoRa, Chirp Spread Spectrum**
- **MAC: duty cycle, channel hopping, no CCA!**
- Power consumption: medium
- Security: 2x128-bit AES session keys (ASK)
  - Network ASK for identification/message integrity protection
  - Application ASK for encryption
- Applications: monitoring/metering, intelligent home/city, healthcare, agriculture, industry, environment



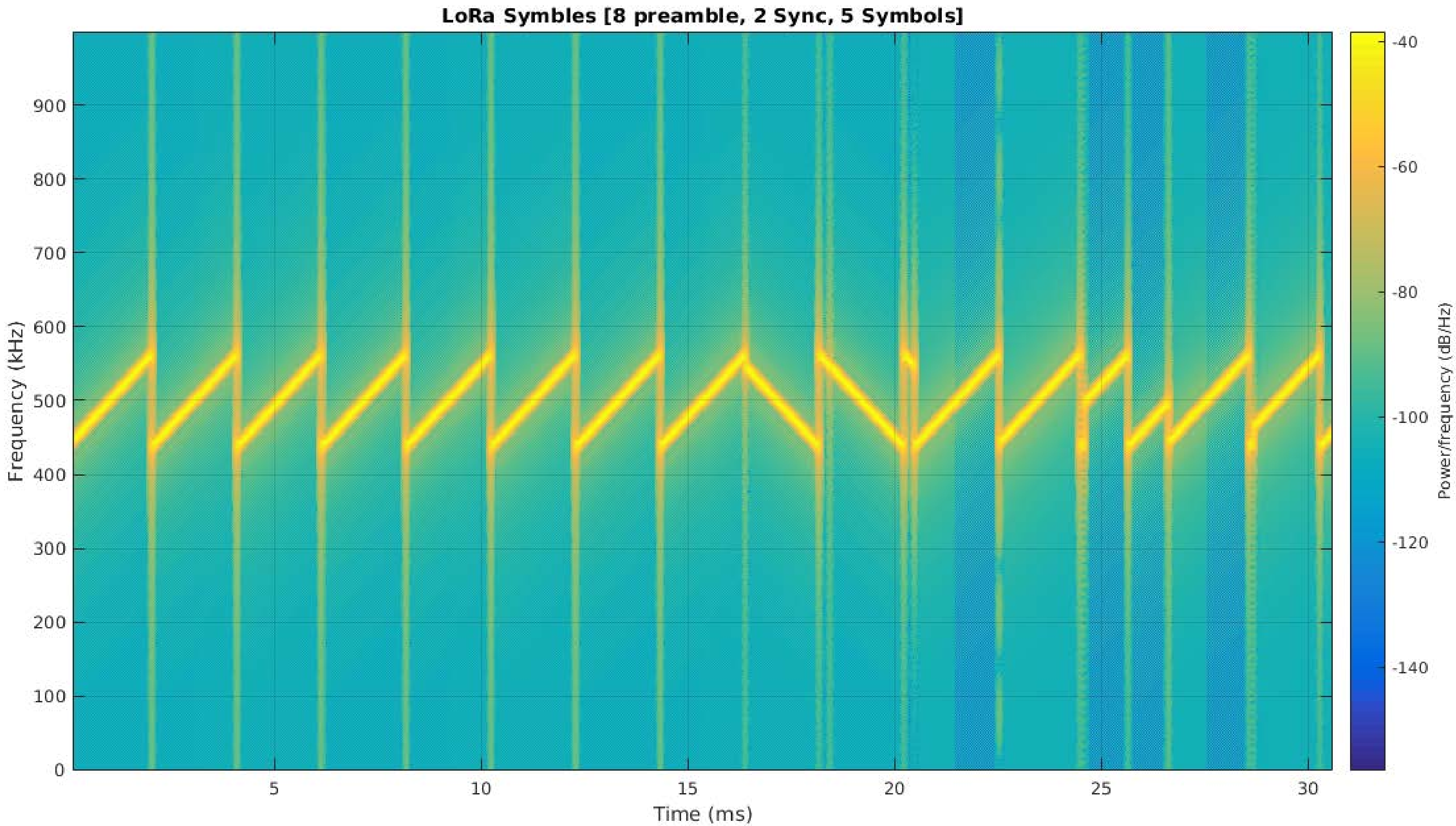
Graphics source: http://www.sghoslya.com/p/lora-is-chirp-spread-spectrum.html

LoRa – Spreading Factor Spectogram



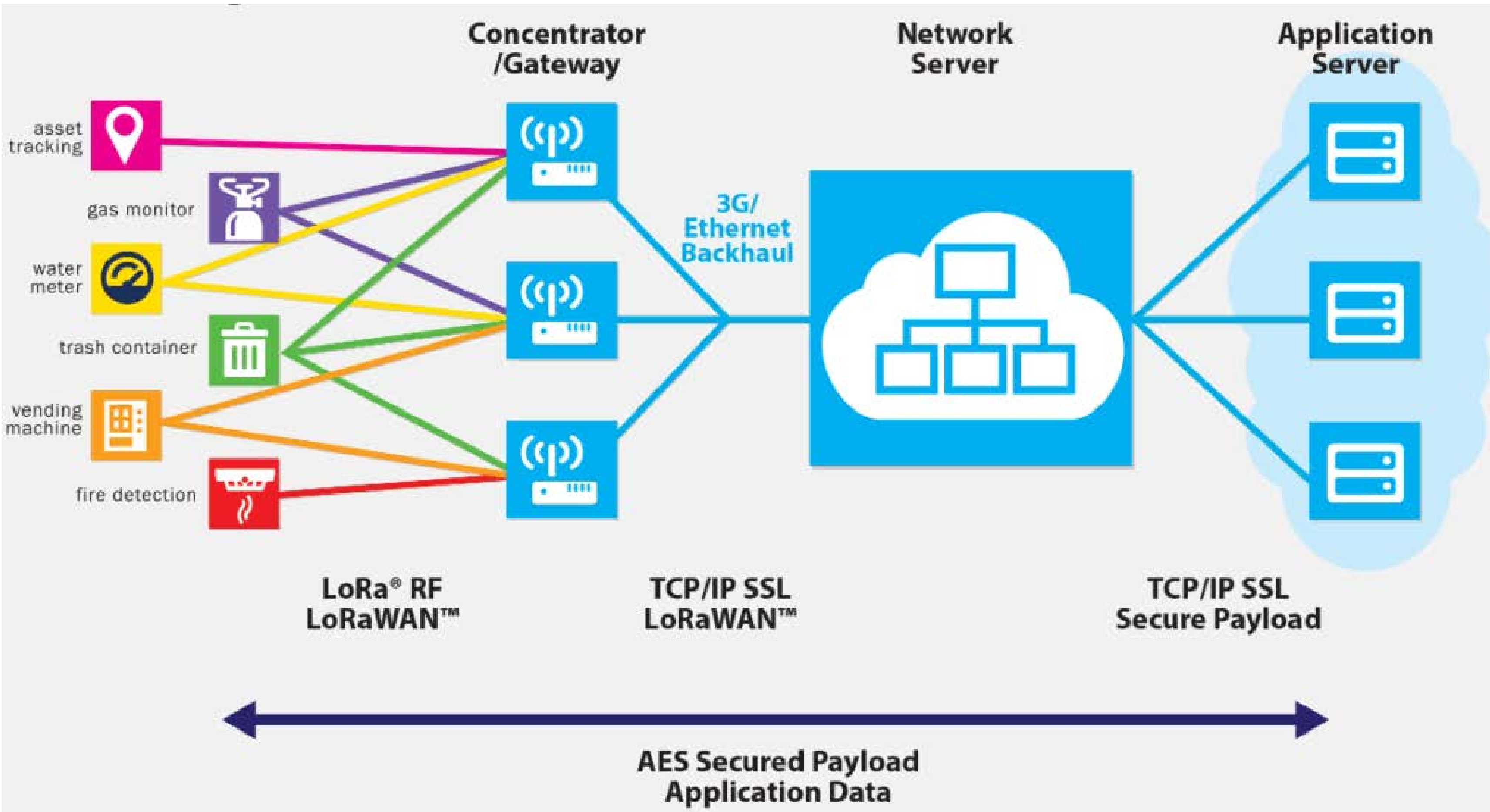
Source: http://www.sghoslya.com/p/lora-is-chirp-spread-spectrum.html

LoRa – CSS
PHY layer spectogram



Source: http://www.sghoslya.com/p/lora-is-chirp-spread-spectrum.html

LoRa Network

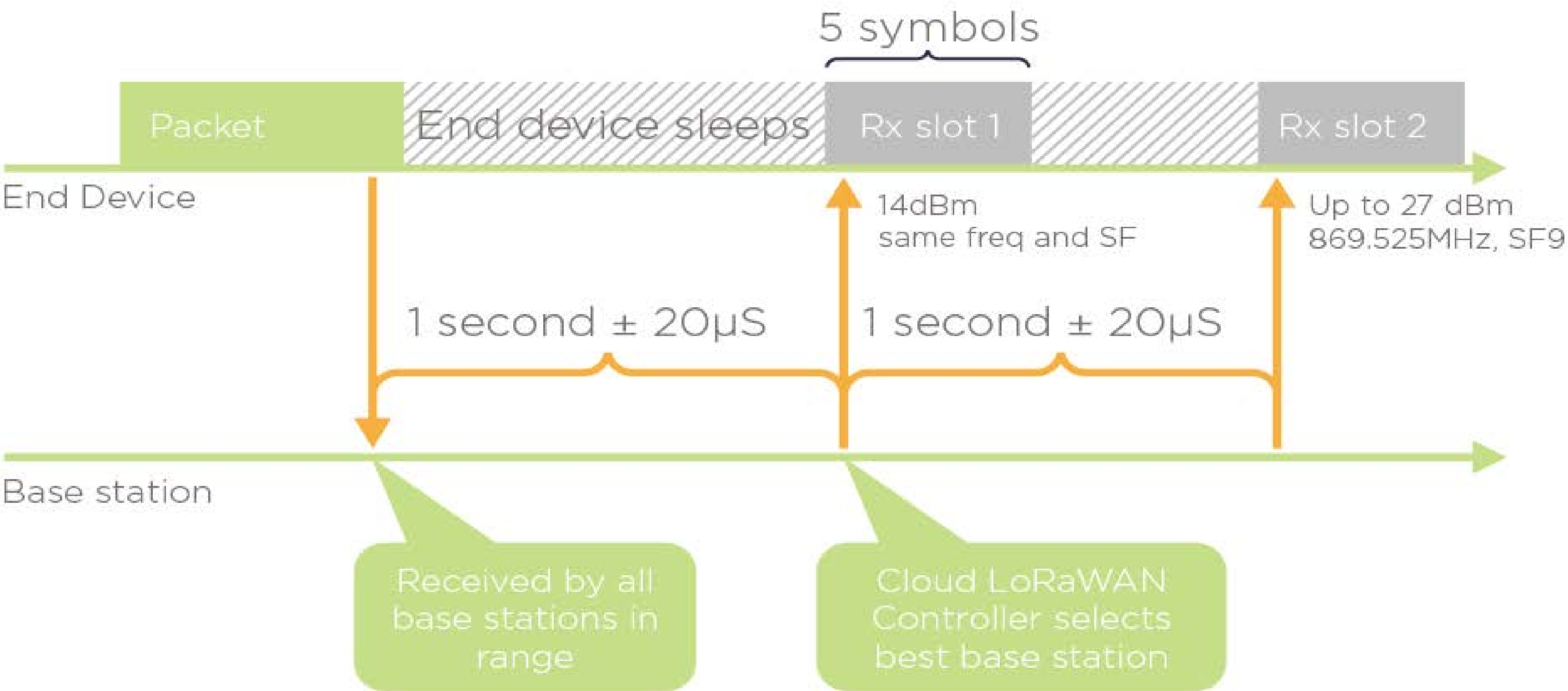


http://www.techplayon.com/lora-technology-benefits-application/

LoRaWAN – MAC

Class A Communications: 1xUL + 2xDL

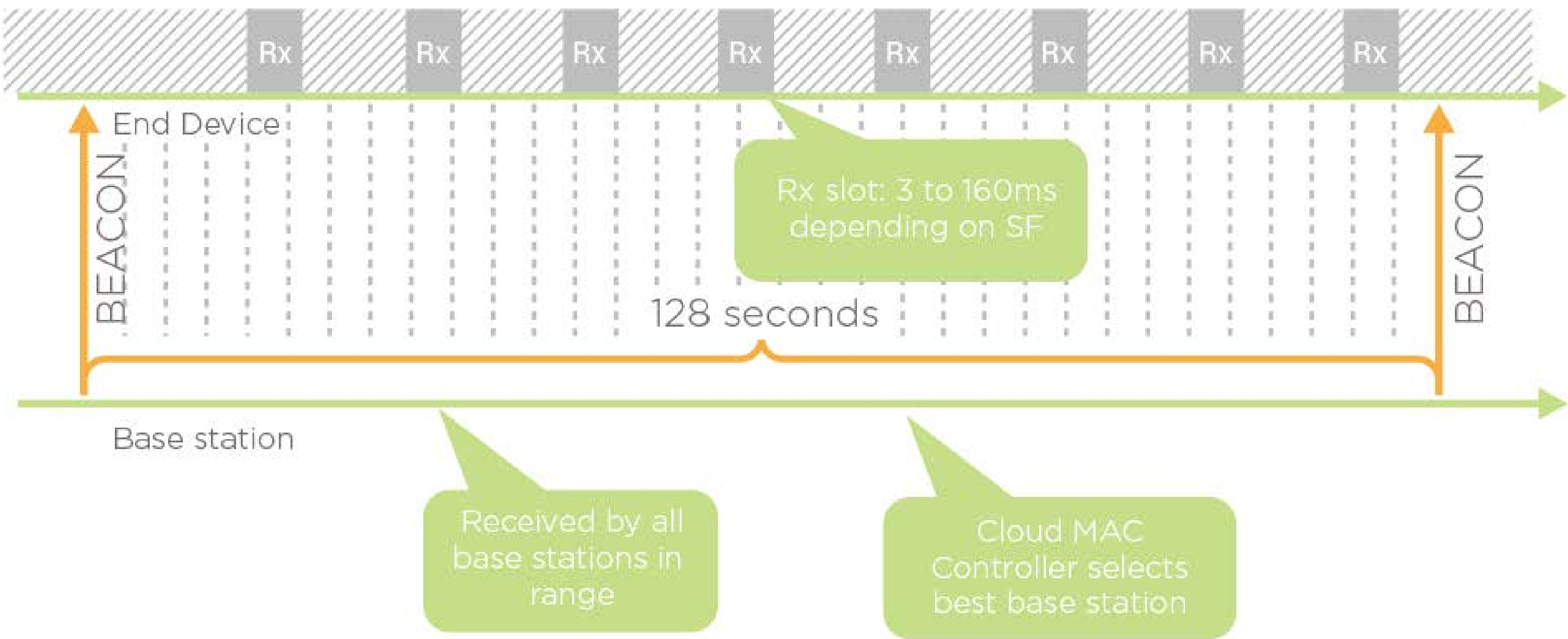
The most power efficient mode



Source: https://sirinsoftware.com/blog/lorawan-mac-layer/

LoRaWAN – MAC

Class B Communications: DL slots



Source: https://sirinsoftware.com/blog/lorawan-mac-layer/

LoRaWAN – MAC

Class C Communications: 1xUL + Continuous DL

Source: https://sirinsoftware.com/blog/lorawan-mac-layer/

LoRa Summary

- Pros
  - Perfect for single-building applications
  - One can build their own network
  - Bi-directional transmissions
  - Long battery life
- Cons
  - Low data rates
  - Requires a gateway
  - Higher latency than, e.g., NB-IoT
  - 1% duty cycle for the used unlicensed band (Europe)

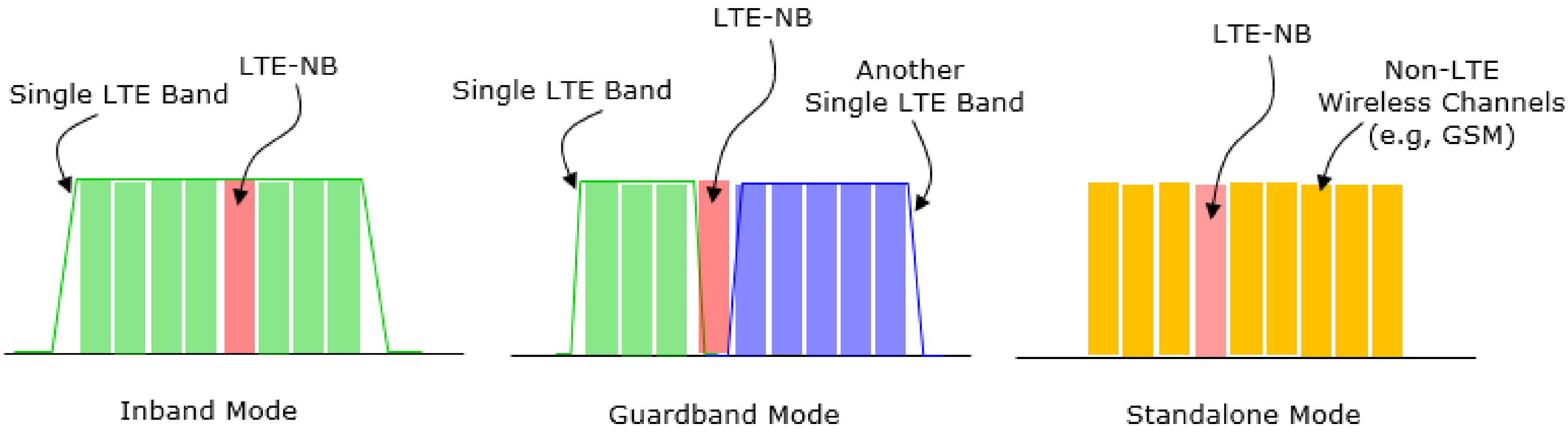
- Saelens, Martijn, et al. "Impact of EU duty cycle and transmission power limitations for sub-GHz LPWAN SRDs: an overview and future challenges." EURASIP Journal on Wireless Communications and Networking 2019

https://www.link-labs.com/blog/nb-iot-vs-lora-vs-sigfox

LTE (Narrow Band-IoT, NB-IoT)

- Licensed band (**cellular, mostly < 1 GHz**)
  - **1 x 180 kHz channel**
- **Max data rate: 250 kb/s**
- Range: **15 km**
- Topology: star (cellular WAN)
- **PHY**: FDD, no MIMO
- **Multiple access protocol**
  - **SC-FDMA (UL)**
  - **OFDMA (DL)**
- Power consumption: high
- Security: cellular quality
- Applications: metering, building/home automation, smart city, agriculture, tracking

NB-IoT

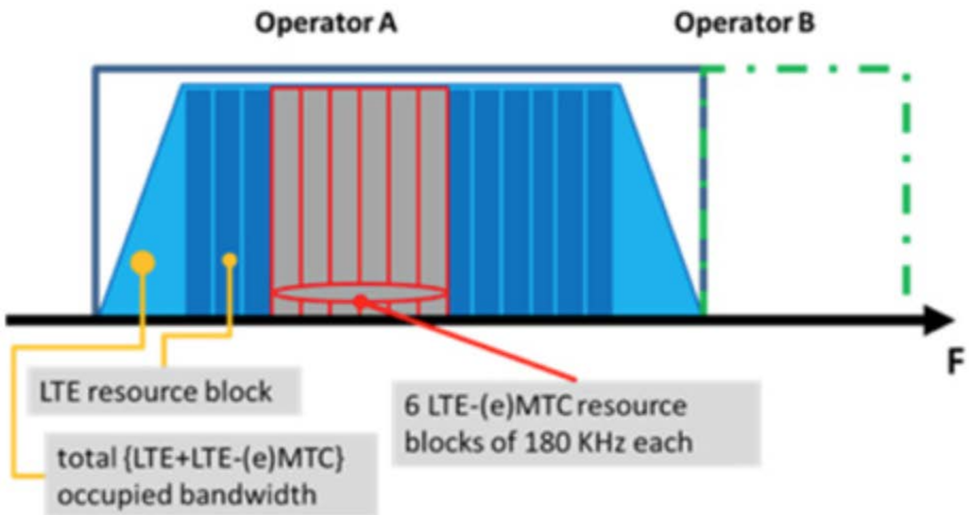


Source: ShareTechnote, 2018.

LTE-M (Enhanced Machine-Type Communications, eMTC)

- Licensed band (cellular, mostly < 1 GHz)
  - **6 x resource block = 6 x 180 kHz = 1.080 MHz**
- **Max data rate: 1 Mb/s (uplink/downlink)**
- Range: 15 km
- Topology: star (cellular WAN)
- PHY: FDD, **TDD**, no MIMO
- **Multiple access protocol**
  - **SC-FDMA (UL), 16-QAM**
  - **OFDMA (DL), 16-QAM**
- Power consumption: high
- Security: cellular quality
- **Applications: healthcare, transportation**

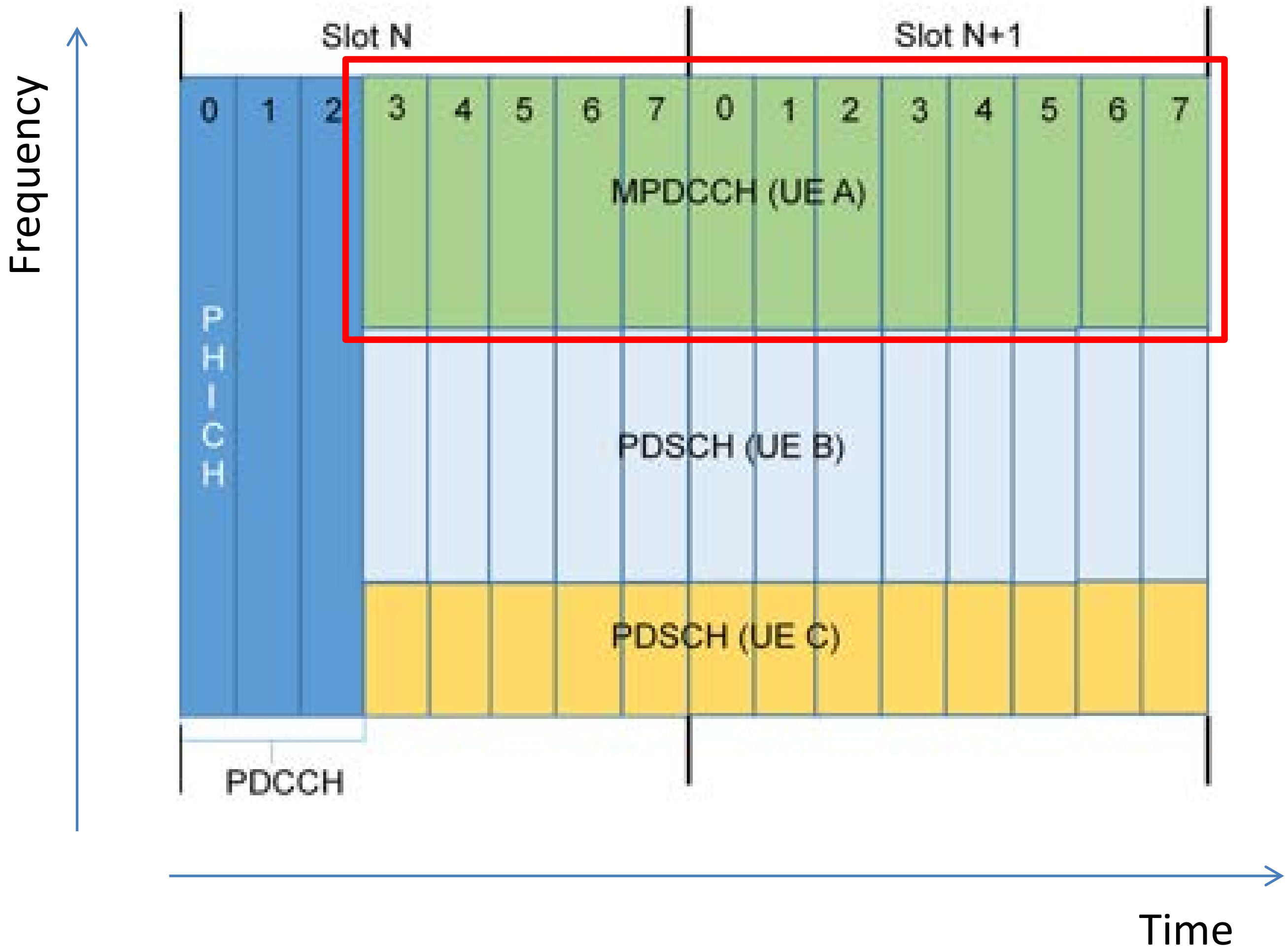
LTE-M (eMTC)



Source: http://apps.cept.org/eccnews/dec-2017/

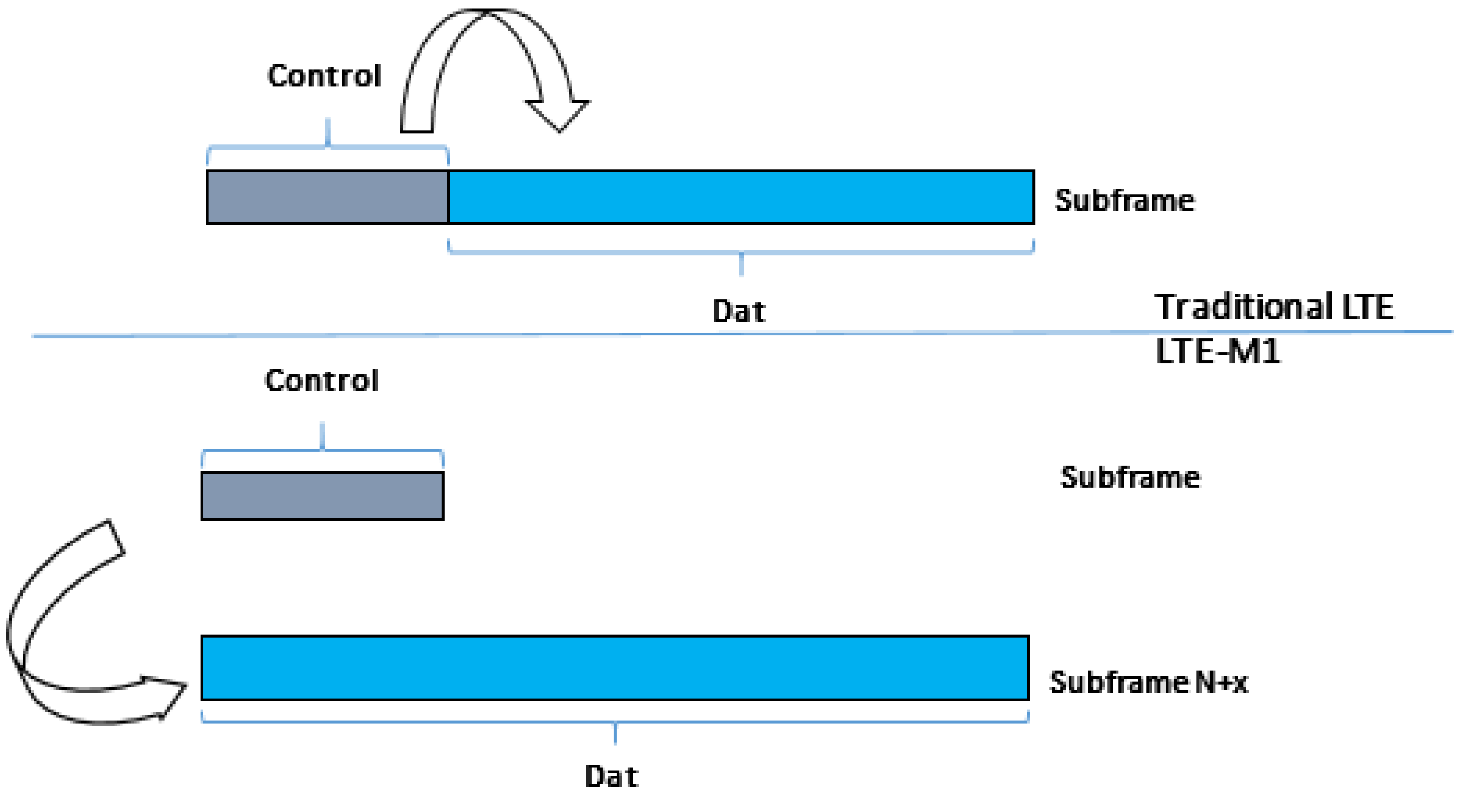
LTE-M (eMTC)

MTC Physical Downlink Control Channel



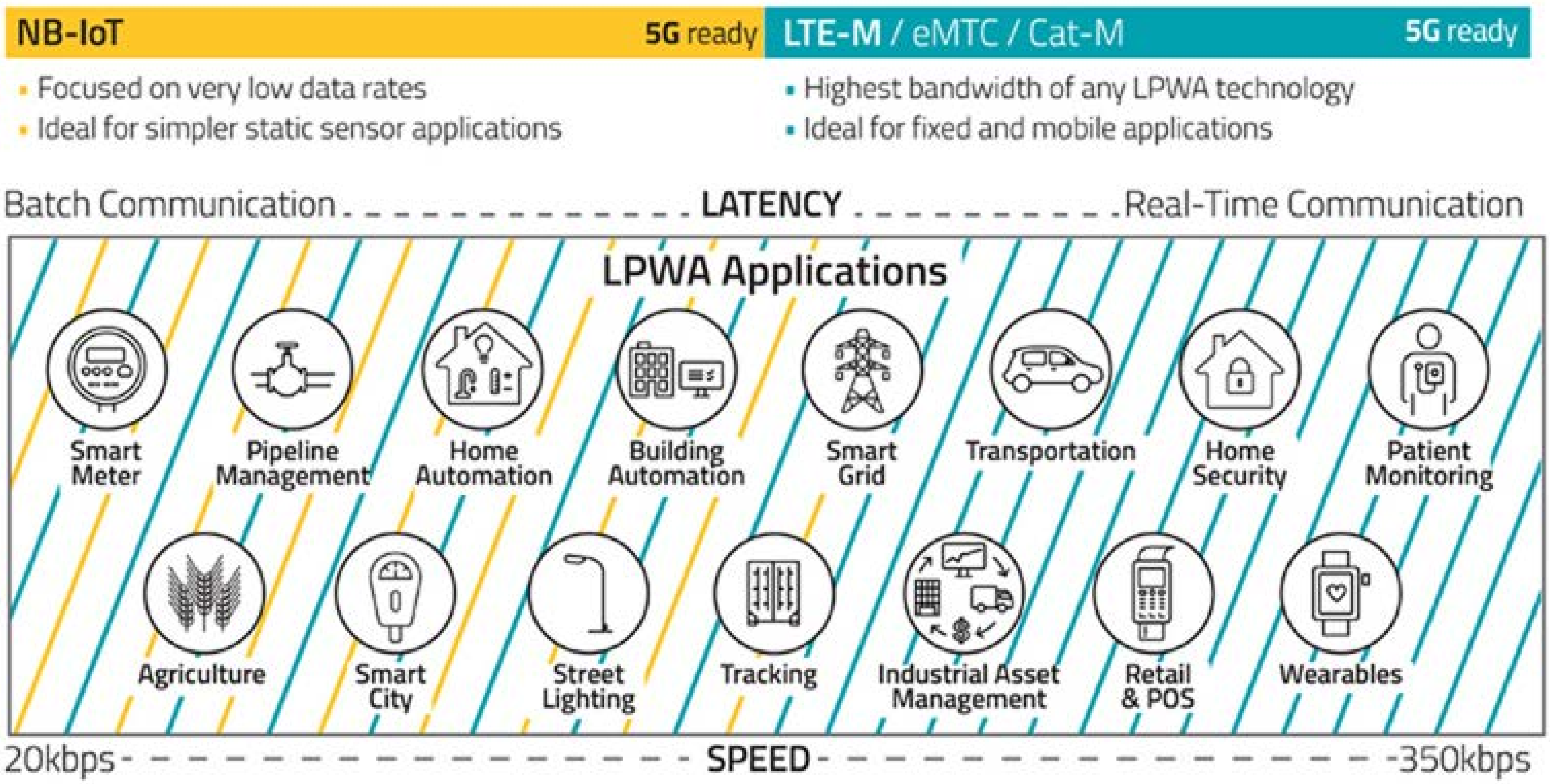
Source: https://connect.aricent.com/

LTE vs LTE-M
Cross-Subframe Scheduling



https://connect.aricent.com/2017/08/emtc-lte-for-connected-devices/

NB-IoT vs LTE-M

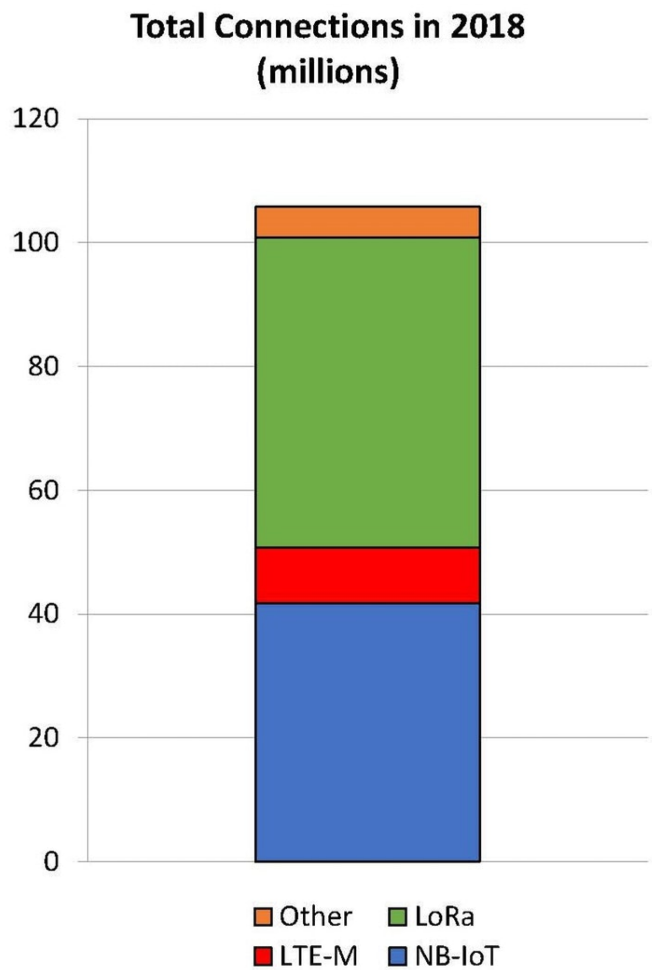


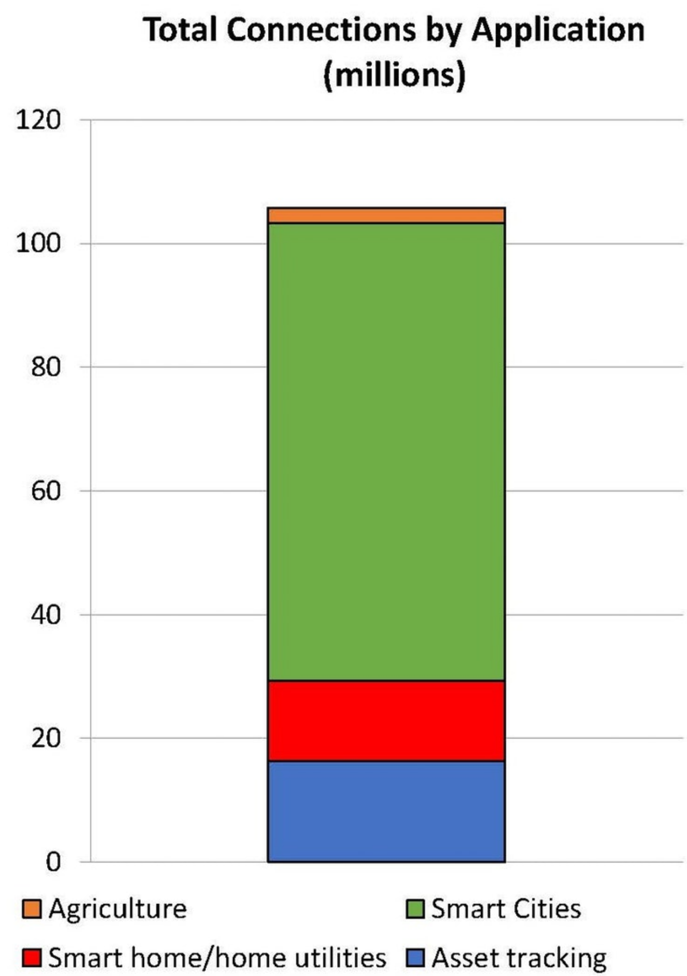
Source: https://www.sierrawireless.com/iot-blog/iot-blog/2018/04/lte-m-vs-nb-iot/

Long Range Communications Comparison

Type	Range [km]	Data rate [Mb/s]	No. of devices	Lat. [s]	MAC	Power consumption	Freq. band
LoRaWAN	15	0.05	1 M (UL), 100 K (DL)	1-10	Duty cycle, channel hopping	Medium	433/780/ 868/915 MHz
SigFox	50	0.1	1 M	1-30	Duty cycle, channel hopping	Medium	868/902 MHz
NB-IoT	15	0.25	> 50 K	2-10	SC-FDMA (UL), OFDMA (DL)	High	Licensed, mostly <1 GHz
LTE-M	15	1	> 50 K	2-10	SC-FDMA (UL), OFDMA (DL)	High	Licensed, mostly <1 GHz

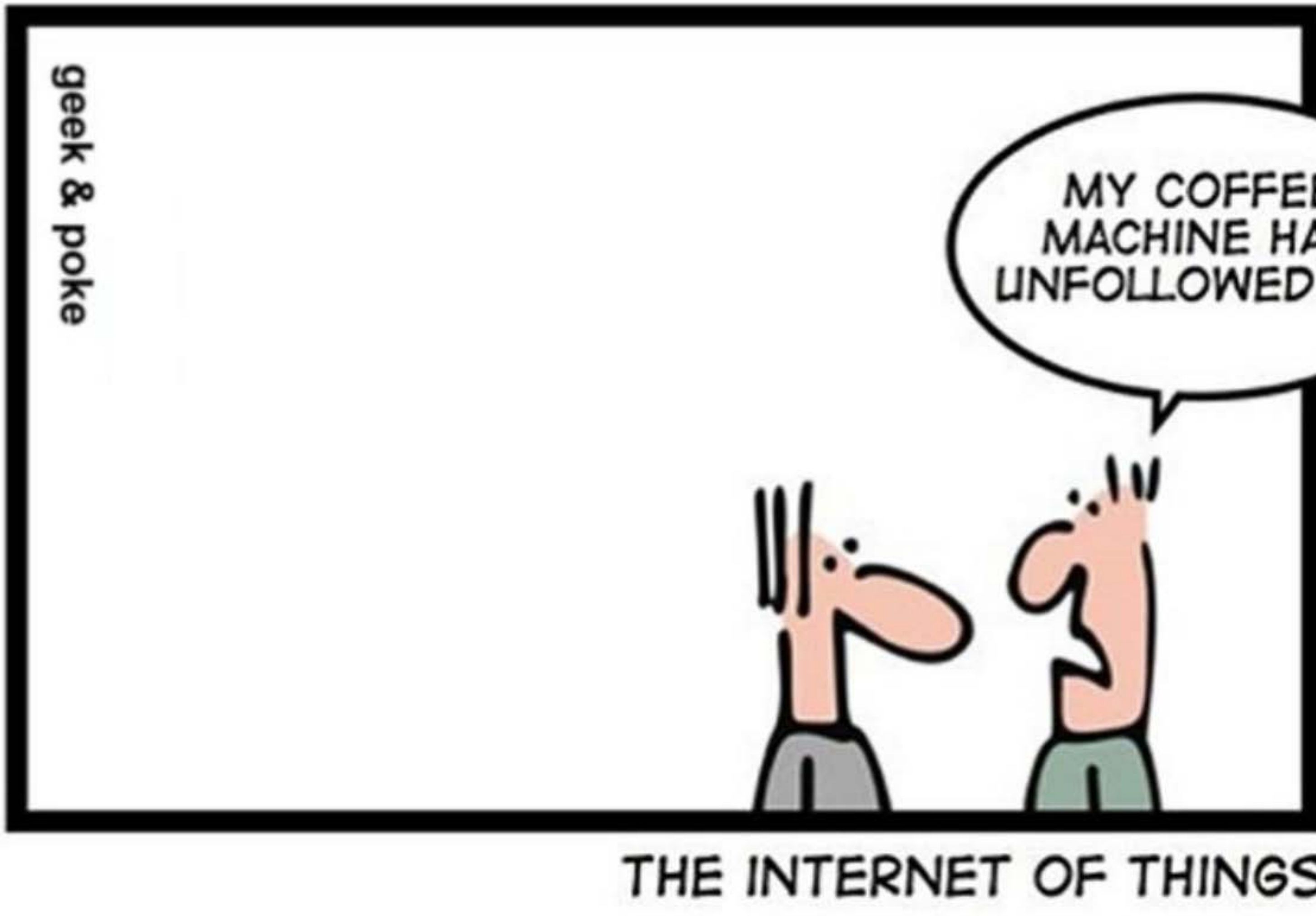
LoRa vs NB-IoT vs LTE-M vs Other





https://www.idtechex.com/en/research-report/low-power-wide-area-networks-2019-2029-global-forecasts-technologies-applications/614

Questions?


geek & poke
MY COFFEE MACHINE HAS UNFOLLOWED ME
THE INTERNET OF THINGS

Recommended Reading

- https://blog.bluetooth.com/ten-important-differences-between-bluetooth-bredr-and-bluetooth-smart
- Transmission of IPv6 Packets over IEEE 802.15.4 Networks, RFC 4944, upd. by RFC 6282/6775
- https://nfc-forum.org/
- www.dash7-alliance.org
- IEEE 802.11-2016, Standard
- IEEE 802.11ah-2016 Amendment
- http://www.3gpp.org/
- www.zigbee.org/
- https://lora-alliance.org/
- https://www.sigfox.com/en
- https://www.rs-online.com/designspark/eleven-internet-of-things-iot-protocols-you-need-to-know-about
- http://www.proxim.com/downloads/WhitePapers/Backhaul/a_guide_book_on_backhaul_design.pdf
- https://www.extremenetworks.com/extreme-networks-blog/what-is-a-clear-channel-assessment-cca/
- Other official sources