Communication Technologies for IoT

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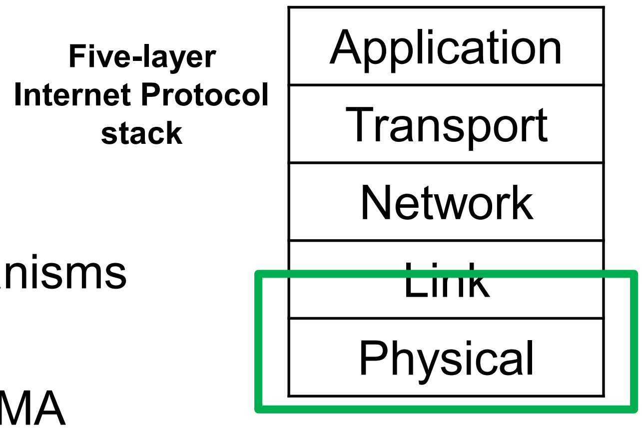
ESW, 09 Oct. 2025

Outline

- Introduction (Last Class)
  - Basic issues
  - Scope of presentation
  - Basics of Communications (MAC)
- Different wireless technologies for IoT (Today)
  - LoRaWAN
  - Cellular Technologies: LTE-M and NB-IoT
  - IEEE 802.11ah (WiFi)
  - IEEE 802.15.4
  - BLE
- Summary

Scope of the Presentation



- Medium access control (MAC)
  - Provides channel access control mechanisms across a shared physical medium
  - Example: Aloha, CSMA/CA, TDMA, CDMA
  - Provides addressing mechanisms

- Physical Layer (PHY)
  - Defines the means of transmitting raw bits rather than logical data packets over a physical link/medium connecting two nodes on the same network
  - Signal processing of bits and physical signals: Modulation, Coding, Bit Interleaving, Synchronization, Carrier sensing and collision detection, etc.
  - Example: WLAN 802.11, LR-WPANs 802.15.4, Ethernet 802.3, Bluetooth 802.15.1

Types of MAC protocols

- Channel Partitioning Protocols (or Fixed Assignment Protocols)
  - TDMA, FDMA, CDMA, SDMA
- Random Access Protocols
  - Aloha, Slotted Aloha, CSMA/CA
- Taking Turn Protocols (or Demand Assignment Protocols)
  - Token Ring
  - Polling

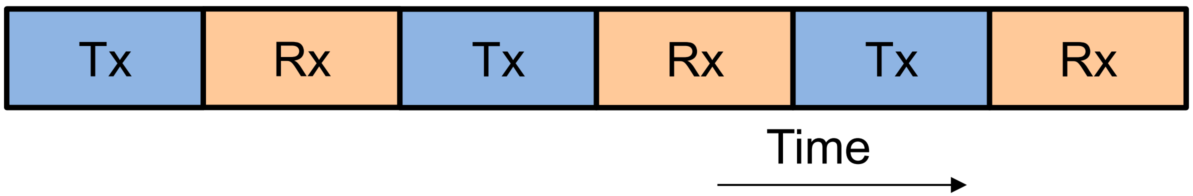
Simplex and Duplexing Communications

- Simplex communication system: one device transmits, other listens
  - TV, FM, Surveillance monitors, wireless microphones

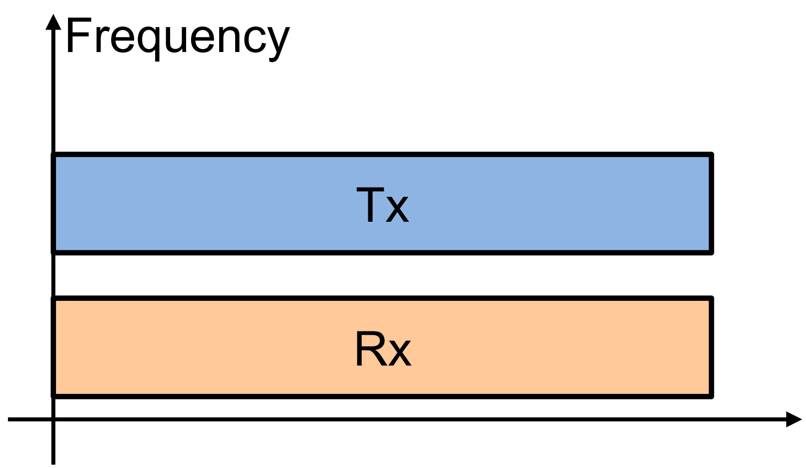
- Duplex communication system: both devices can transmit and receive
  - Most of the communication systems including cellphone, laptops, tablets

Duplexing Methods

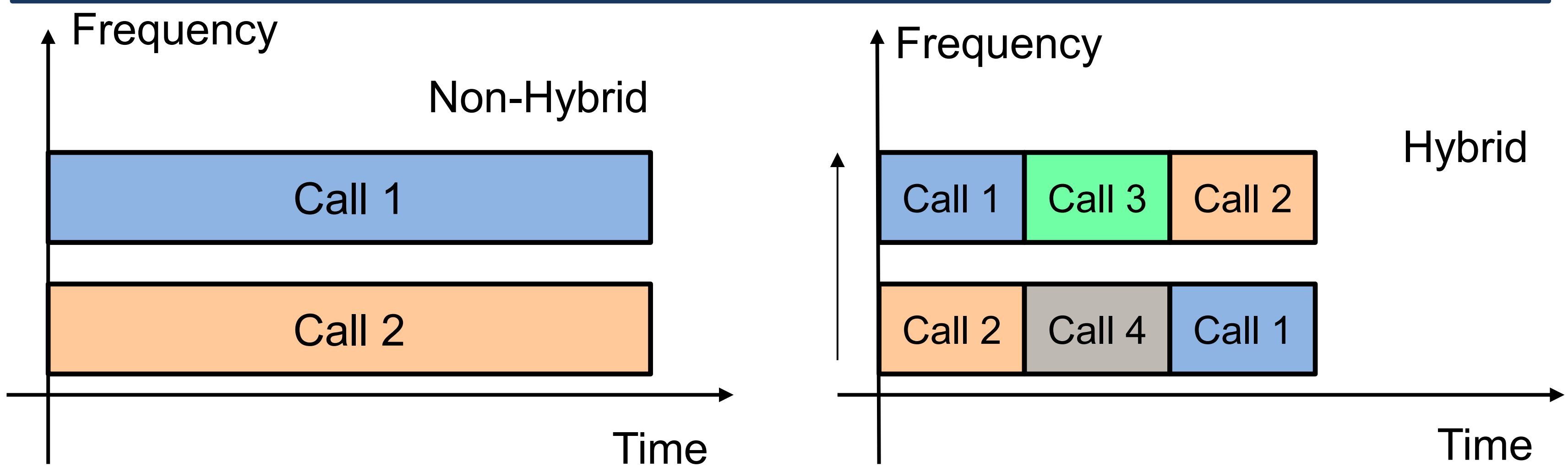
- Methods used for dividing forward and reverse communication channels, they are called as duplexing methods such as
  - Time division duplexing (TDD)



  - Frequency division duplexing (FDD)

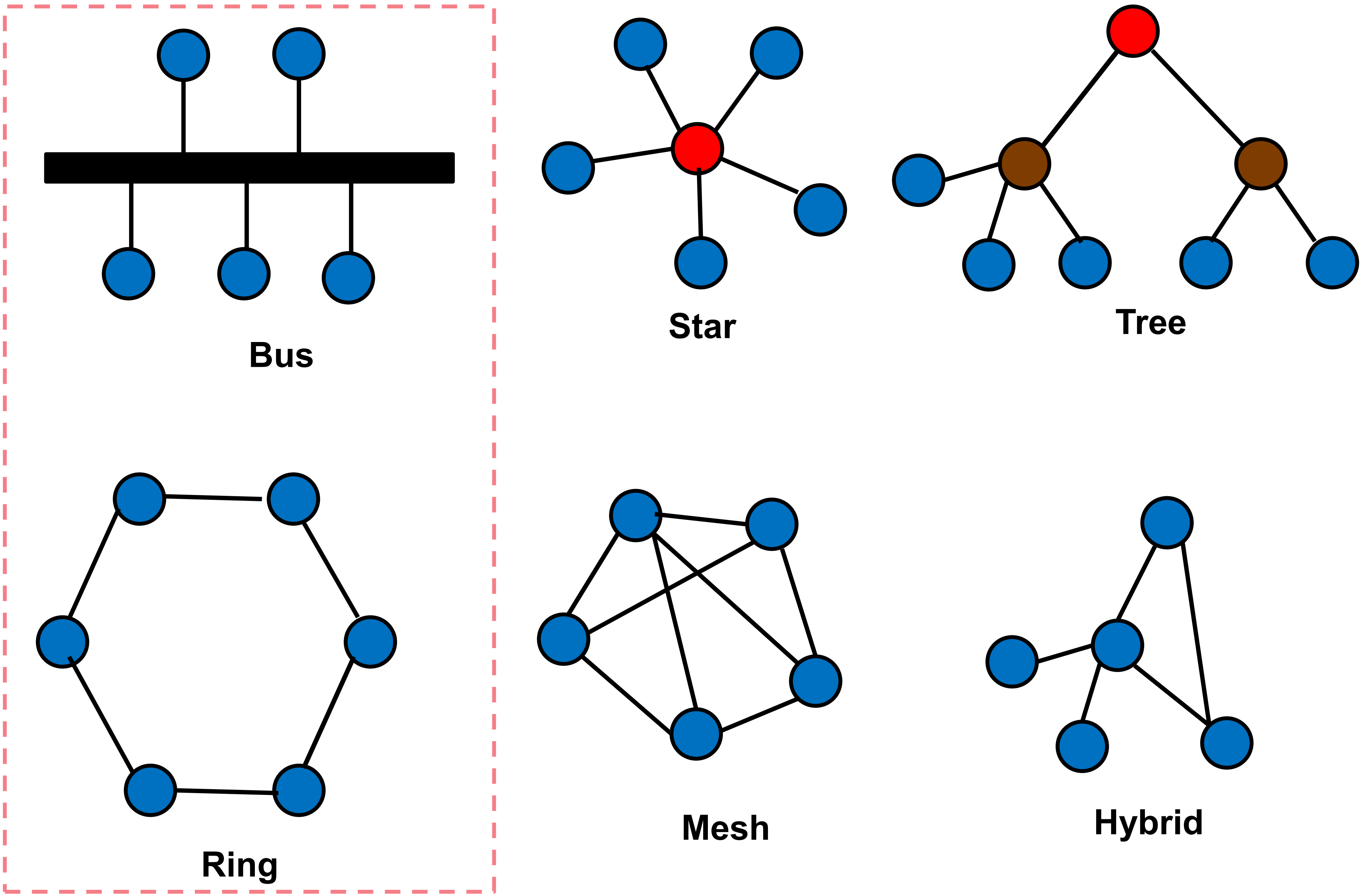


Hybrid Channel Access



- The GSM cellular system combines the use of FDD to prevent interference between outward and return signals with FDMA and TDMA to allow multiple handsets in a single cell.
- Bluetooth packet mode communication combines frequency hopping for shared channel access among several private area networks in the same room with CSMA/CA for shared channel access inside a medium
- IEEE 802.11b WLAN are based on FDMA and DS-CDMA for avoiding interference among adjacent WLAN cells or access points

Network Topologies



Issues in IoT from Communication Perspective

[Not an exhaustive list!]

- Low power consumption
- Support large number of devices with low data rates
- Coverage
- Quality of service
- Low cost
  - Network/Private (DIY)
  - Licensed/Unlicensed
- Privacy and security
- Standardization for interoperability between different vendors

Factors contributing to energy waste/expense

- Energy consumption in transmission
  - Longer distances
  - Higher frequencies
  - More bandwidth

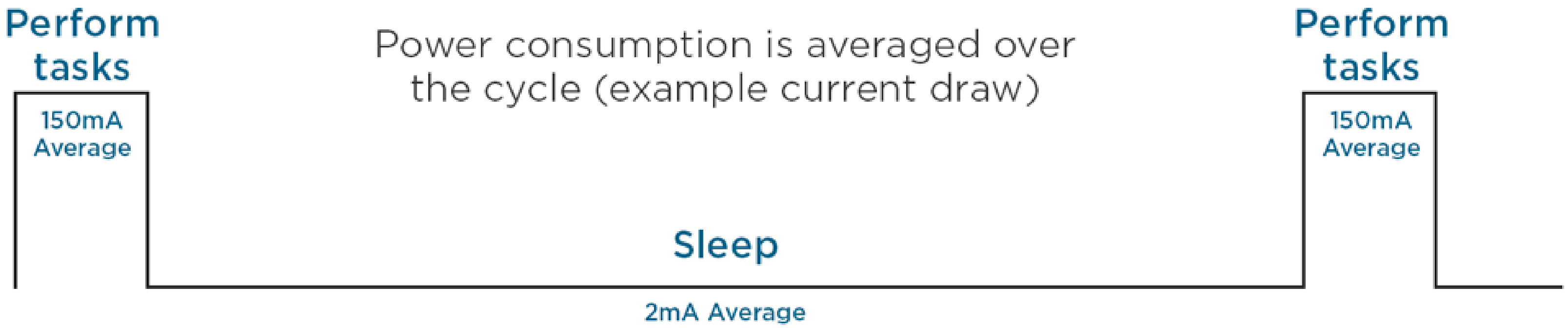
- Energy waste
  - Excessive overhead
  - Idle listening
  - Overhearing
  - Packet collisions and retransmissions

[Not exhaustive!]

Ways to Reduce Energy Waste/Consumption

- Reduced frequency/data rate/ bandwidth/ coverage
- Sleep
  - Low duty cycle
- Energy saving protocols
  - Schedule based (reduction in over-hearing and idle-listening)
    - Licensed spectrum; BLE
  - Contention based (less overhead and no need of synchronization)
    - Zigbee, WiFi
- Multihop and aggregation of data
- Signal processing
  - censoring, predictive filters
- Reduced overhead

Low Duty Cycle



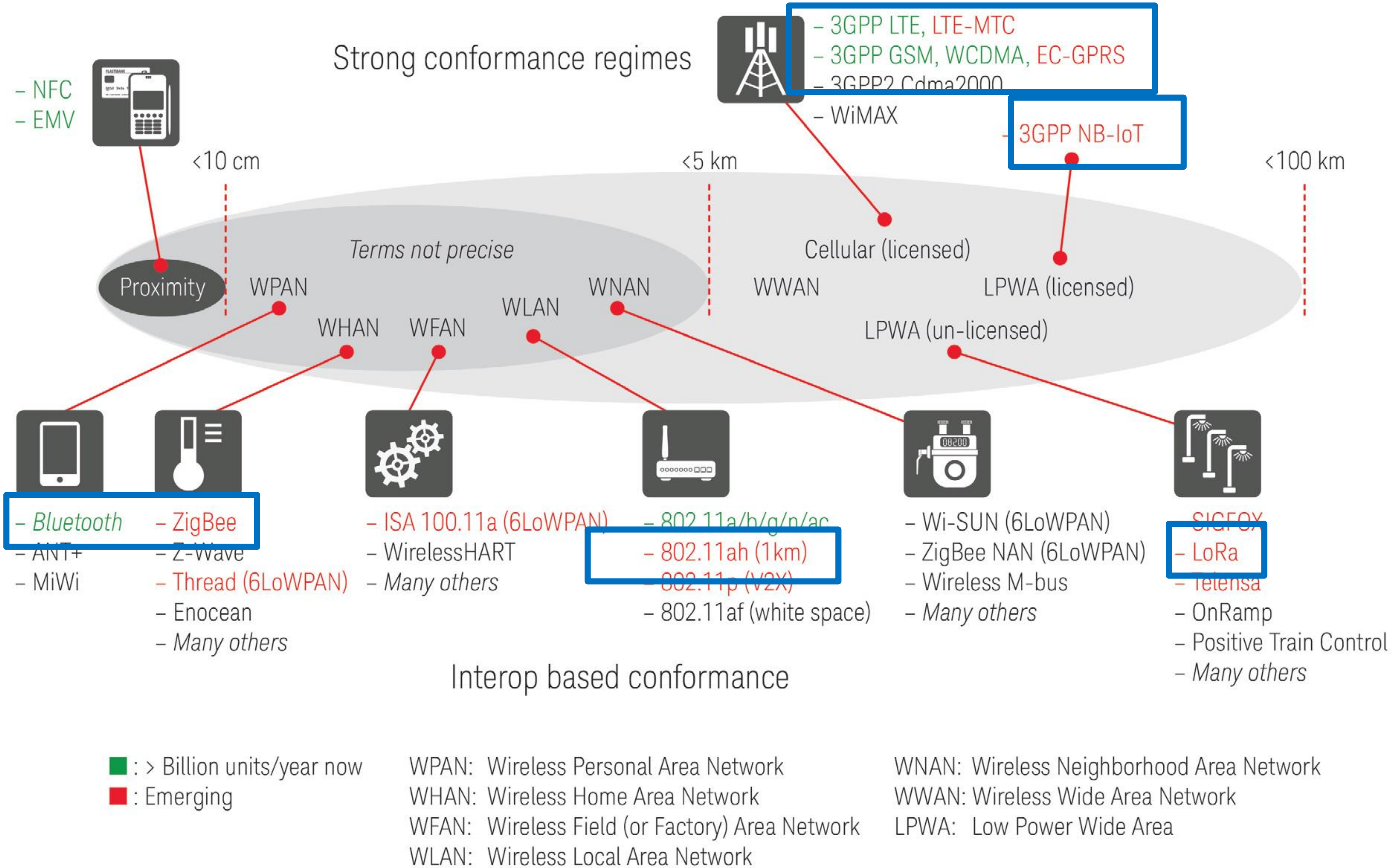
https://core-electronics.com.au/media/wysiwyg/tutorials/sam/example-duty-cycle.png

Duty cycle in our paper 0.66% duty cycle (0.2 of 30ms).
Even with 99% reduction in data-transmissions, the life-time increased only by 3 times

A. Shastri, V. Jain, R. Singh, **S. Chaudhari**, S. Chouhan, S. Werner, "Improving the Accuracy of the Shewhart Test-based Data-Reduction Technique using Piggybacking," *in IEEE WF-IoT*, Ireland, Apr. 2019

Today’s Class

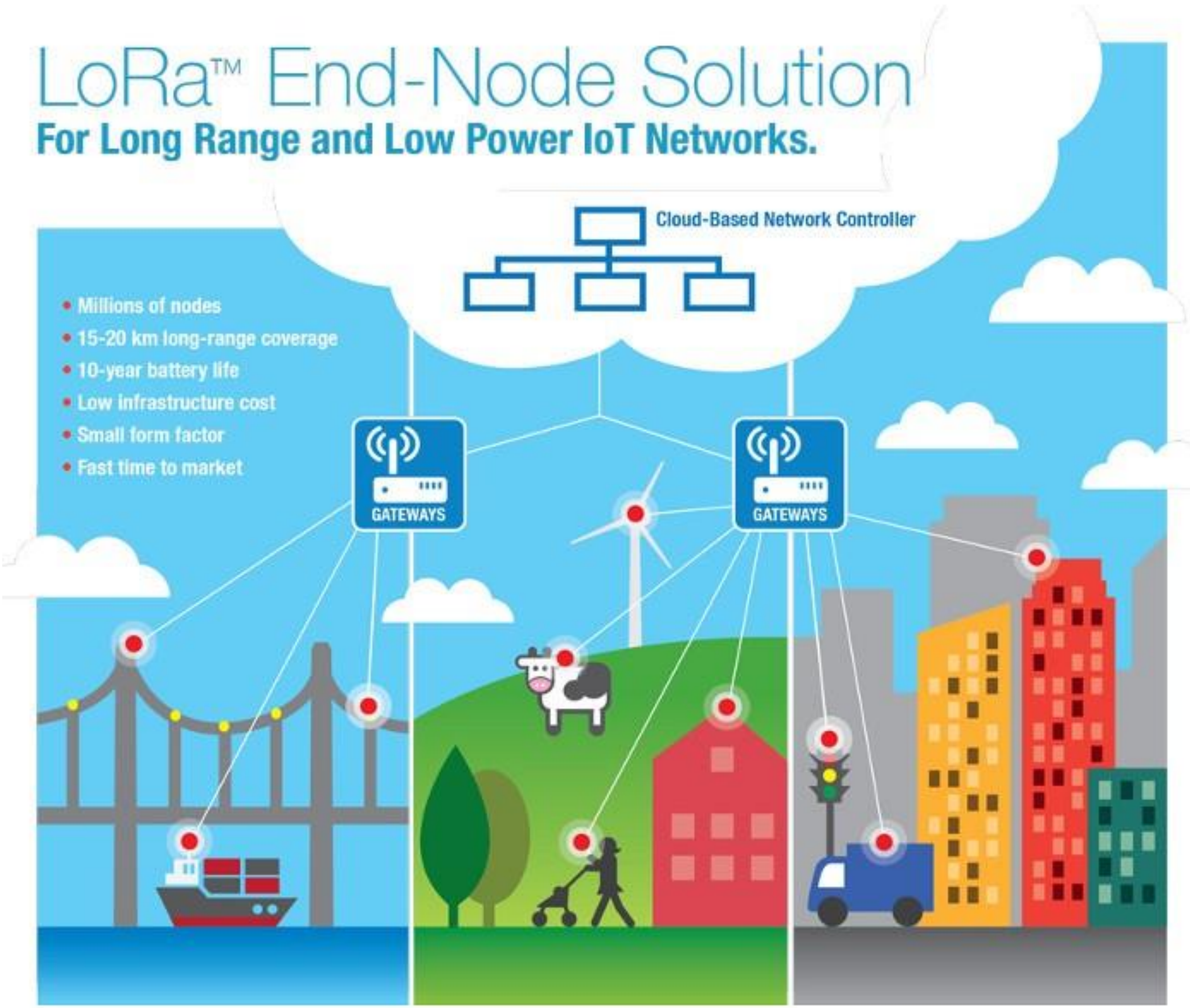
Communication Techniques for IoT



http://2yh5c119vtjz3yoo8229y5bs-wpengine.netdna-ssl.com/wp-content/uploads/2016/04/IoT-technologies-grouped-by-operating-range.jpg

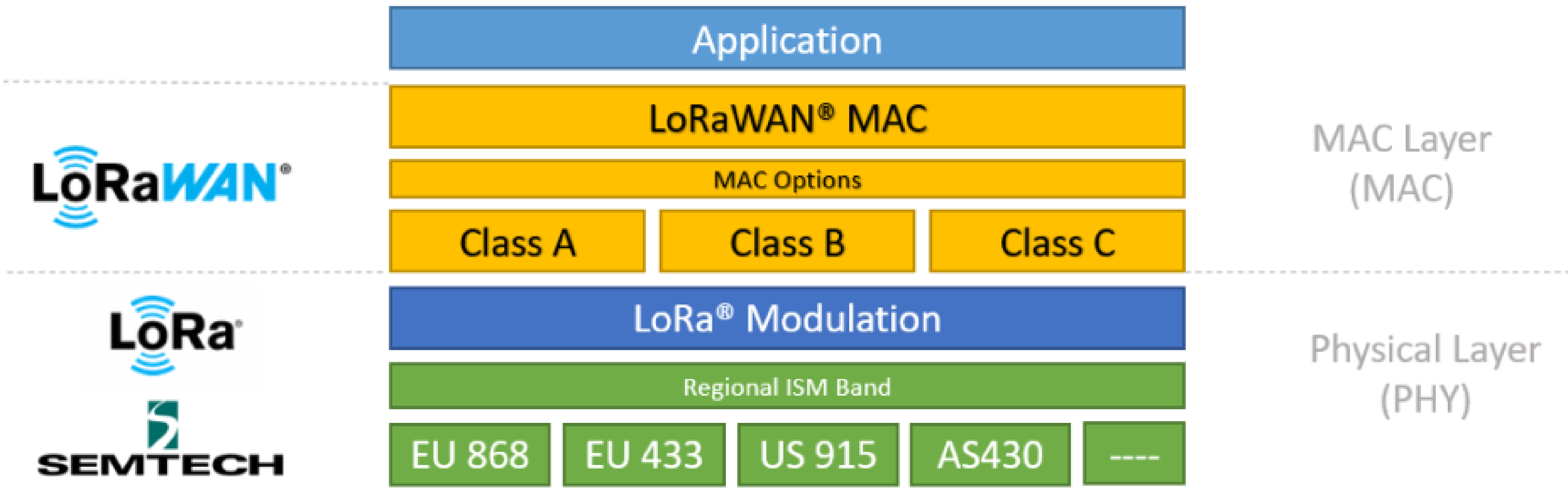
LoRa and LoRaWAN

LoRaWAN



Star of Stars Topology
Data Rate: 0.3-50 kbps
Range: Few Kms

LoRa vs LoRaWAN



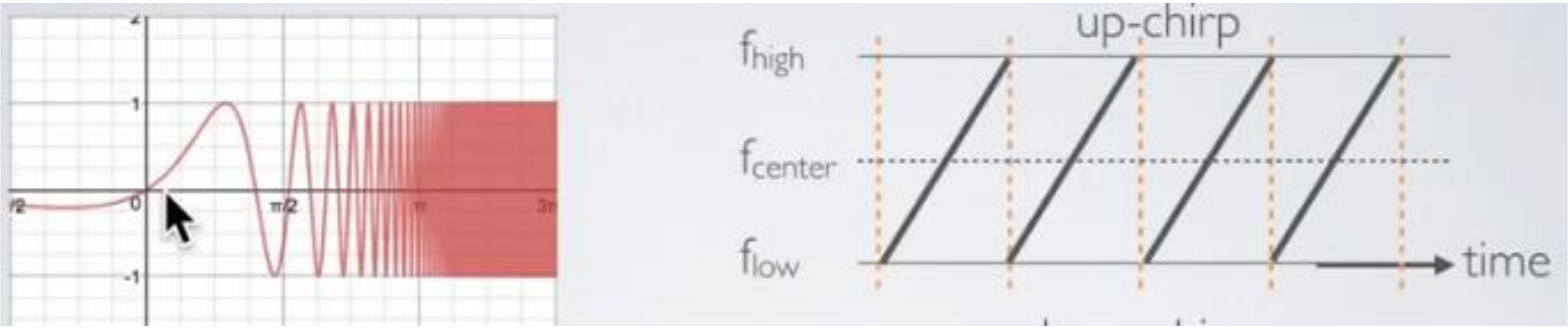
Till 2022: India- 865-867 MHz
Since 2022: India- 865-868 MHz

- LoRa is a proprietary RF modulation technology at PHY
- Created by Cycleo (acquired by Semtech)
- LoRaWAN is technology stack on top of LoRa
  - LoRaWAN alliance of more than 500 companies
  - Semtech a founding member

LoRa (PHY)

LoRa: Modulation

- A proprietary spread spectrum technique derived out of *Chirp Spread Spectrum*
- Chirp spread spectrum (CSS) is a spread spectrum technique that uses wideband linear frequency modulated chirp pulses to encode information
- Chirp
  - *A sinusoidal signal of frequency increase or decrease over time, often with a polynomial expression for the relationship between time and frequency*



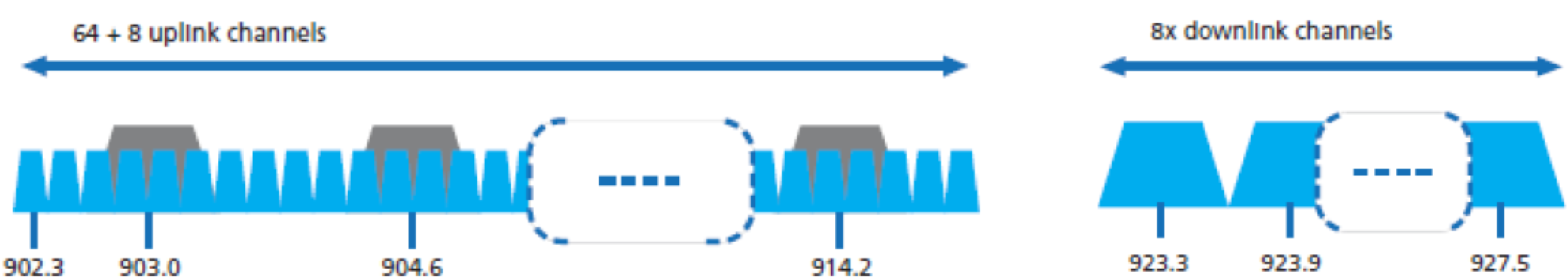
https://www.youtube.com/watch?v=r84GMLeiqg8

LoRa: Frequency and BW

- Unlicensed Sub-GHz frequencies
  - Europe
    - 433.05-434.79 MHz
    - 863-870 MHz
  - Australia: 915–928 MHz
  - North America: 902–928 MHz
  - India: 865–868 MHz
  - Southeast Asia: 433.05-434.79 MHz

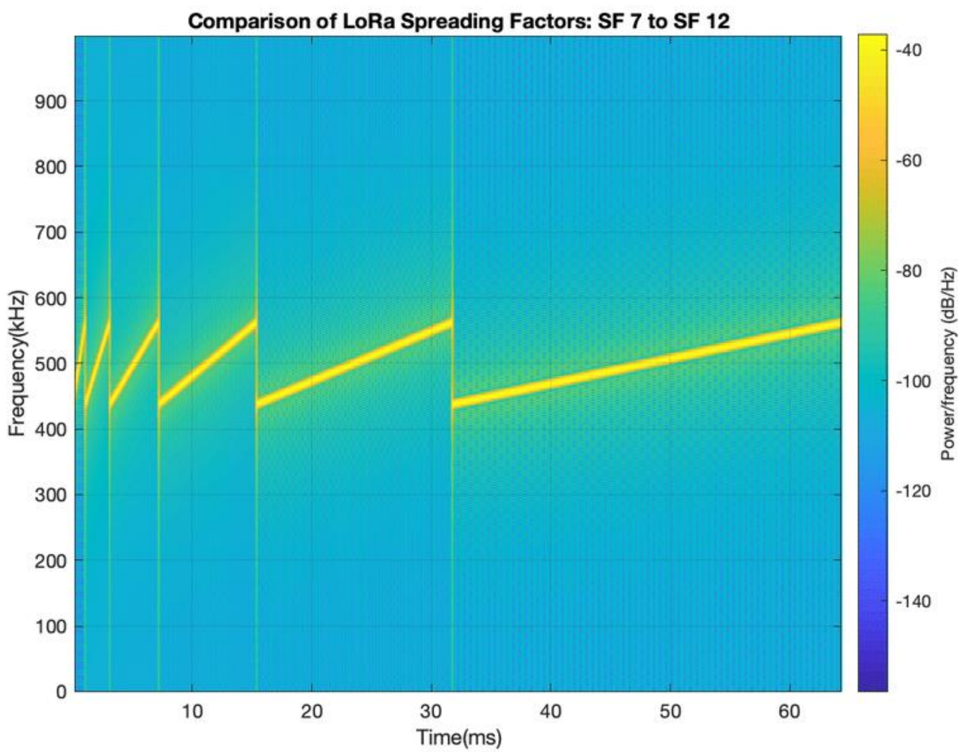
  https://lora-alliance.org/wp-content/uploads/2019/11/rp_2-1.0.0_final_release.pdf

- Fixed bandwidths
  - Uplink: 125 KHz channels or 500 KHz (or 250 KHz)
  - Downlink: 500 KHz



Spreading Factor

- Processing gain by multiplying by spreading code
  - Increase in frequency component
- Six frequency spreading factors (SFs) are possible: 7-12
- Symbol rate is given by $R = BW/2^{SF}$
  - When spreading factor increases from n to $n+1$, the symbol duration ($T = 1/R$) doubles
- Tradeoff b
  - Larger S ... ansmit
- Adaptive
  - End dev ... should use higher SF



https://www.researchgate.net/figure/LoRa-uses-a-chirp-spread-spectrum-modulation-technique-The-figure-also-shows-that-LoRa_fig3_332151302

Spreading Factor Orthogonality

- LoRa signals in same frequency bands with different SFs are orthogonal
- Two packets with the same SF in same slots will collide
  - However, if one of the two packets is stronger by six dB, it will survive.

LoRa Modulation Characteristics

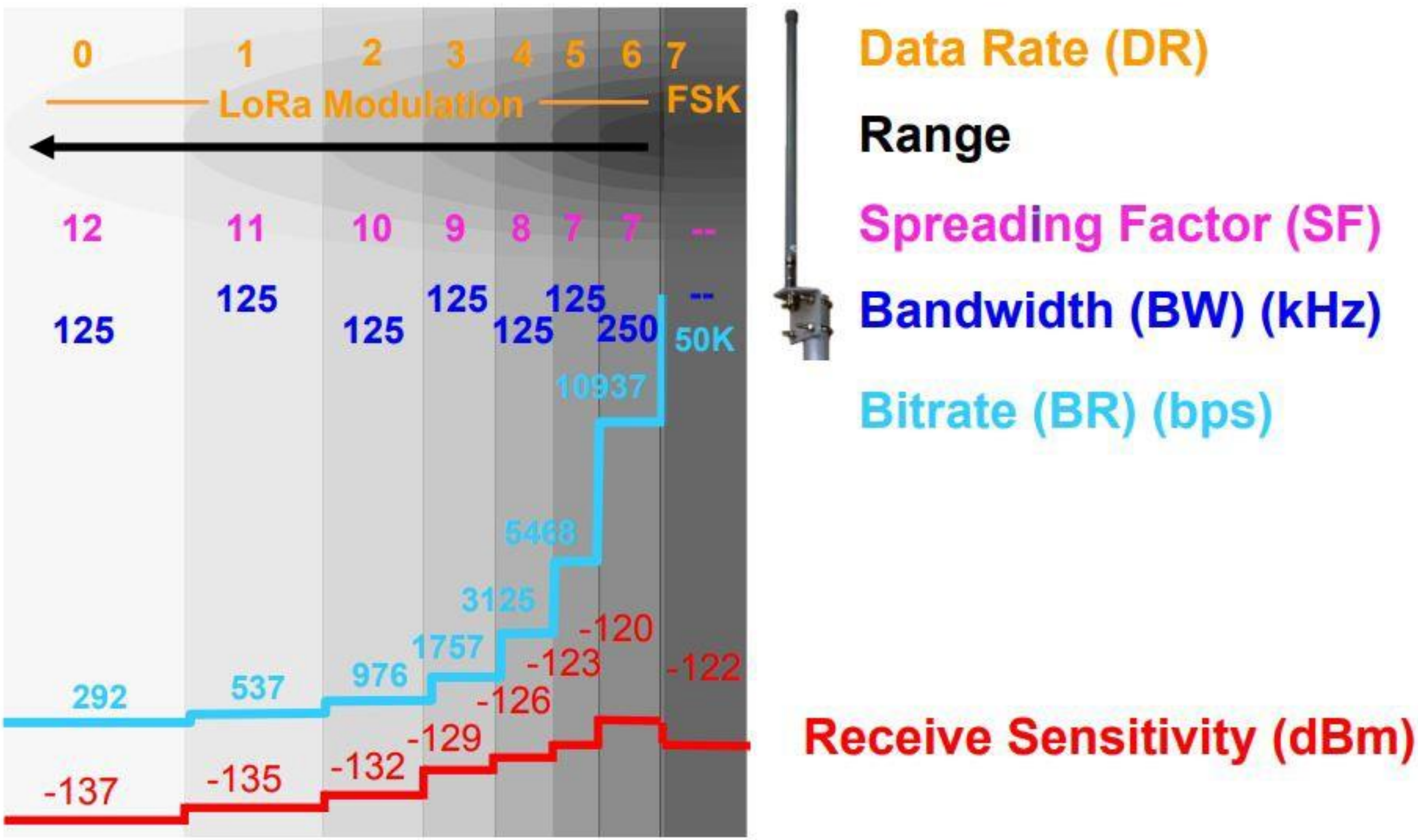
Data Rate (DR)	Spreading Factor (SF)	Channel Frequency	Uplink or Downlink	Bitrate (Bits/Sec)	Maximum User Payload Size (Bytes)
0	SF10	125 kHz	Uplink	980	11
1	SF9	125 kHz	Uplink	1,760	53
2	SF8	125 kHz	Uplink	3,125	125
3	SF7	125 kHz	Uplink	5,470	242
4	SF8	500 kHz	Uplink	12,500	242
5 – 7					
8	SF12	500 kHz	Downlink	980	53
9	SF11	500 kHz	Downlink	1,760	129
10	SF10	500 kHz	Downlink	3,125	242
11	SF9	500 kHz	Downlink	5,470	242
12	SF8	500 kHz	Downlink	12,500	242
13	SF8	500 kHz	Downlink	21,900	242

LoRa Modulation Characteristics

Modulation	Spreading factor	Bandwidth [kHz]	Maximum application throughput per channel [bps]	Maximum application layer throughput per end device per channel [bps]		
				10% duty cycle[1]	1% duty cycle[2]	0.1% duty cycle[3]
LoRa	12	125	146.1	14.61	1.46	0.15
LoRa	11	125	261.4	26.14	2.61	0.26
LoRa	10	125	584.2	58.42	5.84	0.58
LoRa	9	125	1359.2	135.92	13.59	1.36
LoRa	8	125	2738.1	273.81	27.38	2.74
LoRa	7	125	4844.7	484.47	48.45	4.84
LoRa	7	250	9689.3	968.93	96.89	9.69
GFSK	-	150	45660.4	1851.6[4]	456.6	45.66

https://www.researchgate.net/figure/Maximum-throughput-per-LoRaWAN-end-device-per-channel_tbl2_315119434

Spreading factor: Tradeoff

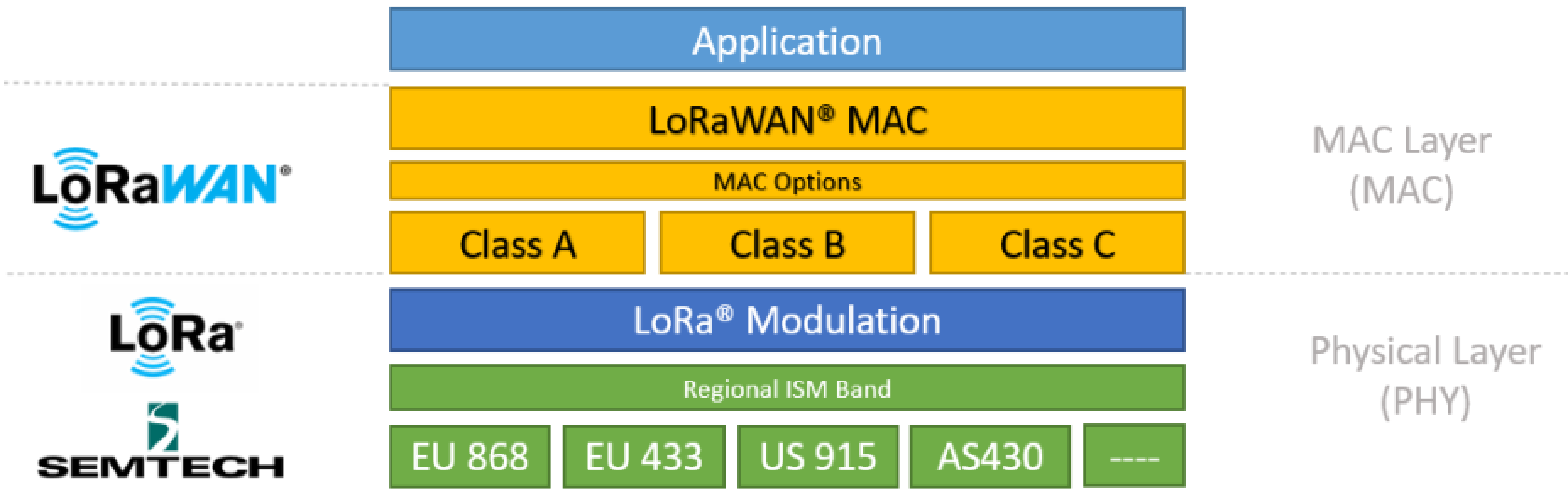


Spreading Factor

Spreading Factor (For UL at 125 KHz)	Bit Rate	Range (Depends on Terrain)	Time on Air for an 11-byte payload
SF10	980 bps	8 km	371 ms
SF9	1760 bps	6 km	185 ms
SF8	3125 bps	4 km	103 ms
SF7	5470 bps	2 km	61 ms

LoRaWAN

LoRaWAN Technology Stack



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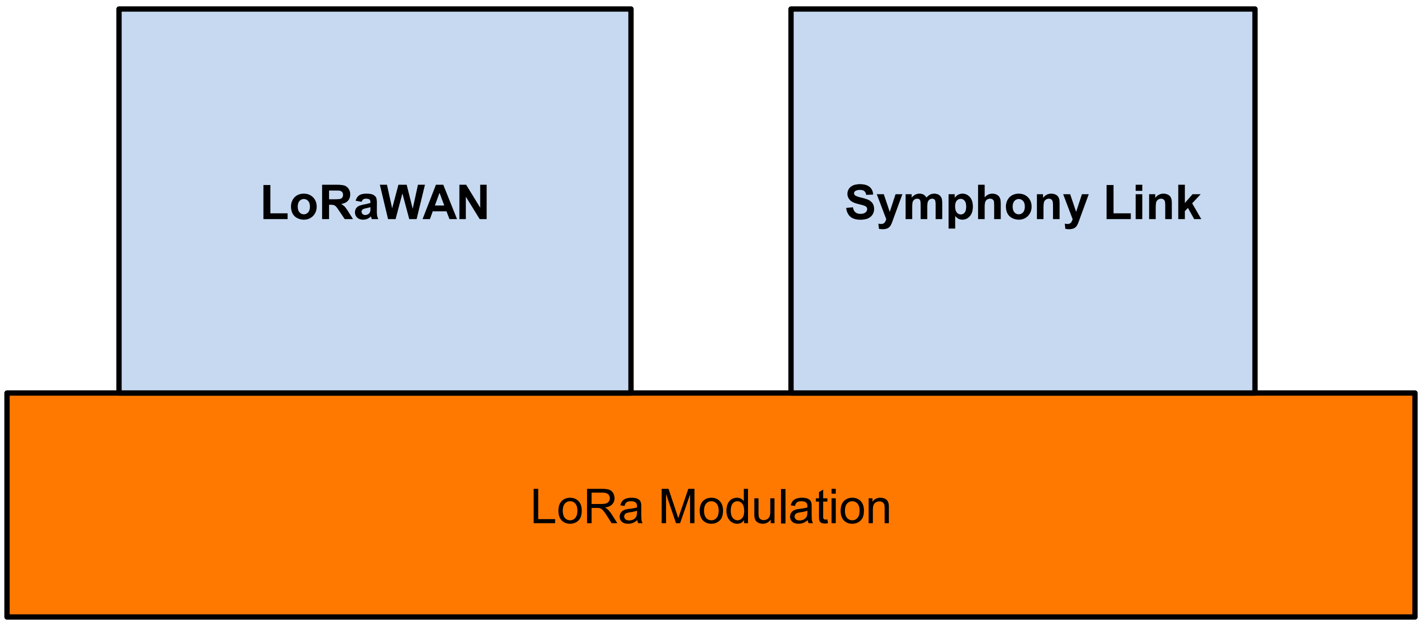
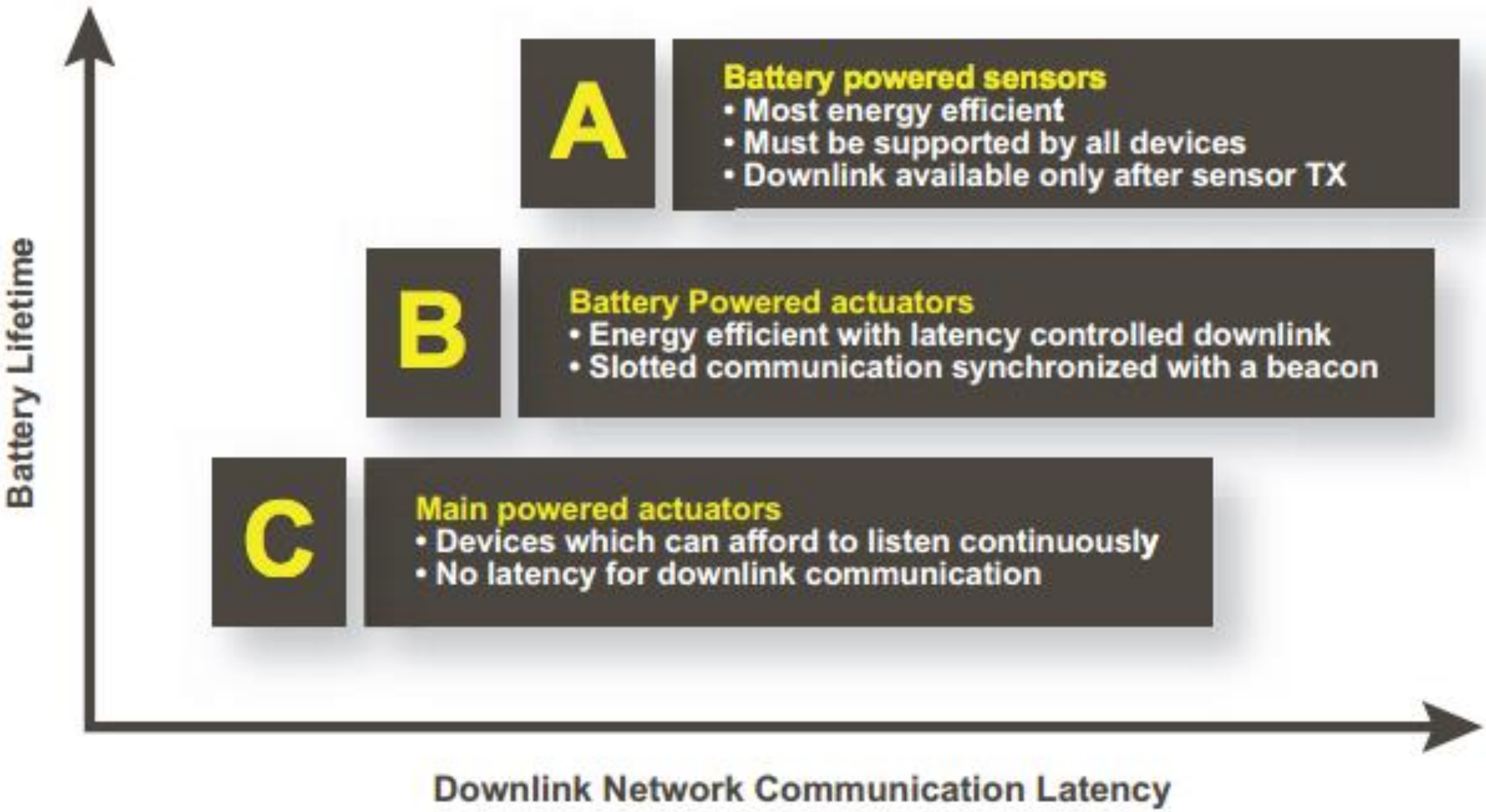
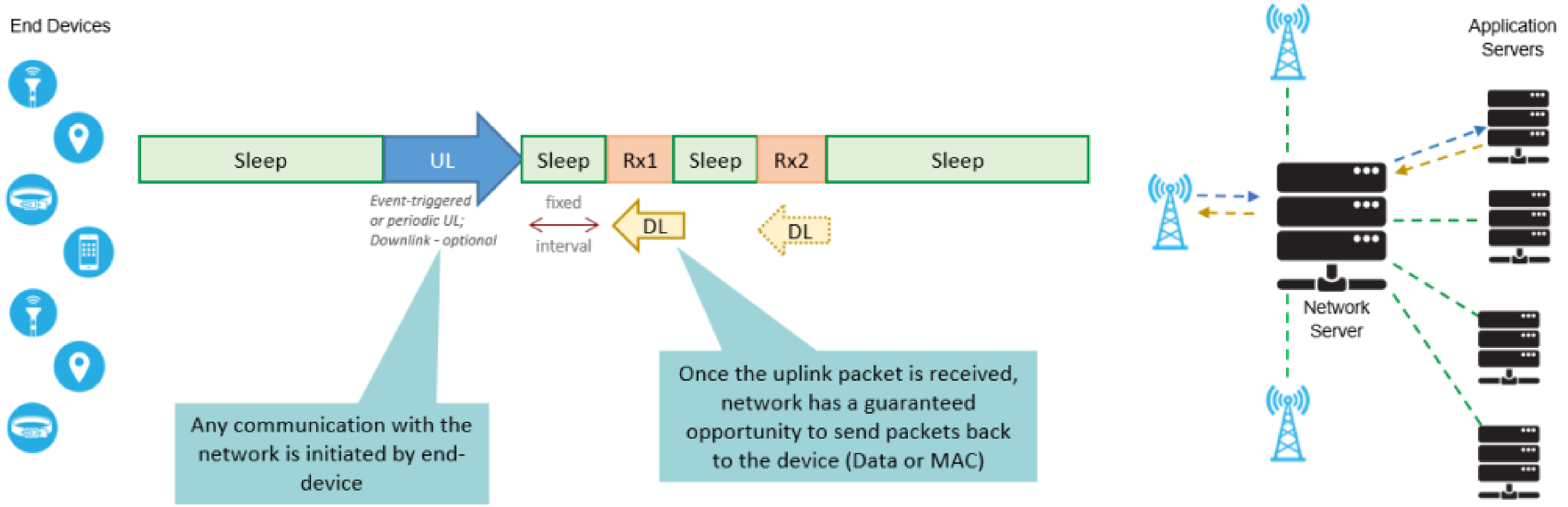
Other solutions possible with LoRa



LoRaWAN classes

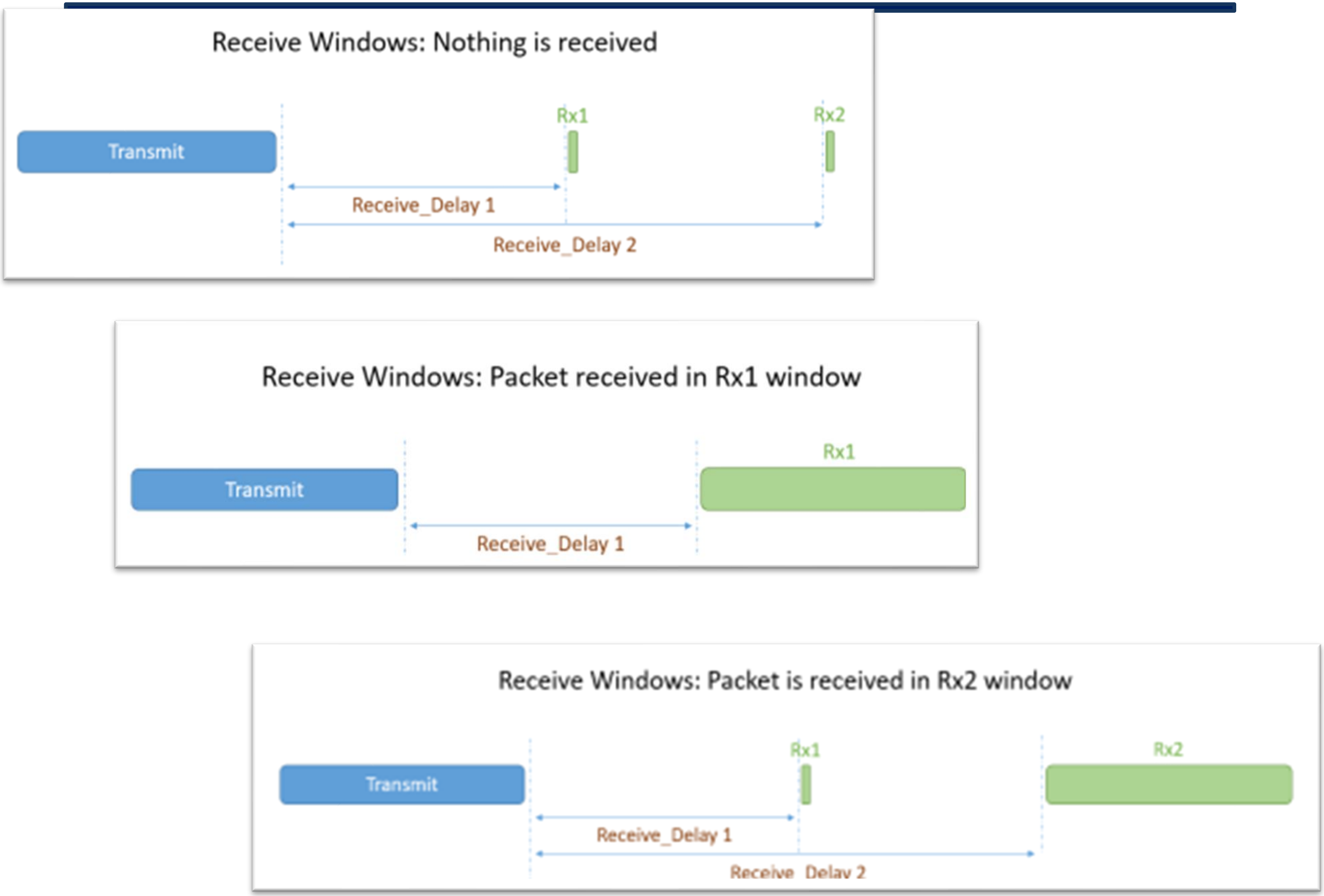


Class A operation

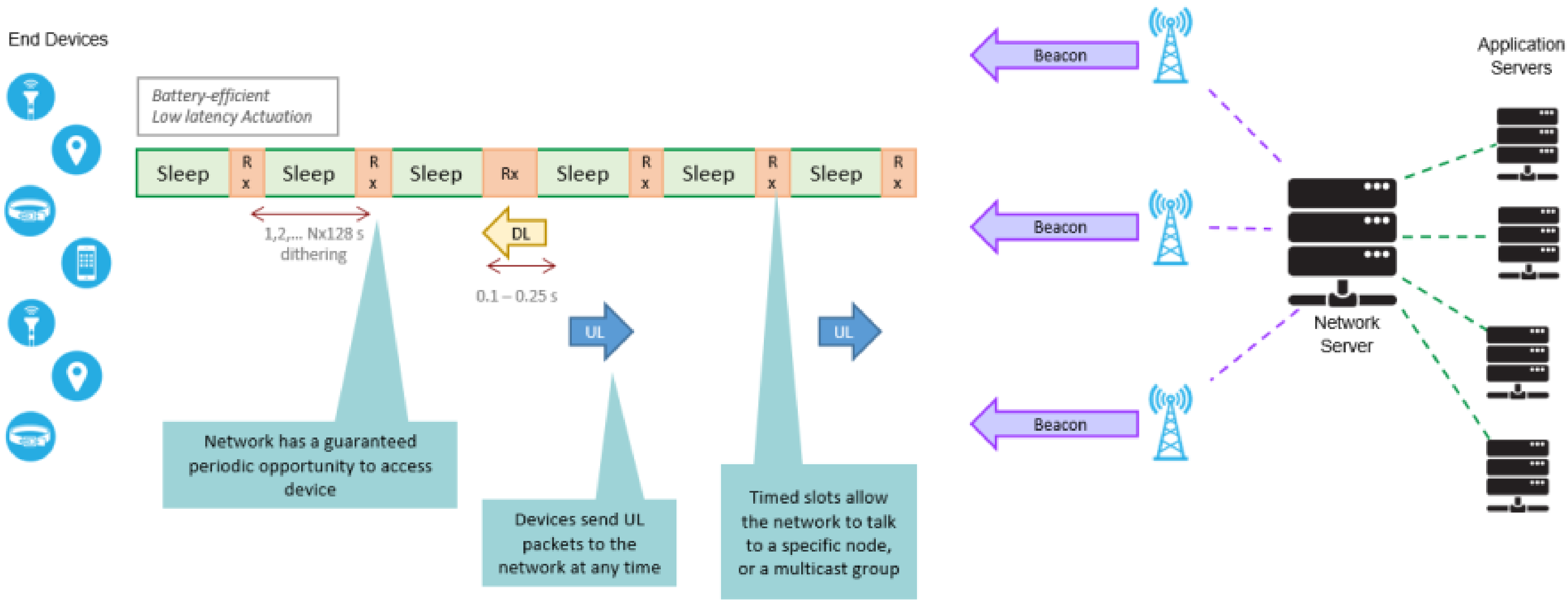


- Downlink only after uplink transmission
- Any communication is initiated by end-device
- Most energy efficient
- All devices should support this
- Default mode
- No way application can wakeup the end-device
    - Serious latency issues
    - Not suitable for actuators

Class A operation

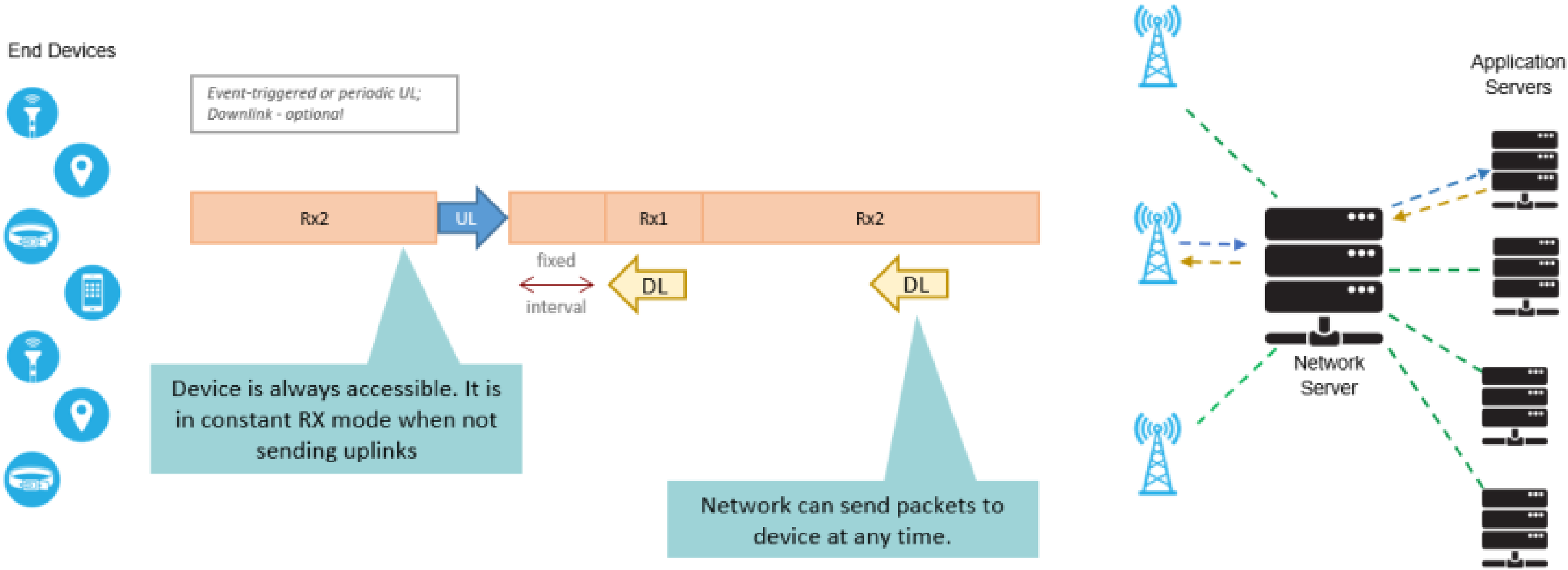


Class B operation



- Fixed time slots for an end device to receive downlinks
- Beacon required to synchronize the nodes
- Gateways need GPS timing source
- Beacon interval of 128 s (675 beacons in day)
- Suitable for battery powered actuators

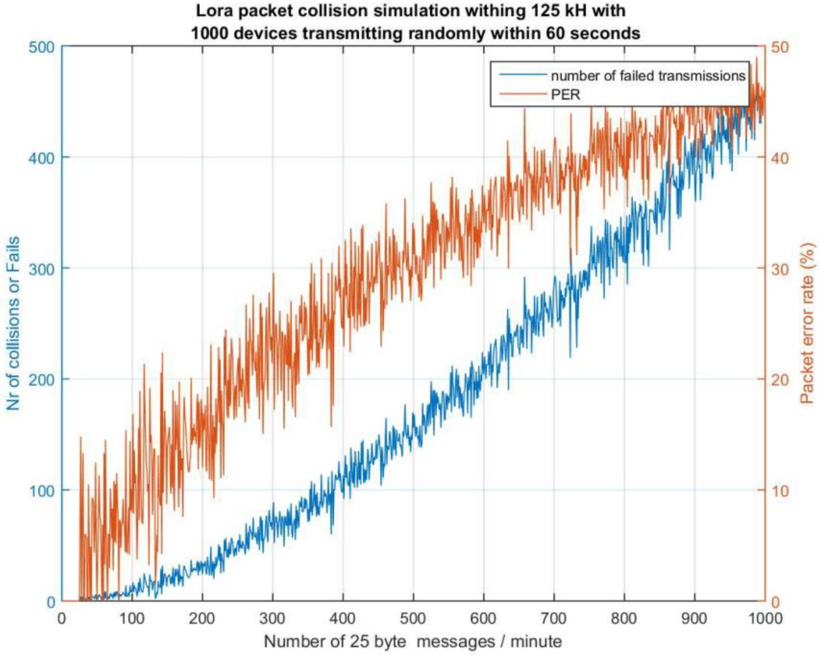
Class C Operation



- Class C devices are always ON
  - Streetlights, electrical meters
- Devices are always listening for downlink messages, unless they are transmitting an uplink
  - Lowest latency for communication from the server to an end device.

LoRaWAN

- Gateways listen on 8 frequencies on all spreading factor
- Collision prevented by maximum duty cycle



Source: https://sites.google.com/a/wesdec.be/mweyn/lpwan

Frequencies and Channels

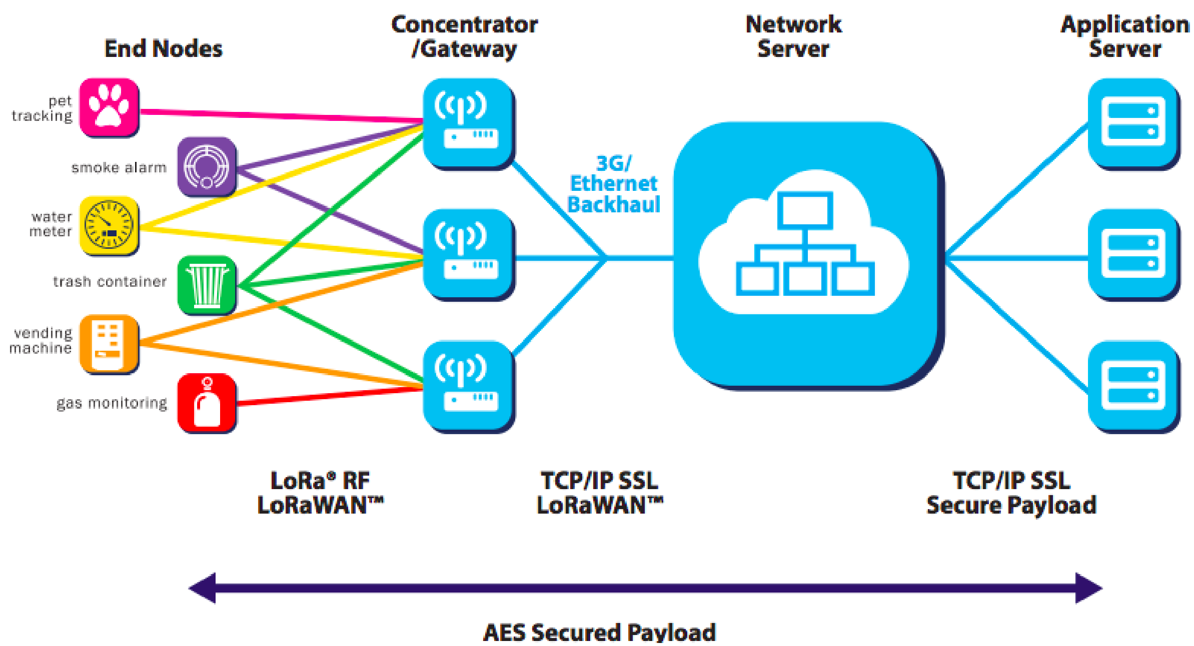
Region / Band Name	Frequency Range (MHz)	Uplink Channels	Downlink Channels	Bandwidth (kHz)
EU863–870 (Europe)	863–870	3 mandatory + optional up to 16	Same as uplink	125 / 250
US902–928 (North America)	902–928	64 × 125 kHz + 8 × 500 kHz	8 × 500 kHz	125 / 500
IN865–867 (India)	865–867	3	Same as uplink	125
AU915–928 (Australia / New Zealand)	915–928	64 × 125 kHz + 8 × 500 kHz	8 × 500 kHz	125 / 500
CN470–510 (China)	470–510	96 × 125 kHz	48 × 125 kHz	125
AS923 (Southeast Asia, Japan, parts of Middle East)	923–925 (±)	4 or more	4 or more	125
JP920–923 (Japan)	920–923	4	4	125
KR920–923 (Korea)	920.9–923.3	4	4	125
RU864–870 (Russia)	864–870	4–8	Same as uplink	125
CN779–787 (China alt.)	779–787	3	Same as uplink	125

Capacity of network

- LoRaWAN network can support millions of message
- A single gateway of 8 channels can support 1.5 Million messages over a day
  - If each device sends data every hour, a gateway can support 60,000 devices
- Add new gateway for more capacity and coverage
- Alternatively, we can use 16- or 64-channel gateway
- 64-channel is only used outdoors while others can be used indoors as well

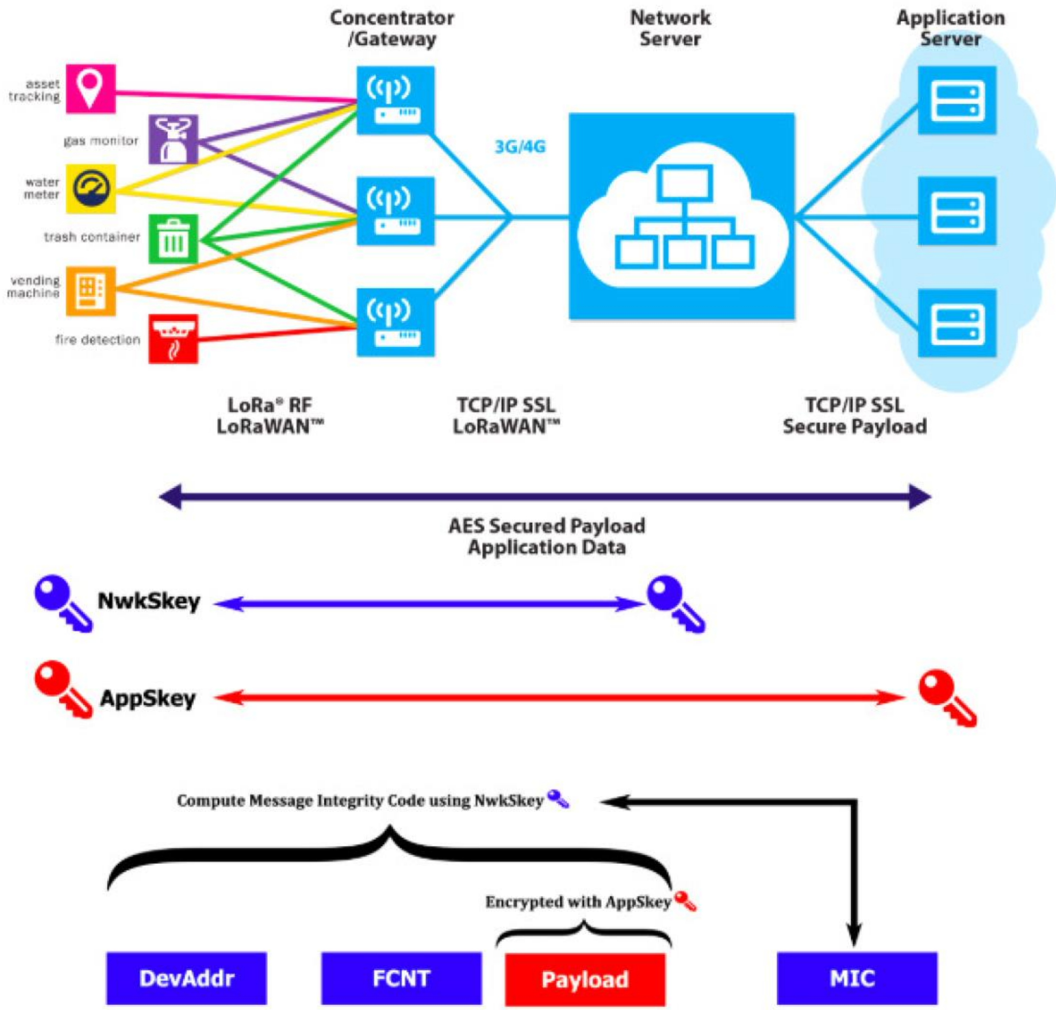
LoRaWAN

- LoRaWAN is a software layer above LoRa
  - Pure Aloha (18.4% efficiency) + CSS
  - Dumb Gateways and Smart Server: *Filters data at server*
  - Makes transmission reliable by allowing retransmissions
  - Transposes data on IP network
    - The gateways are connected to the network server via standard IP connections and act as a transparent bridge, simply converting RF packets to IP packets and vice versa.



https://medium.com/coinmonks/lpwan-lora-lorawan-and-the-internet-of-things-aed7d5975d5d

LoRaWAN security



LoRaWAN adds security as LoRa does not have security

NwkSkey to guarantee the message integrity from the device to LoRa server

AppSKey to used for end to end AES-128 bit encryption from device to application server

https://medium.com/coinmonks/lpwan-lora-lorawan-and-the-internet-of-things-aed7d5975d5d

IoT Features: *Advantages*

- Designed for the majority of IoT applications
- Low-powered sensors (Battery life of 2-5 years)
  - Class A and B
- Wide coverage area up to 15 Kms
- Simple Architecture and Low Costs
  - Free (unlicensed) frequencies
- One gateway can support thousands of end devices
- Security: a layer of security for the network and one for the application with AES encryption.
- Localization without GPS
- Roaming
- LoRa Alliance: 500+ member companies, including IBM and Cisco
  - More than 5 million devices deployed in 2022
- LoRa mesh is now possible
- LoRaPlus: SatCom, support for 2.4 GHz
  - https://www.semtech.com/products/wireless-rf/lora-plus/lr2021

IoT Features: *Disadvantages*

- Payload limited to 100 bytes
- High latency (actuators are not possible except for class C)
- Low data rates
  - Does not support voice or video
- Low duty cycles (1% in EU)
- Interference issues
  - Unlicensed frequency for other technology users
  - Crowding of LoRaWAN gateways increase interference
  - High packet error rate
- Cost in terms of cloud-based servers for network and applications
  - Things Network, LoRIoT
- Needs fair amount of development work
  - DIY
  - Not a complete protocol stack

IoT Features: *Disadvantages*

- Not for continuous or real-time monitoring and actuations (most of low-latency industry cases)
  - High latency (actuators are not possible)
  - High packet error rate
  - Low data rates
  - Low duty cycles

Few Use Cases

- Utility monitoring
  - Water, Electricity, Gas
- Environment monitoring
  - Air Pollution, Water Quality, Soil Detection
- Animal Tracking
- Farming
- Smart building
  - Temperature, humidity sensors
- Smart Cities
  - Street Lights, Parking, Dustbins

References

- P. Lea, *Internet of Things for Architect*, Packt, 2018
- Semtech, “LoRa and LoRaWAN: A Technical Overview,” Feb. 11, 2020
  - [Online: https://lora-developers.semtech.com/uploads/documents/files/LoRa_and_LoRaWAN-A_Tech_Overview-Downloadable.pdf]
  - https://www.youtube.com/watch?v=qI4a9JHO2sc How LoRa works?

Questions?

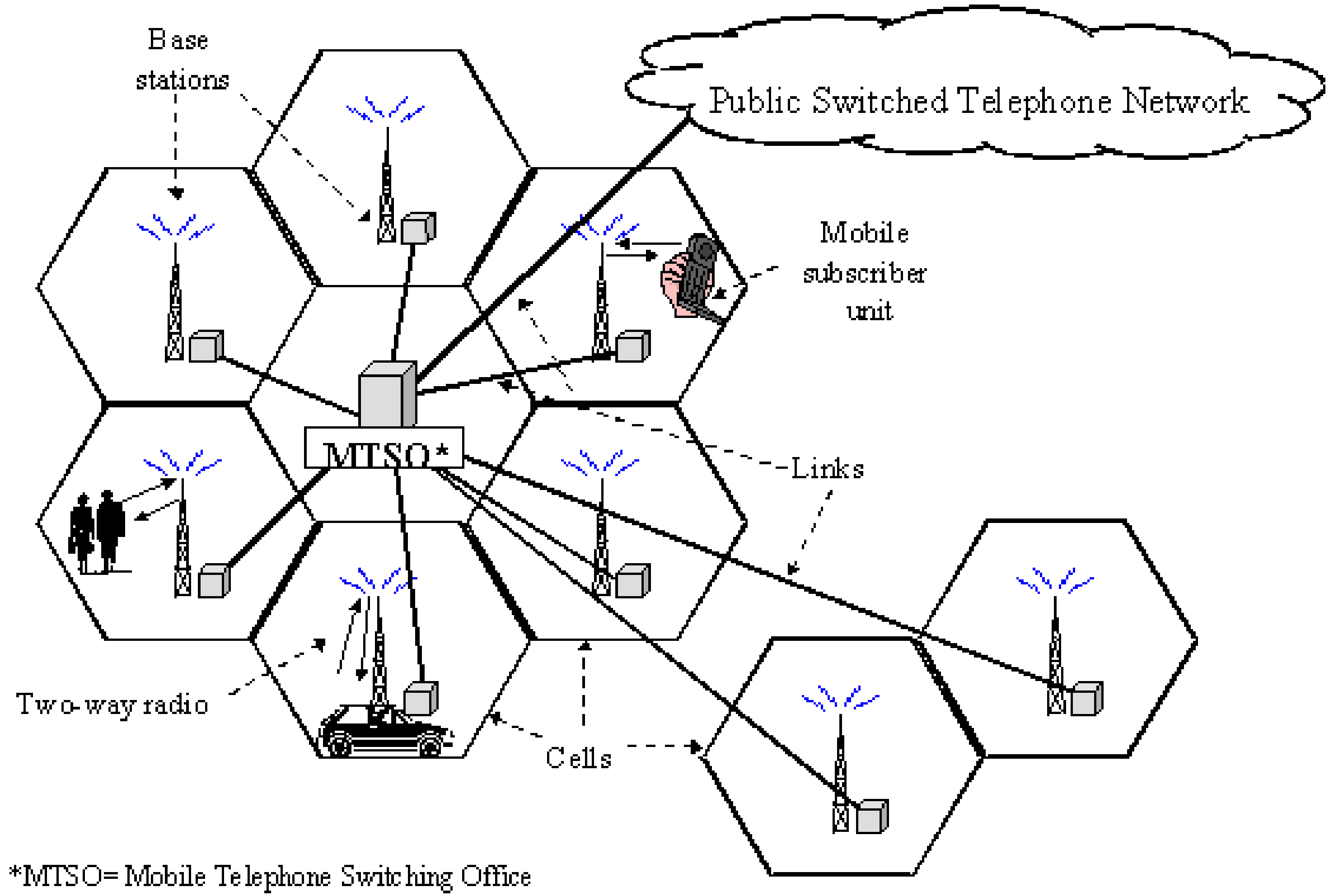
Cellular Technologies: 2G, 3G, 4G, 5G

Motivation for Cellular Communication

- Most popular wireless technology!
  - Mobility and Ubiquitous: “Anytime Anywhere communication”
  - Several functions in a device which fits in a pocket
  - Amazing technical achievement
  - Smart phone has become necessity
  - Also, addiction in some cases
    - Teenagers and technology: 'I'd rather give up my kidney than my phone’
    - Digital communication is not just prevalent in teenagers' lives. It IS teenagers' lives
    - https://www.theguardian.com/lifeandstyle/2010/jul/16/teenagers-mobiles-facebook-social-networking
- One of the most advanced wireless communication systems!
  - Spearheading wireless technology research and revolution
  - Standard based architecture
  - Convergence

Cellular Architecture: an example of 2G

https://www.itu.int/osg/spu/ni/3G/technology/index.html



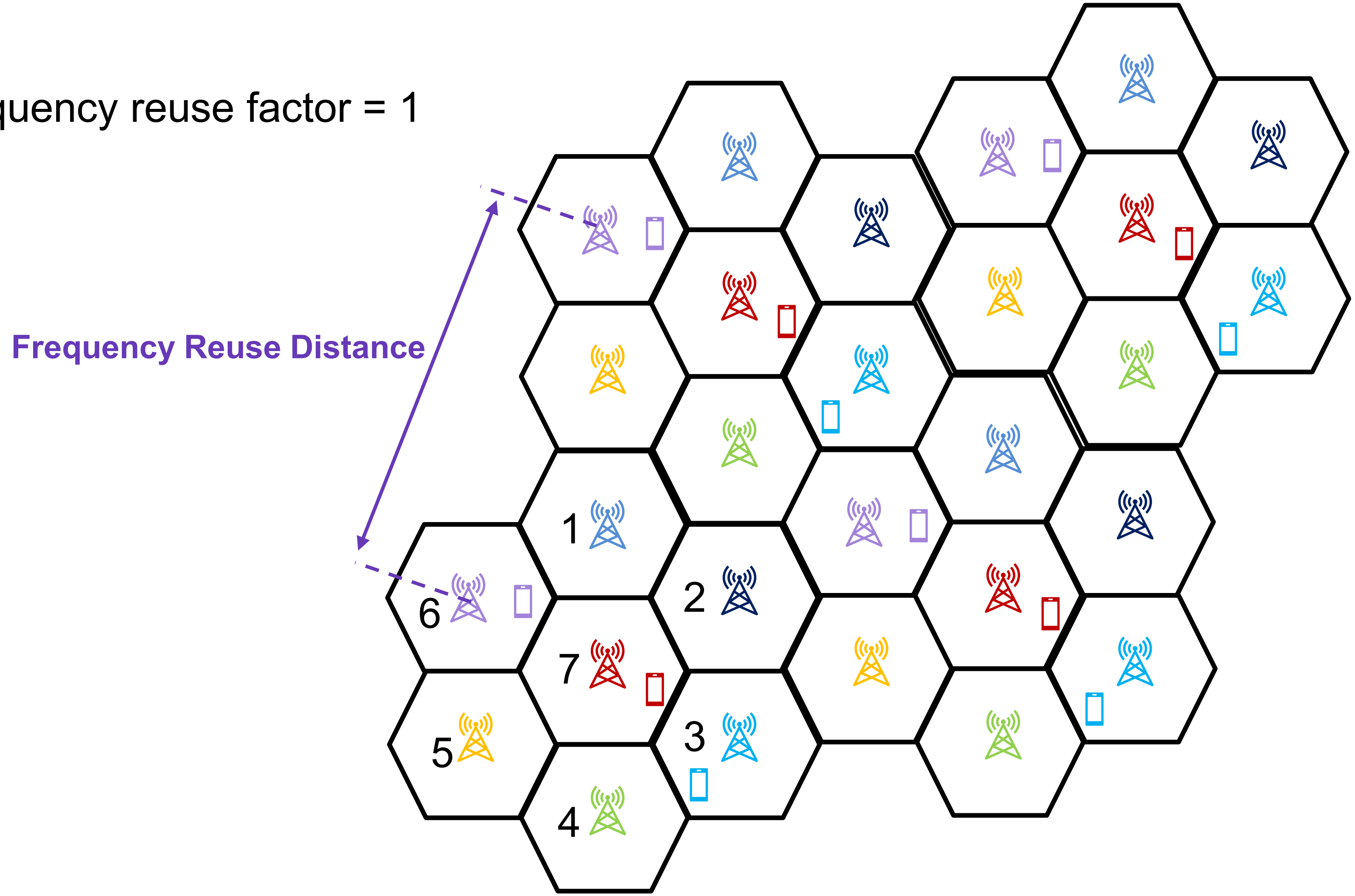
Good introduction to cellular communication: https://www.youtube.com/watch?v=1JZG9x_VOwA

Cellular Communication: *Enablers*

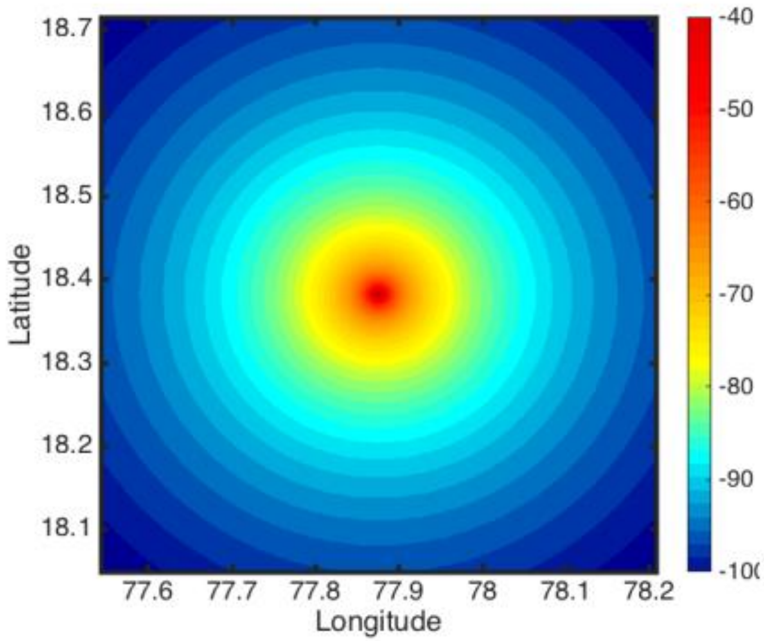
- Frequency reuse
- Backhaul
  - BTSs connected by optical fiber or microwave links
- Mobility
  - Handoffs across cells

Frequency Reuse

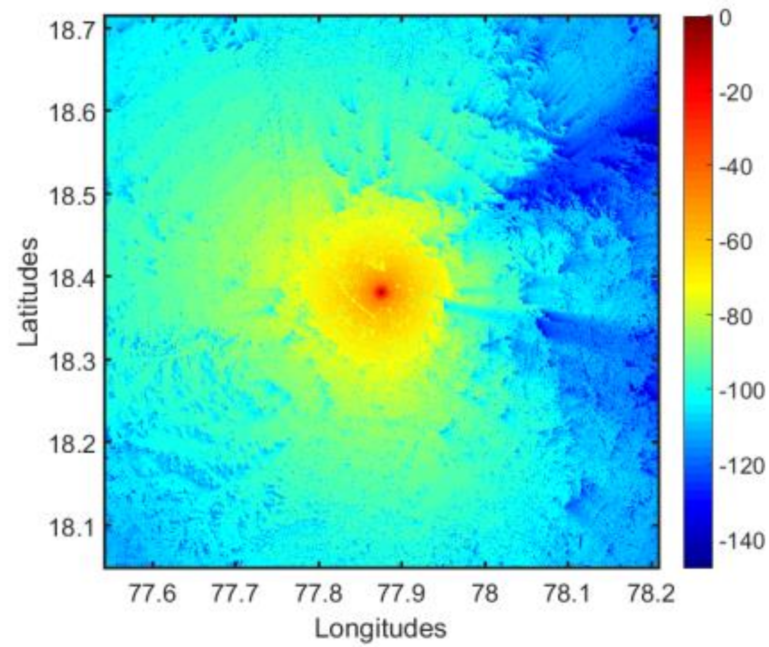
- Increases system capacity by reusing resources
- 2G: Frequency reuse factor = 7
  - Avoid inter-cell interference
- 3G/4G
  - Frequency reuse factor = 1



Signal Strength From Transmitter



Ideal free space path loss

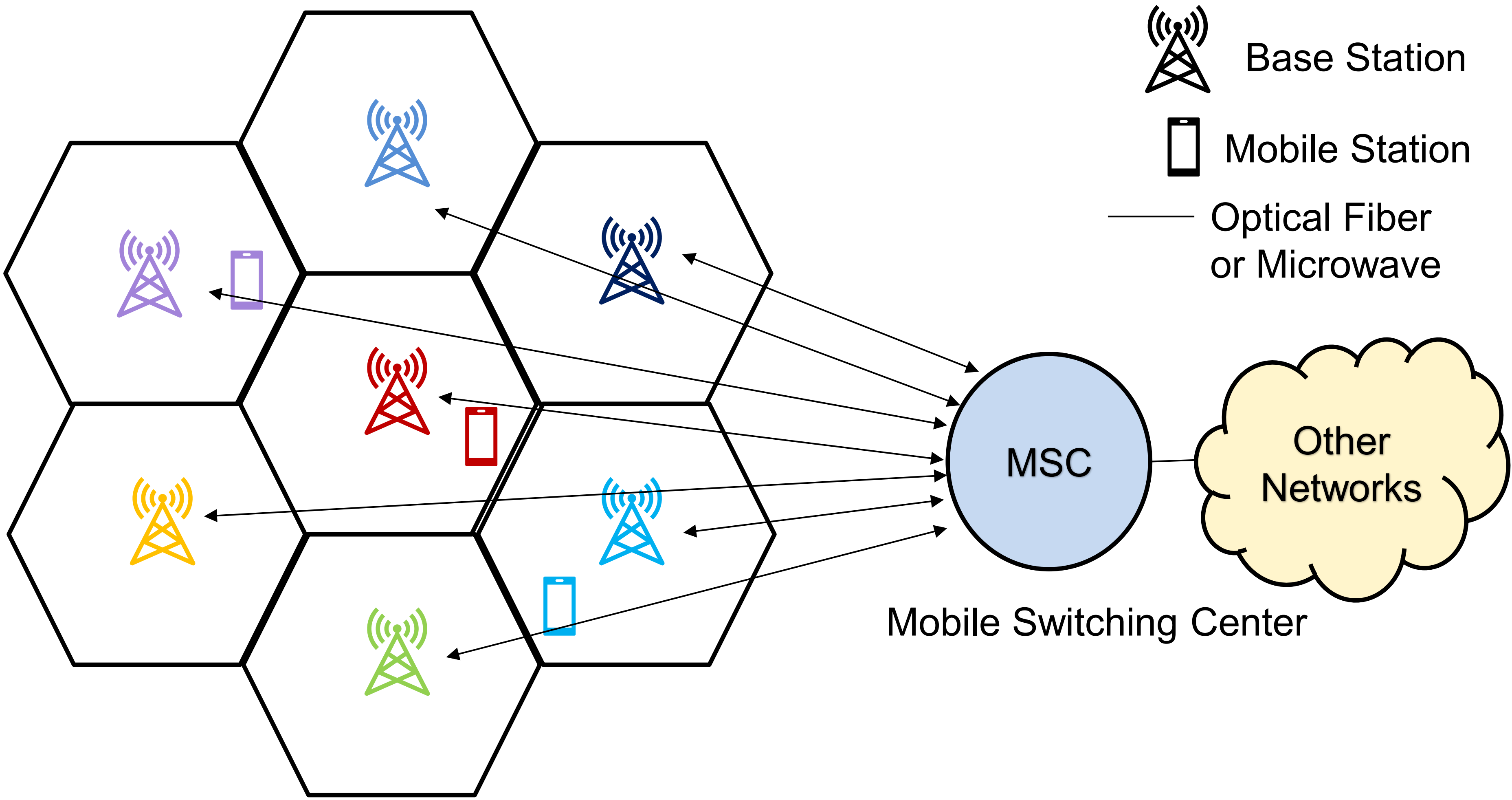


Terrain, obstacles, and other geographical factors will result in irregular contours

- R. Chowdary, A. Eturu, **S. Chaudhari**, and J. Oksanen, "Improved Estimation of TV White Spaces in India using Terrain Data," *in NCC* , Chennai, Mar. 2017

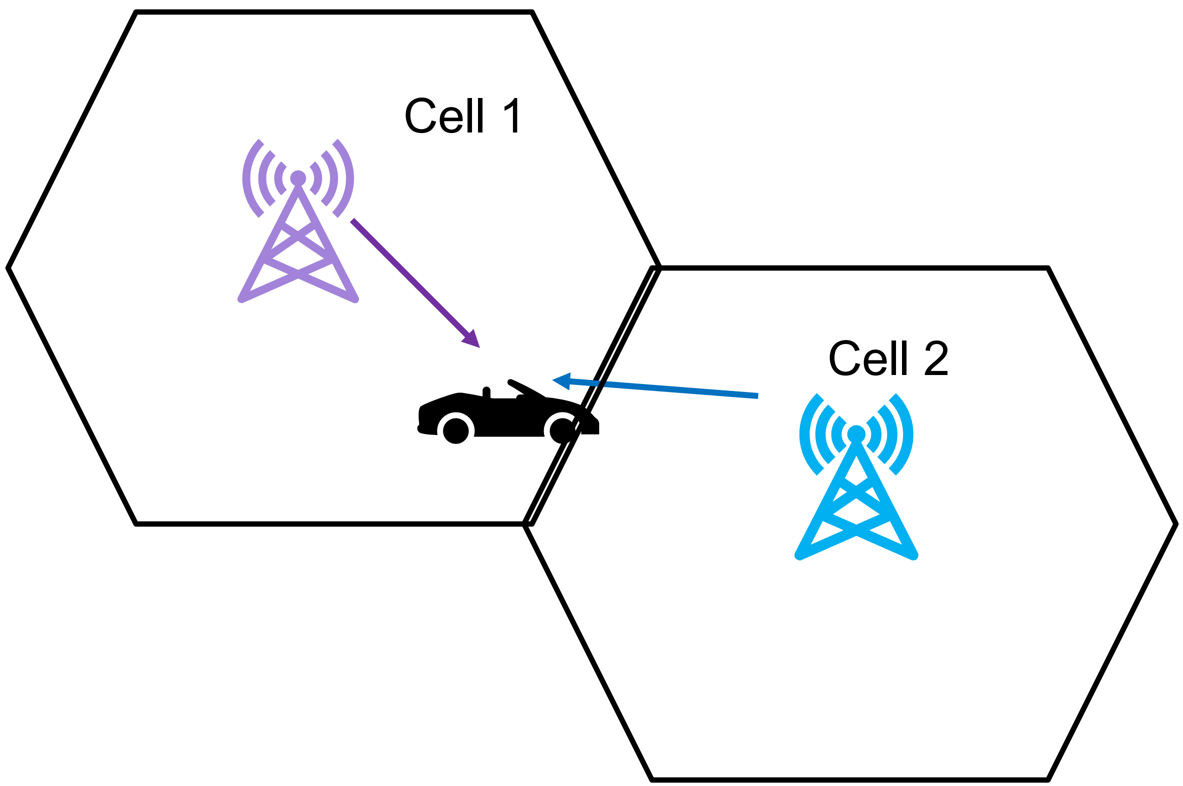
Cellular Communication: *Backhaul*

- BTS connected by optical fiber or microwave links

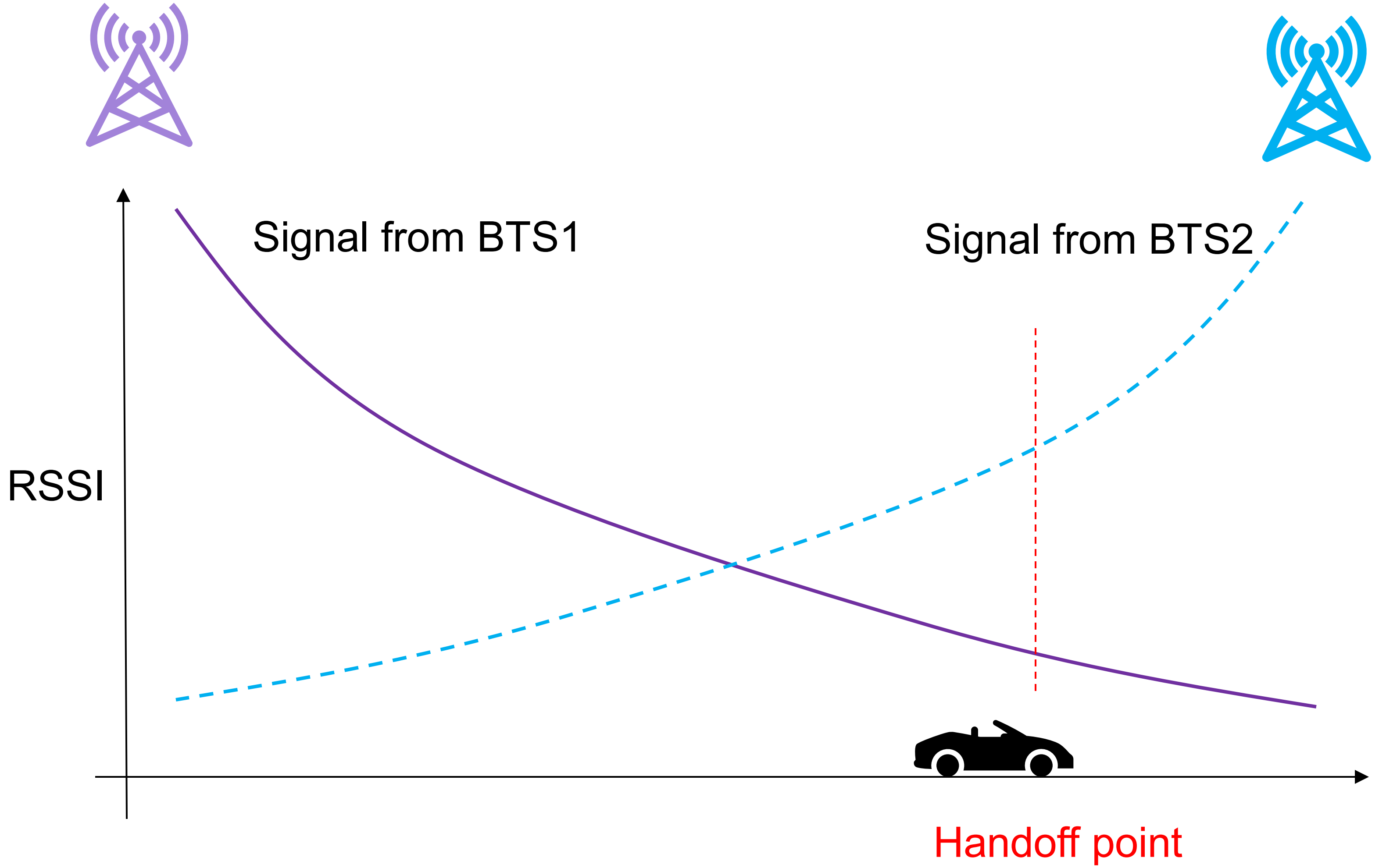


Handover/ Handoff

- When the user is moving from one cell to the other cell, continuity is maintained by MSC through handover
- Two types of handover
  - Hard (break before make)
  - Soft (make before break)



Handover/ Handoff



Spectrum Chart in India

- 2G: GSM 900 / GSM 1800
- 3G: UMTS 900, UMTS 2100
- 4G: LTE 850, 1800, 2100, 2300, 2500
- 5G: 700 MHz, 800 MHz, 900 MHz, 1800 MHz,
  2100 MHz, 2500 MHz, 3300 MHz, and 26 GHz.

https://www.gsmarena.com/network-bands.php3?sCountry=INDIA

Exact allocation:
National Frequency Allocation Plan, 2022

Cellular Technologies for IoT

- Licensed
  - 2G, 3G, 4G
    - Why not use these for IoT?
  - MTC: Cat-1, Cat-0, LTE-CatM1, NB-IoT, 5G
    - low-power, long-range applications

Cat-1, Cat-0, eMTC, NB-IoT and EC-GSM-IoT

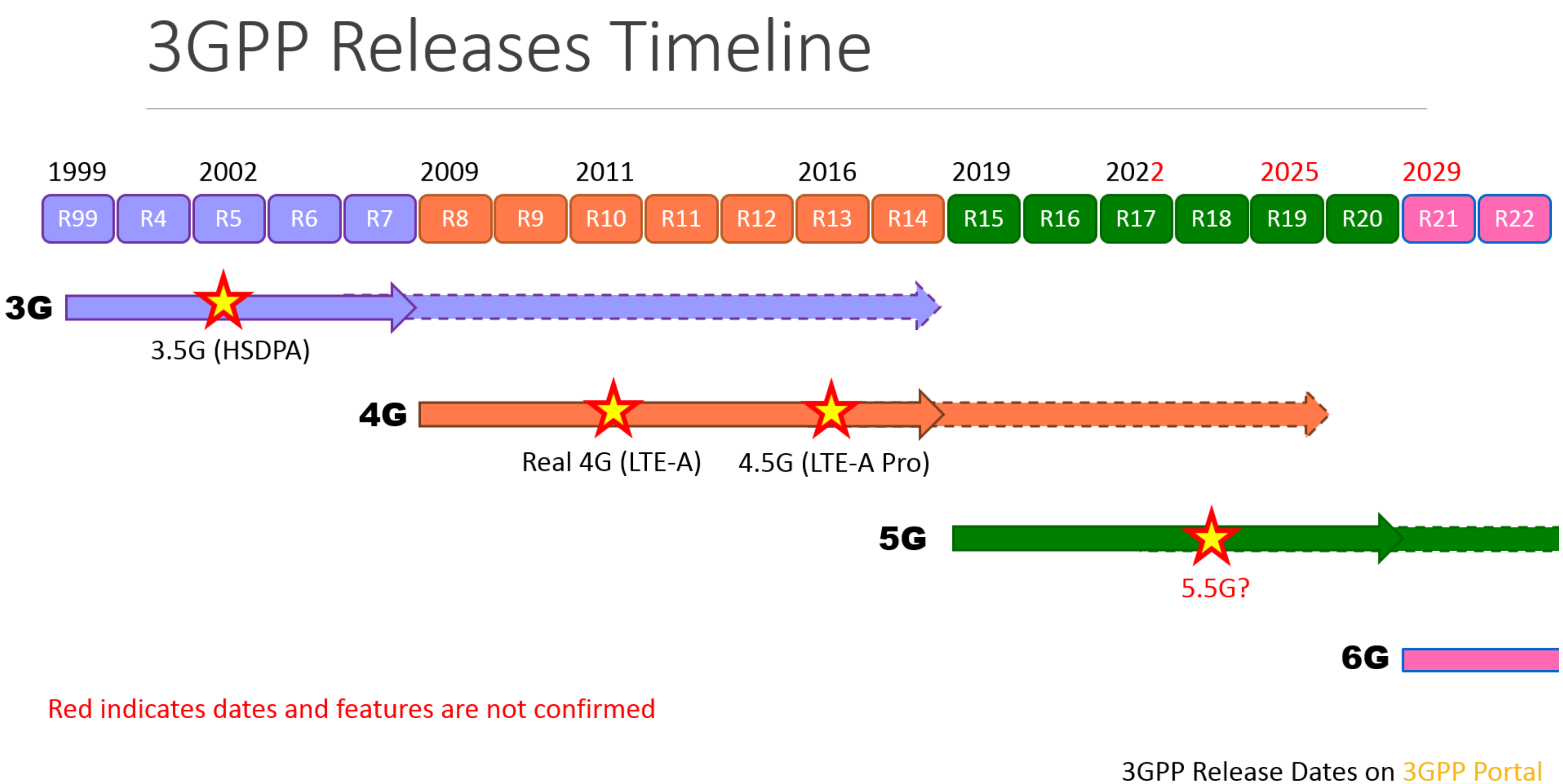
LTE-M or LTE-MTC or LTE Cat M1

	LTE Cat 1	LTE Cat 0	LTE Cat M1 (eMTC)	LTE Cat NB1 (NB-IoT)	EC-GSM-IoT
3GPP Release	Release 8	Release 12	Release 13	Release 13	Release 13
Downlink Peak Rate	10 Mbit/s	1 Mbit/s	1 Mbit/s	250 kbit/s	474 kbit/s (EDGE) 2 Mbit/s (EGPRS2B)
Uplink Peak Rate	5 Mbit/s	1 Mbit/s	1 Mbit/s	250 kbit/s (multi-tone) 20 kbit/s (single-tone)	474 kbit/s (EDGE) 2 Mbit/s (EGPRS2B)
Latency	50–100ms	not deployed	10ms–15ms	1.6s–10s	700ms–2s
Number of Antennas	2	1	1	1	1–2
Duplex Mode	Full Duplex	Full or Half Duplex	Full or Half Duplex	Half Duplex	Half Duplex
Device Receive Bandwidth	1.08 – 18 MHz	1.08 – 18 MHz	1.08 MHz	180 kHz	200 kHz
Receiver Chains	2 (MIMO)	1 (SISO)	1 (SISO)	1 (SISO)	1–2
Device Transmit Power	23 dBm	23 dBm	20 / 23 dBm	20 / 23 dBm	23 / 33 dBm

LTE-M and NB-IoT enhanced in Release 14

http://www.3gpp.org/images/articleimages/iot_summary_large.jpg

3GPP Releases Timeline



https://twitter.com/3g4gUK/status/1226448108197945345/photo/1

Cat-1, Cat-0, and EC-GSM-IoT

- Cat-1
  - IoT support in LTE 3G (Release 8)
  - Premium IoT applications
- Cat-0
  - IoT support in LTE-A 4G (Release 12)
  - Optimized cost as compared to Cat-1
- EC-GSM
  - IoT support in GSM networks
  - Extended Coverage

Cat-M1 (eMTC)

- IoT support in LTE-A 4G (Release 13)
- Compatible with existing LTE network (only software upgrade)
- 1.4 MHz bandwidth
- Supports mobility and voice-over LTE (VoLTE)
- Asset tracking and wearables

NB-IoT or Cat-M2

- Competing against Sigfox, LoRa (Release 13)
- Support of massive number of low throughput devices, ultra-low device cost, low device power consumption and optimized network architecture
- Improved indoor coverage
  - Power boosting
  - Repetition
- flexible spectrum: in-band and guard band in LTE; standalone deployment; GSM re-farming possible
- Not backward compatible with other 3G/4G devices
- No mobility support and not suitable for latency low applications
- LPWAN applications like smart metering

NB-IoT deployment

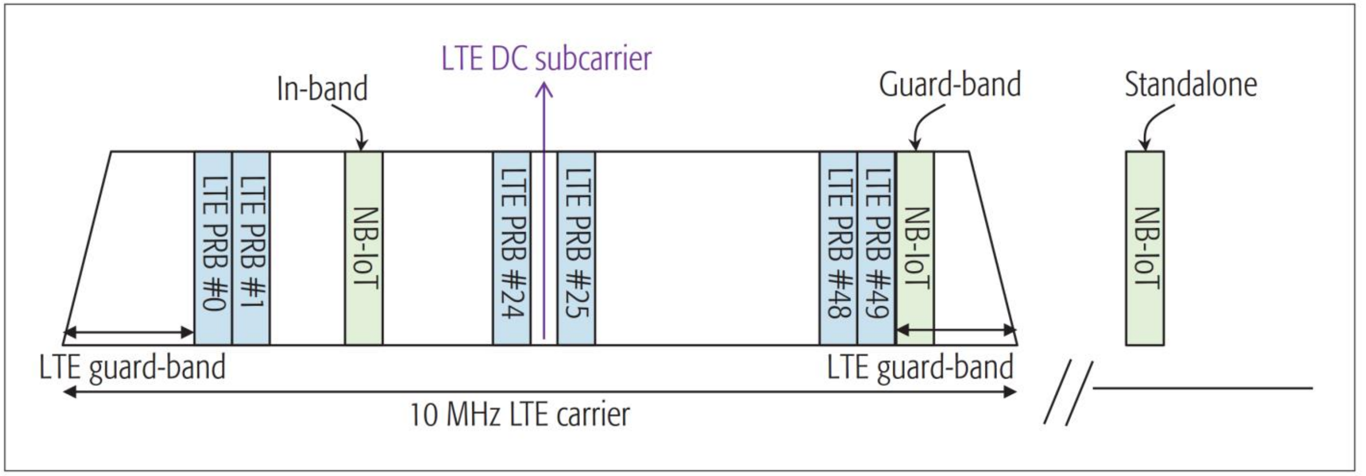


Figure 1. Examples of NB-IoT stand-alone deployment and LTE in-band and guard-band deployments.

https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7876968

NB-IoT Evolution

Release 13	Release 14	Release 15	Release 16	Release 17
*Cat-NB1 *Coverage extension *UL 3.75kHz/ 15kHz UL single-tone/multi-tone *Extended Discontinuous Reception *Power Saving Mode *Multi-carrier	*Cat-NB2 *Enhanced TBS/Dual HARQ *Non-anchor carrier *Release assistance indicator *Re-connection with RLF *Positioning *Channel Quality Indicator report *Measurement report *Maximum Tx power 14 dBm *Single-cell multicast	*Mixed mode multi-carrier *SR report *Wakeup signal *Early Data Transmission *UE differentiation *Reduced system acquisition time *New PRACH format *Small cell support *TDD support	*NR coexistence *Connection to 5G core *Improved multi-carrier operation *UE-group wakeup signal *Mobile-terminated early data transmission *Semi-Persistent Scheduling enhancement *Inter-RAT cell selection *SON	*Increased data rates: DL 16QAM/ 64 QAM or carrier aggregation *Power enhancements *Reduced RRC reestablishment time

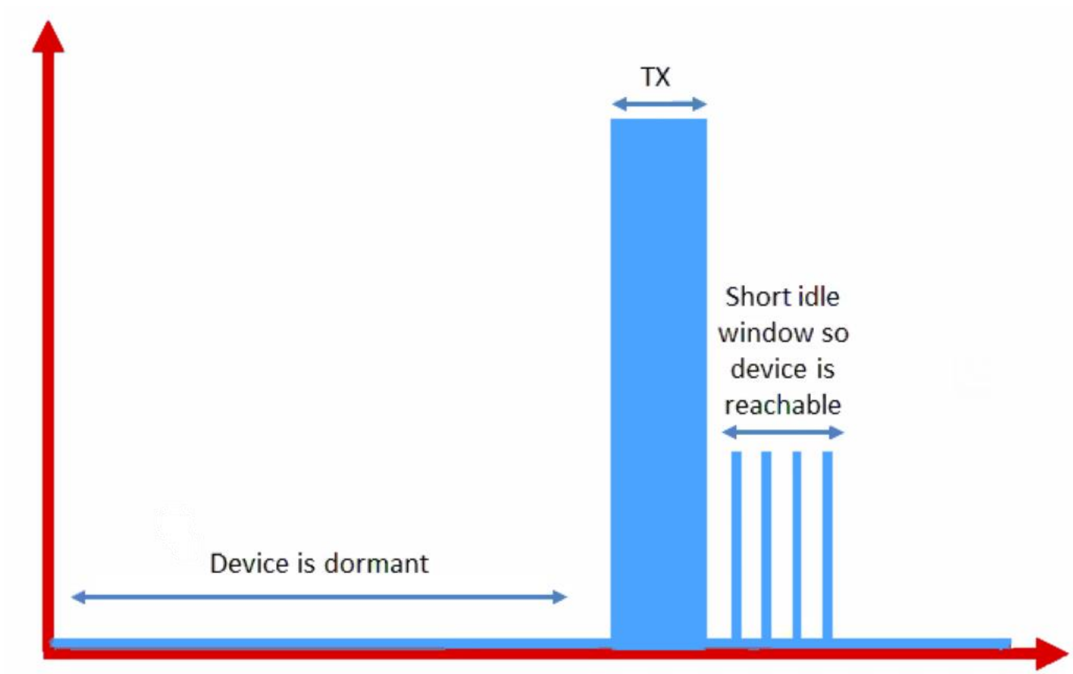
https://www.linkedin.com/pulse/nb-iot-evolution-3gpp-releases-sraas/

Few Power Saving Features

- Power Saving Mode
- Extended Discontinuous Reception

Power Saving Mode

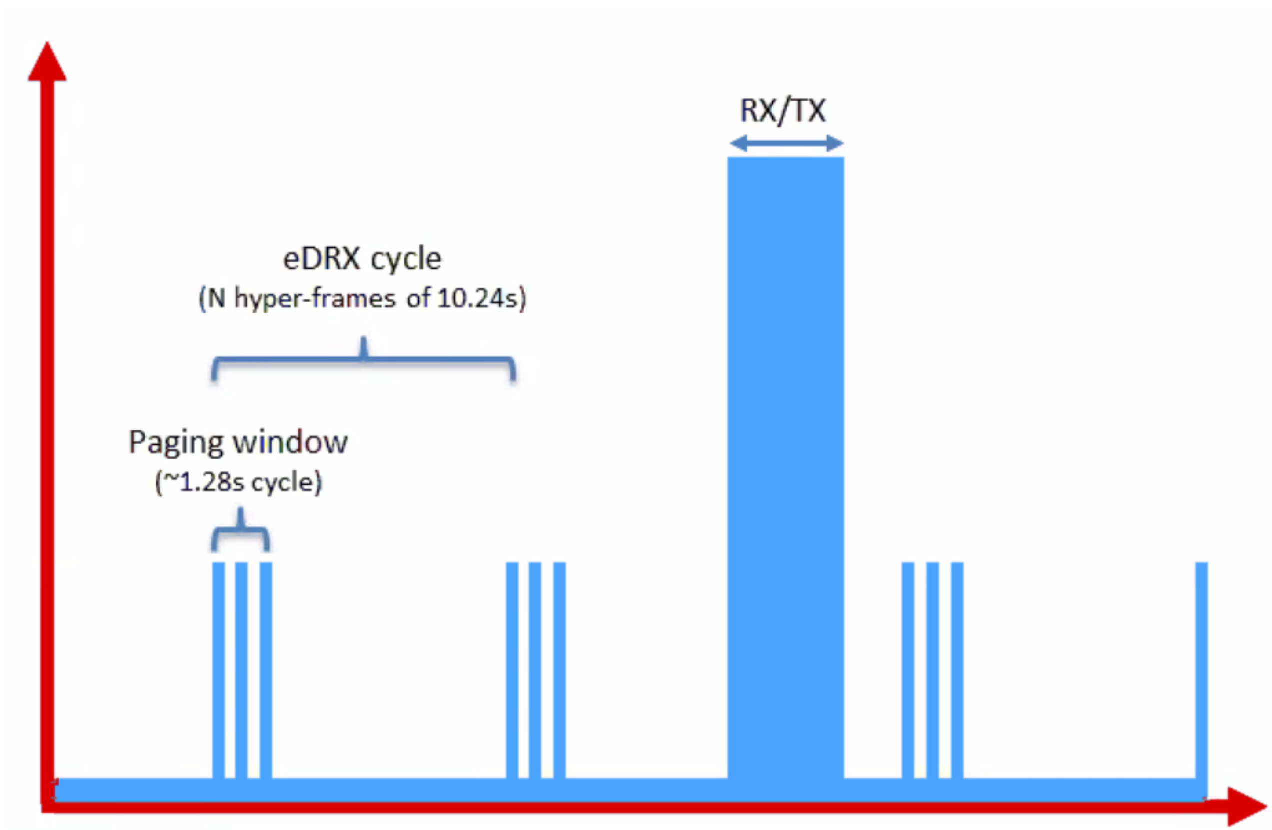
- PSM allows LTE-M devices to go idle without having to re-join the network when they wake up.
- Device that transmits once per day in full PSM mode could last well over 10 years on 2 AA batteries.



https://www.link-labs.com/blog/lte-e-drx-psm-explained-for-lte-m1

Extended Discontinuous Reception (eDRX)

- Node can skip several paging cycles
- For 10 minutes of sleeping cycle (60 hyper-frames), a life of 4.7 years is possible on 2 AA batteries.

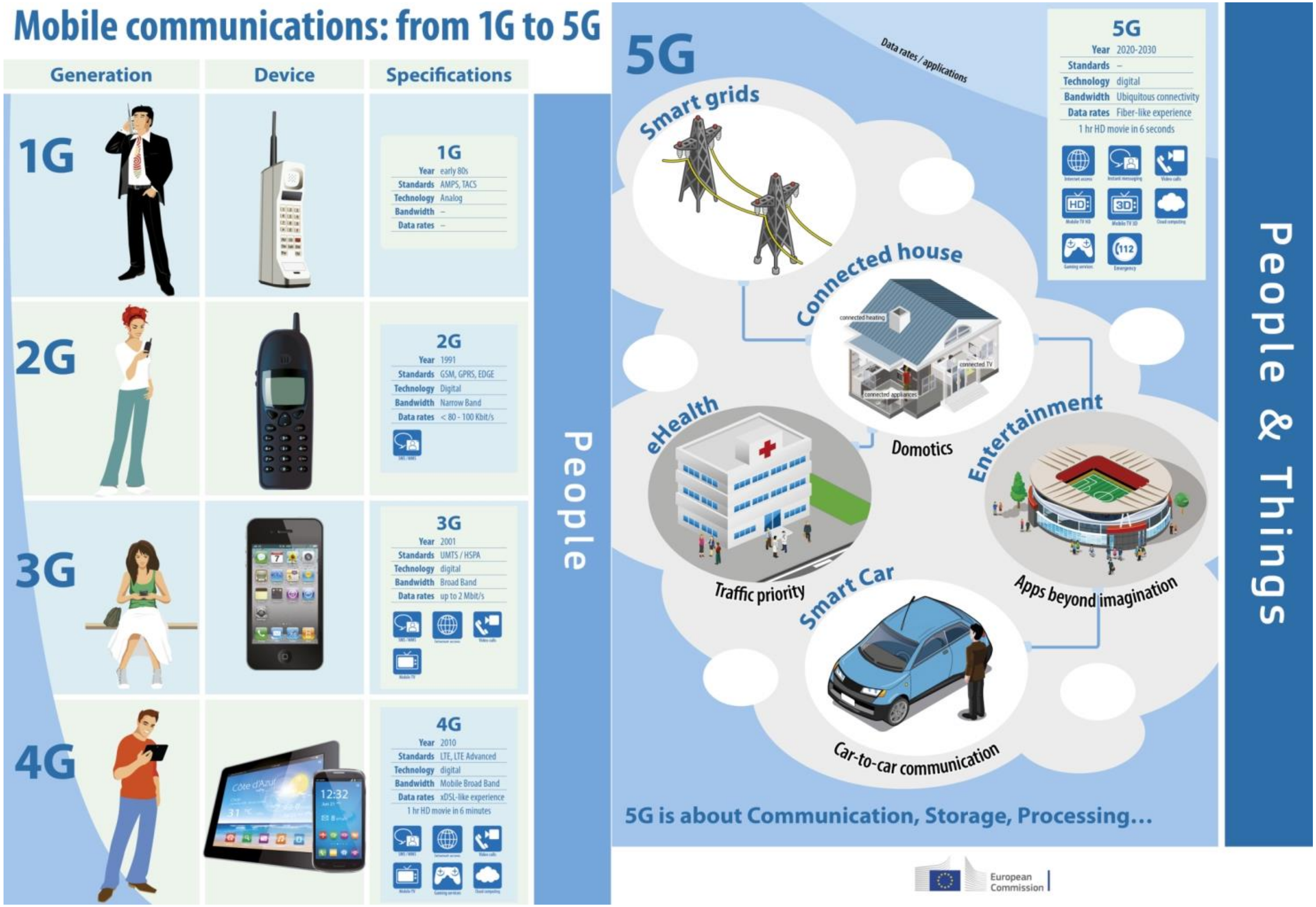


https://www.link-labs.com/blog/lte-e-drx-psm-explained-for-lte-m1

Comparison between PSM and eDRX

Feature	Power Saving Mode (PSM)	Extended DRX (eDRX)
Purpose	Deep sleep to save maximum power	Moderate sleep, still reachable
Network Reachability	Not reachable (radio off)	Reachable during PTW
Typical Duration	Hours → months	Seconds → ~40 min
Wake-up Trigger	Timer expiry (T3412) or device event	Periodic paging window
Power Consumption	Extremely low	Moderate
Use Case	Sensors, meters, loggers	Trackers, alarms, wearables
Defined In	3GPP Rel-13 onward	3GPP Rel-13 onward
Key Timers	T3324 (Active), T3412 (TAU)	eDRX cycle, PTW

1G to 5G



https://www.ng-voice.com/the-evolution-of-wireless-generations/

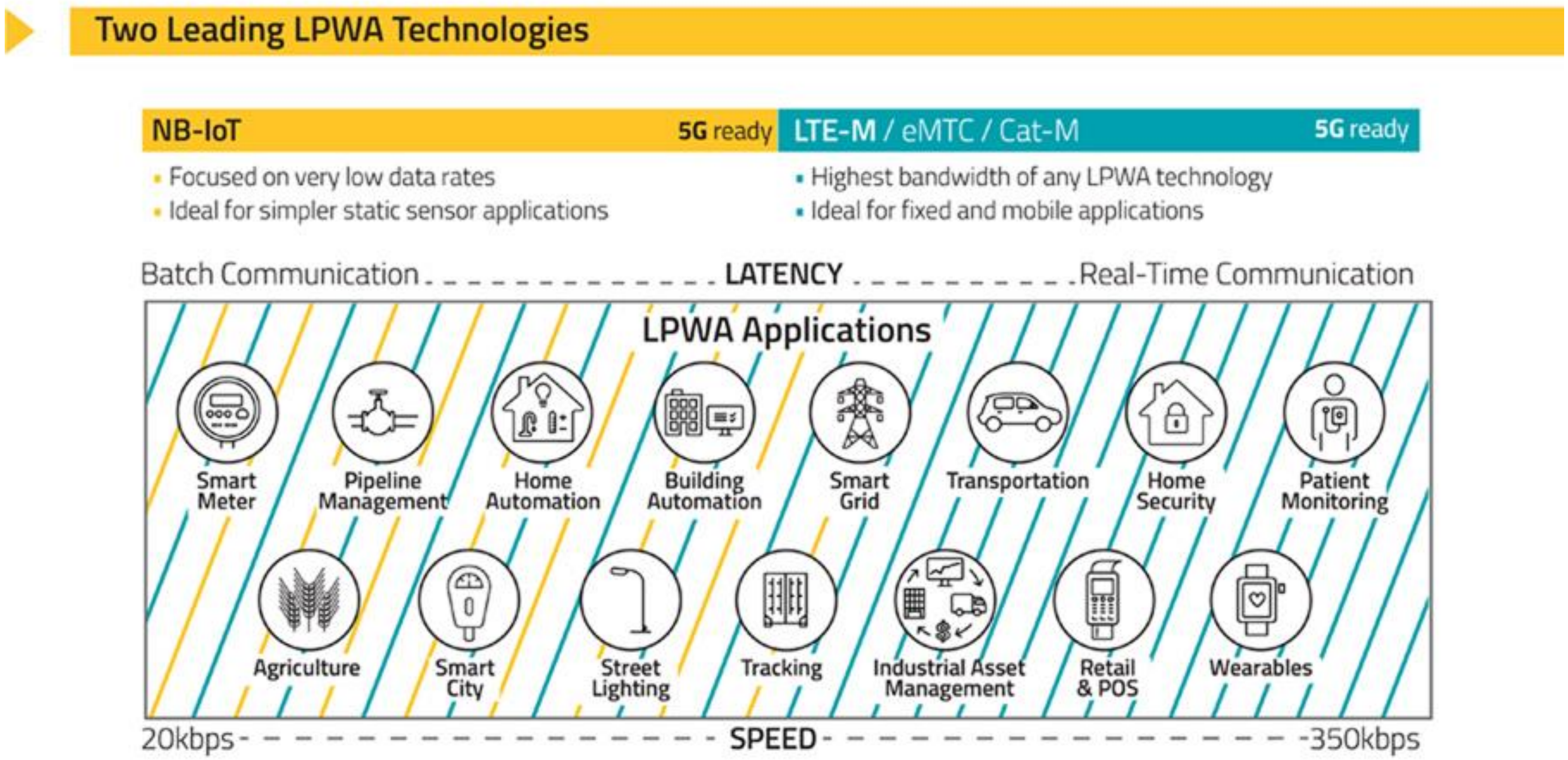
IoT in 5G Era

- ❑ **Mobile IoT/Massive IoT/LPWA:** improved network coverage, long device operational lifetime and a high density of connections. This is also known as mMTC (Massive MTC)
- ❑ **Enhanced Mobile Broadband:** improved performance and a more seamless user experience accessing multimedia content for human-centric
- ❑ **Critical Communications:** high performance, ultra-reliable, low latency industrial IoT and mission critical applications. This is also known as Critical IoT, URLLC (Ultra Reliable Low Latency Communications)

S

LTE-M and NB-IoT=Massive IoT

IoT in 5G era



https://www.iotforall.com/cellular-iot-explained-nb-iot-vs-lte-m/

Key IoT features

Advantages

- Quality of service
  - Licensed band
  - Low latency
- Ubiquitous
- Security: SIM card protection + AES 256 bit (best)
- Great coverage: 2 km (LTE), 10 km (NB-IoT), 35 km (GSM)
- Global mobility and roaming support
- Scalable
- Connected even during power failure

Issues

- Cost: License, Capex and Opex, subscription
- High power
- Not possible to make your own network
  - Now private 5G network is possible

NB-IoT or Cat-M2: *Issues*

- Not backward compatible with other 3G/4G devices
  - New base stations to be deployed
- No mobility support
- Not suitable for low latency applications

Smart Metering Applications

- Cellular: NB-IoT, LTE-M
  - Digikey Link
  - Acrel (4G)
  - Sierra Wireless (NB-IoT and LTE-M)
  - Kigg

WiFi: IEEE 802.11 family

WiFi: What's in a name?

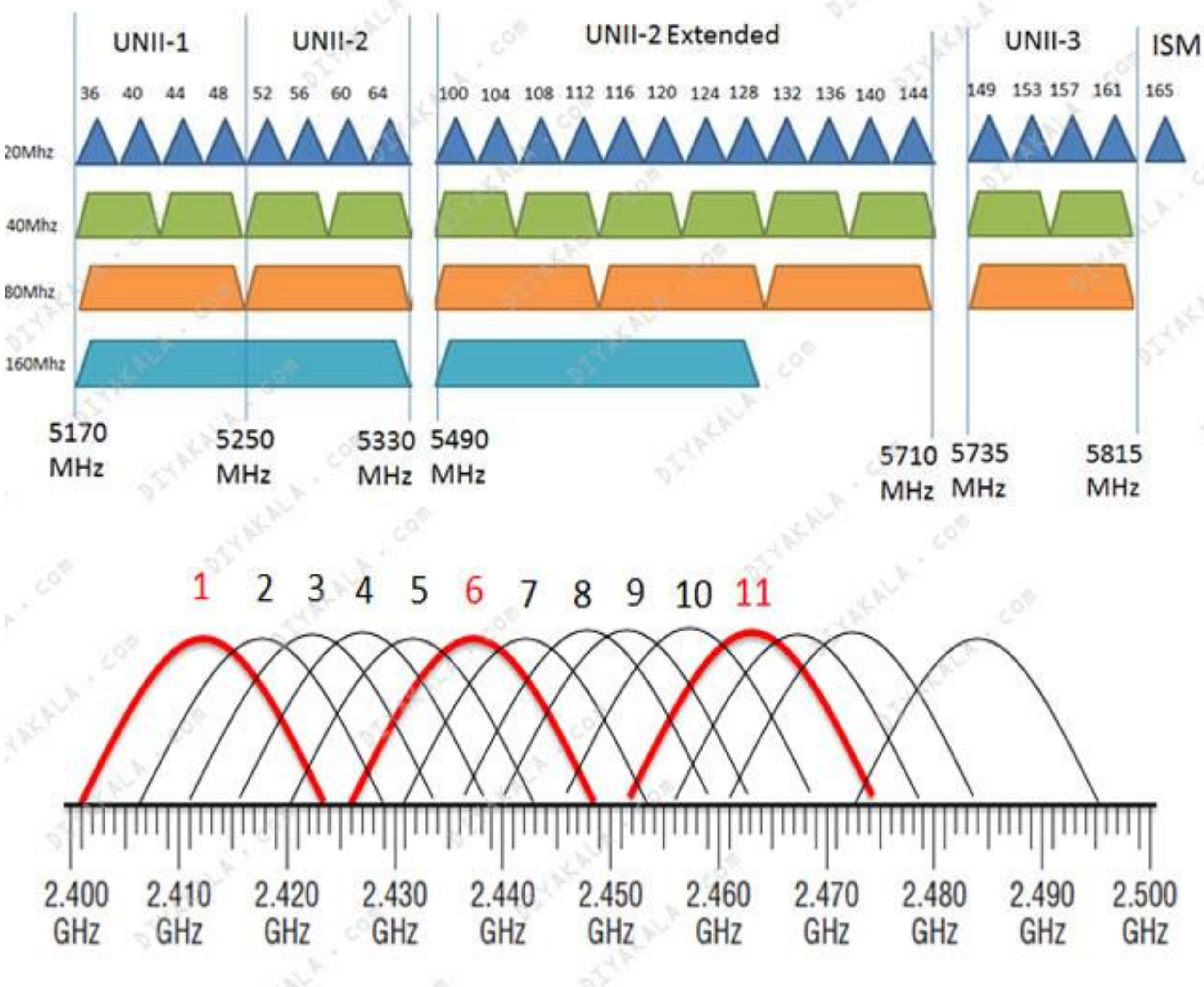
- WiFi is a short name for Wireless Fidelity
- On the lines of *Hi-Fi* (high fidelity), a term for high-quality audio technology
- *Fidelity is defined as the degree of exactness with which something is copied or reproduced.*
- This is also called Wireless Local Area Network (WLAN)

WLAN Standards

	1G	2/3G	4G	5G		6G
	2000	2004	2008	2012	2016	2020
Standard	11b	11a/g	11n	11ac (wave1)	11ac (wave2)	11ax
MCS	Spread Spectrum	OFDM				OFDM (OFDMA)
Freq	2.4GHz	2.4GHz 5GHz				Same Freq (<7GHz)
Bandwidth	20MHz	20MHz	+40MHz	+80MHz	+160MHz	Same BW (+320M)
Multiple Antenna			MIMO Beamforming		MU-MIMO (DL)	MU-MIMO (UL)
PHY Rate	11Mbps	54Mbps	600Mbps (40M,4SS)	1.7Gbps (80M,4SS)	6.7Gbps (160M,8SS)	9.6GHz (160M,8SS)
MAC	CSMA/CA in DCF	Security QoS	Aggregation			BSS Management

https://www.wlanpedia.org/tech/overview/wlan-standard-in-ieee802-11/

WLAN Bandwidths



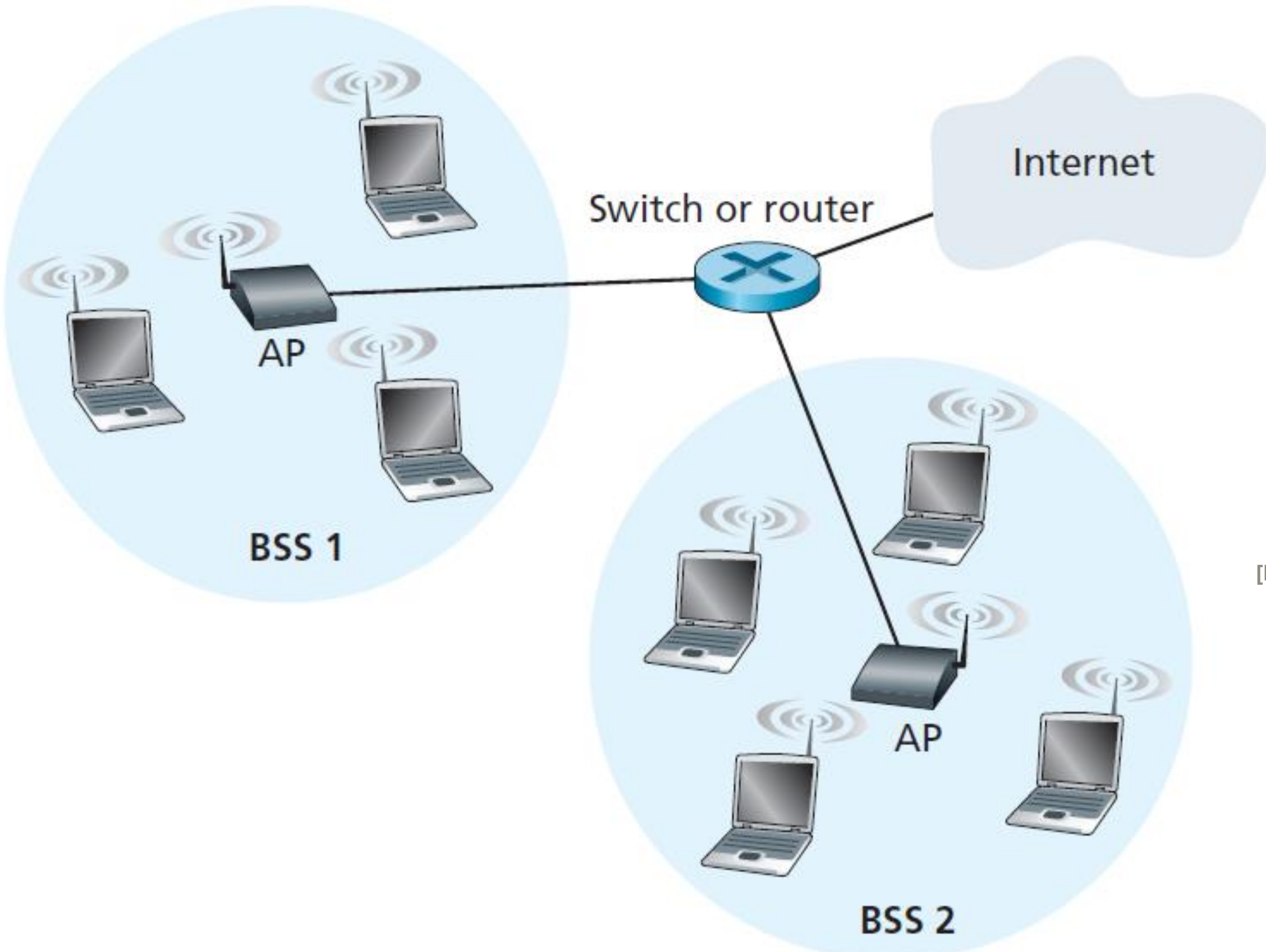
https://commons.wikimedia.org/wiki/File:Frequency-bandwitch-wifi-camera-wireless-camera.jpg

IEEE 802.11 Network Topologies

Nodes as stations and cluster head as access point

- Basic service set (BSS) or Star
- Extended service set (ESS) or cluster tree
- Independent basic service set (IBSS)
  - Ad-hoc = Mesh without access point
- Mesh basic service set (MBSS)
  - (wired or wireless) Mesh of cluster heads (Hybrid)

WLAN architecture: *Infrastructure mode*



[Kurose2012]

WLAN: *Adhoc mode*

- Also called WiFi Direct

MAC Frame Format

Frame (numbers indicate field length in bytes):

2	2	6	6	6	2	6	0-2312	4
Frame control	Duration	Address 1	Address 2	Address 3	Seq control	Address 4	Payload	CRC

Frame control field expanded (numbers indicate field length in bits):

2	2	4	1	1	1	1	1	1	1	1
Protocol version	Type	Subtype	To AP	From AP	More frag	Retry	Power mgt	More data	WEP	Rsvd

- CRC: 32-bit Cyclic Redundancy Check
- WEP: Wired Equivalent Privacy

How IEEE 802.11 adopted for IoT?

802.11ac (5G of WiFi) and 802.11ah (WiFi-Halow)

	802.11ac	802.11ah
Operating Bands	2.4 and 5 GHz	Sub 1-GHz
Spectrum available	100 + 150 MHz	26 MHz
Use Cases	Broadband wireless	Sensors and Meters Extended WiFi
Data Rate Requirement	20 Mbps - 3 Gbps	100 Kbps
Single Frame Size	Large (e.g., 1500 bytes)	Small (e.g., 100 bytes)
Traffic type	Video Streaming/ Large file transfer	Periodic packet transmission every few to tens minutes
Distance between devices	Up to 60 m	Up to 1 Km
Number of stations	3-20	8191
Location	Mostly indoor	Indoor and outdoor
Backward compatibility	Yes	No

[Park2015, Gonzalvez2016]

PHY parameters for 802.11ah

- Use of orthogonal frequency division multiplexing (OFDM)
- Basically adapted a scaled-down version of 802.11ac
  - Bandwidths of 20-160 MHz to 2-16 MHz
  - Same number of subcarrier
  - Increased symbol duration

[Park2015]

Parameters	Supported Values
Channel Bandwidthds	2, 4, 8, and 16 MHz
Modulation Schemes	BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM
Code Rates	1/2 with 2 times repetition 1/2 , 2/3, 3/4 and 5/6 Convolution or low-density parity check (LDPC)
MIMO	Support up to 4 by 4
Data Rates	150 Kbps (1 MHz bandwidth, 1 spatial stream, BPSK, ½ coding rate, repetition) to 347 Mbps (16 MHz bandwidth, 4 spatial streams, 256 QAM, 5/6 coding rate)

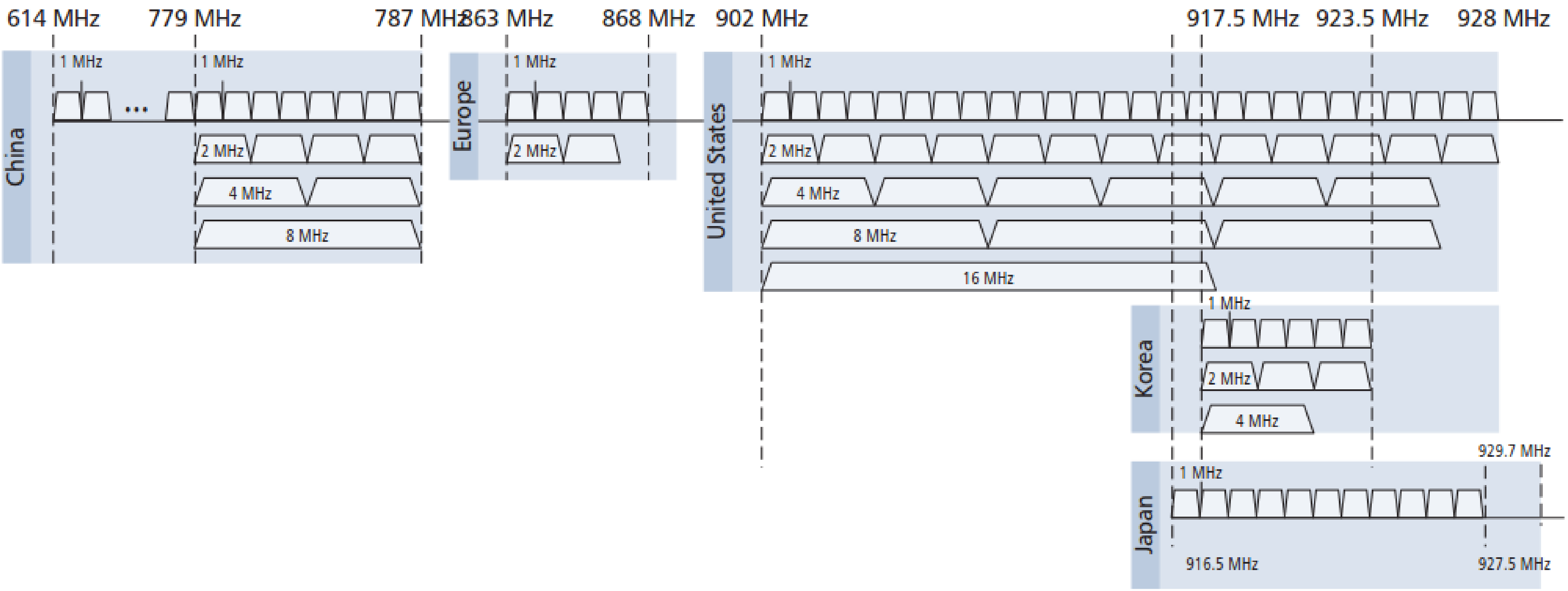
Link Budget Comparison

Parameters	Link budget enhancements of 900 MHz 802.11ah over 2.4 GHz 802.11n
Free space path loss	+8.5 dB
Noise bandwidth	+10 dB
Sub-total link budget gain	+18.5 dB
1 MHz channel width	+3 dB
Repetition coding	+3 dB
Total link budget gain	+24.5 dB

[Park2015]

Low Power and Low Cost Support for Indoor Sensors:
This can reduce the transmit energy consumption and also lower the cost of an 802.11ah radio of a small sensor device.

Frequency Bands in Different Countries



[Park2015]

802.11ah MAC features

- Hierarchical association identifier
- Access scheme: Hybrid Coordination Function (HCF)
- Optional Restricted Access Window (RAW)
- Increased sleep time
- Target wake-up time
- Bidirectional transmission opportunity
- Short MAC frame
- Null data packet for ACK
- Synchronization frame operation
- And few more!

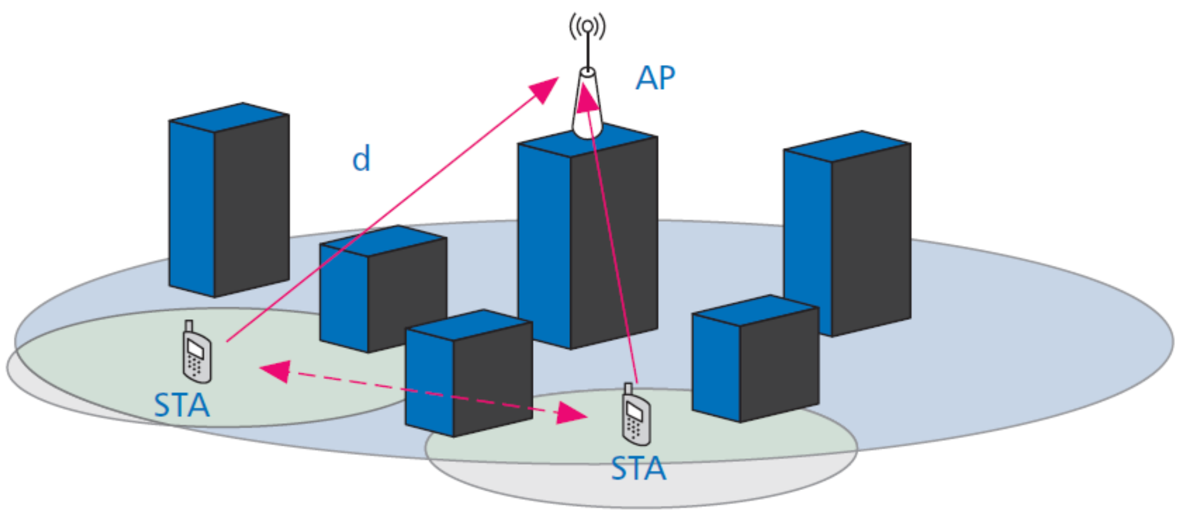
Hybrid Coordination Function (HCF)

- 802.11
  - CSMA/CA
- 802.11ah
  - HCF controlled channel access
    - Polling based for infrastructure based networks
    - Guarantees Quality of Service
  - Enhanced distributed channel access (EDCA)
    - EDCA is extension of CSMA/CA that tries to implement service differentiation by classifying the traffic into different categories with different priorities

[Gonzalez2016]

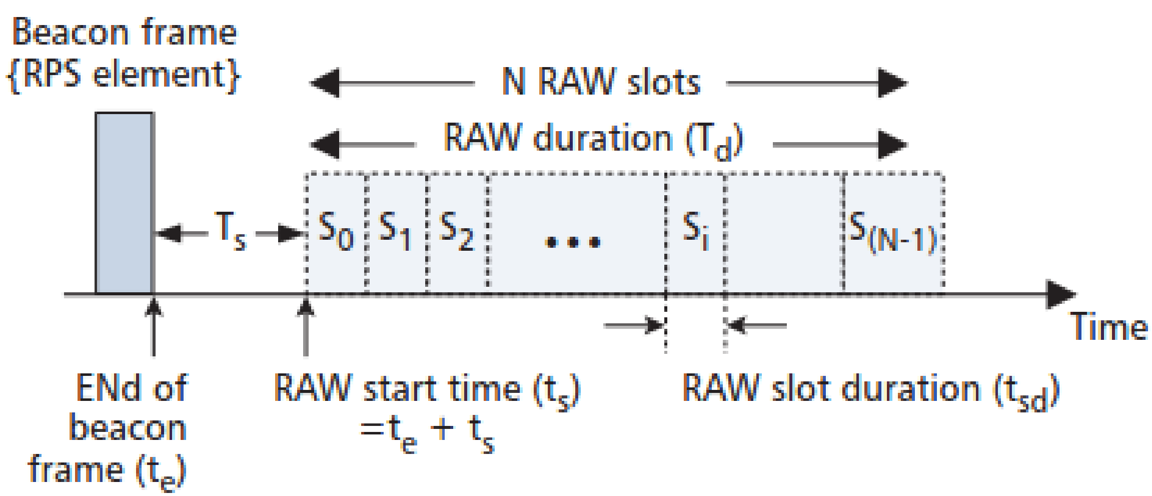
Restricted Access Window (RAW)

- ❑ Issue with supporting 1 Km range outdoors
  - ➢ Access point for outdoor applications are installed on top while users are near grounds
    - High path loss and Shadowing
  - ➢ Severe hidden node problem between several APs supporting thousands of nodes
    - Several collisions and subsequent retransmissions cause energy consumption
- ❑ RAW minimizes the issue



Restricted Access Window (RAW)

- ❑ Station or node grouping mechanism
- ❑ New optional contention channel access scheme
  - ➢ Combination of TDMA and CSMA/CA
- ❑ In the time window frame is divided into RAW slots
  - ➢ maximum of 64 slots
- ❑ Nodes are divided into groups and only members of a particular group have access to that time slot
- ❑ Reduces collisions, improve channel efficiency, and allows an increasing number of users



Increased Sleep Time

- In 802.11, the max sleep time is 18 hours without getting disassociated with the AP
- For 802.11ah, the max sleep time is redefined such that the station can sleep for approximately 5.2 years

Target Wakeup Time (TWT)

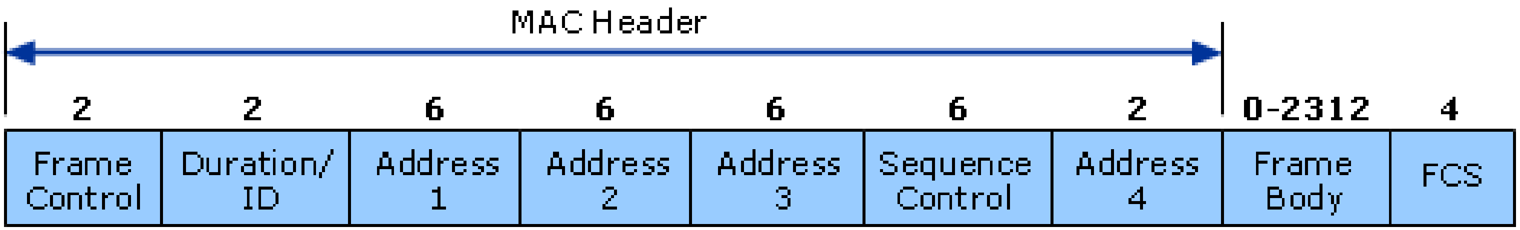
- 802.11
  - An AP buffers data destined for a station while the station is in sleep state
  - The station periodically wakes up at beacon transmission times and receives a beacon to see if there is any buffered data at the AP based on the information in traffic indication map (TIM)
  - If TIM indicates that there is data buffered at AP, it sends a PS-Poll frame to the AP to indicate the station is awake and is ready to receive the buffered data
  - The AP needs time to find the buffered data and has to contend for the medium: this indefinite latency makes the station consume energy waiting for the buffered data
- 802.11ah
  - Uses target wake-up time between an AP and a station so that the AP knows when the station will be awake
  - Removes the processing time and medium access latency

Bidirectional Transmission Opportunity

- Bidirectional transmission (BDT) allows an AP and a station to exchange one or more uplink and downlink packets in one TXOP.
- Packets are separated by short inter frame space (SIFS)
- In the BDT procedure, a station uses the More Data bit in the SIGNAL field of PHY preamble of a packet to indicate whether the station has more data to transmit following the current packet transmission.
- This reduces the number of contention-based channel accesses, improves channel efficiency by minimizing the number of frame exchanges required for uplink and downlink data frames, and enables stations to extend battery lifetime by keeping Awake-times short.

Short MAC Frame

- In 802.11n, the MAC header can be 30 bytes long



https://technet.microsoft.com/en-us/library/cc757419(v=ws.10).aspx

- For IoT application transmitting only 50 bytes of data infrequently, this is big overhead
- In 802.11ah, the length of header is reduced to 12 bytes

802.11ax (6G of WiFi)

- Convergence of high data rates and IoT applications
- Smarter access points for improved outdoor coverage with longer guard intervals
- Target Wake-up Time
- BSS coloring to reduce interference
- Only on 5 GHz
- Comparison with 802.11ac
  - 6 times speed, 7 times battery life with TWT, 4 times range
  - Support much more than 7 devices
- OFDMA instead of OFDM
- MU-MIMO
- 1024 QAM and 160 MHz bandwidth to give multi-giga bit data rates

Key IoT Features (802.11ah)

- ❑ High data rates
  - ➢ Can handle diverse range of applications including camera
- ❑ Longer range than traditional WiFi
- ❑ Scalable to thousands of nodes
- ❑ Widely used

Issues

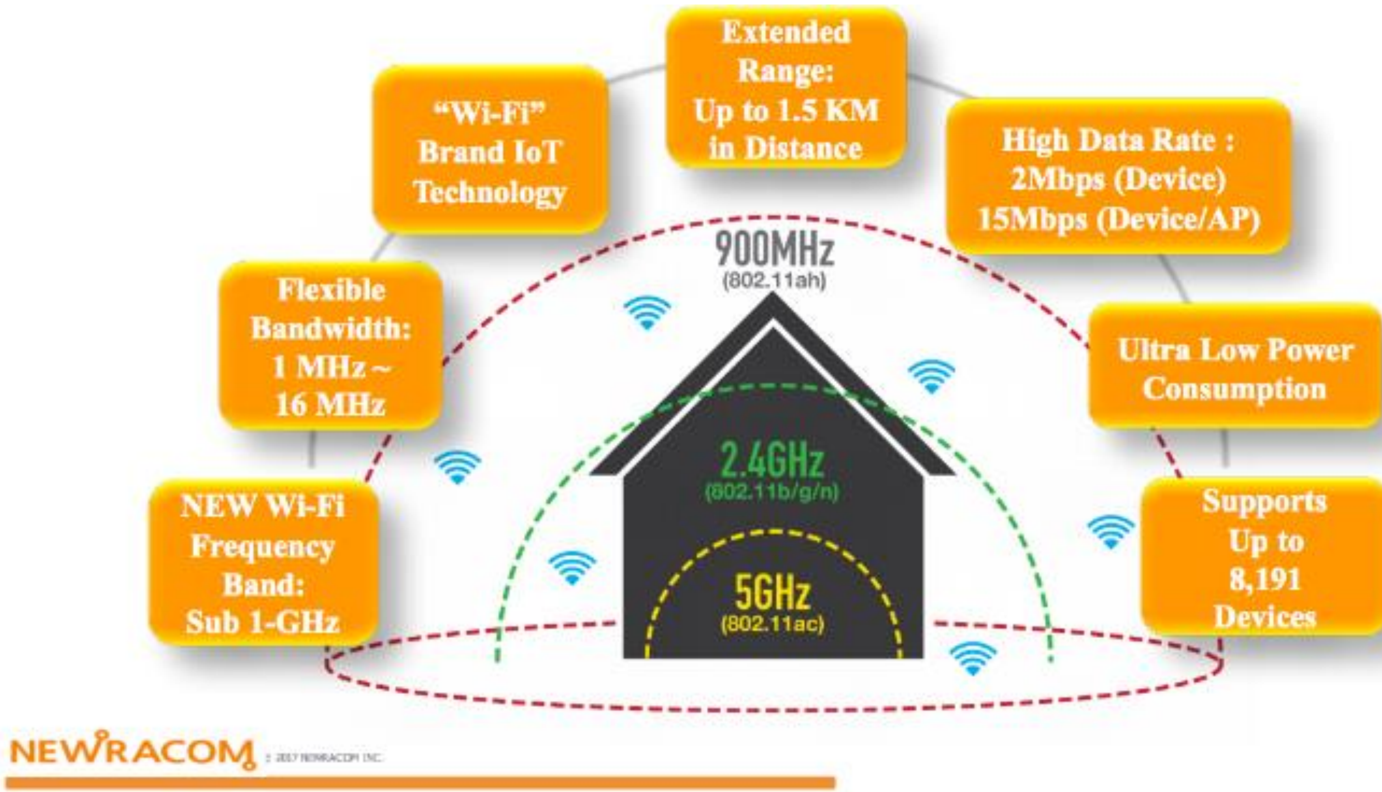
- ❑ Most of the world is using 2.4 GHz
  - ➢ Problem for 802.11ah
- ❑ 802.11ah available, but products are hardly there
  - ➢ Mostly using 802.11b/g/n
- ❑ Security
- ❑ High power consumption
- ❑ Roaming

WiFi Halow products

- Adapt-IP
- Alfa wireless
- Methods2Business
- Newratek / Newracom
- Palma Ceia SemiDesign
- Huge-IC
- Silex Technology's SX-NEWAH

Links embedded

Example of SX-NEWAH



https://www.silextechnology.com/connectivity-solutions/embedded-wireless/sx-newah

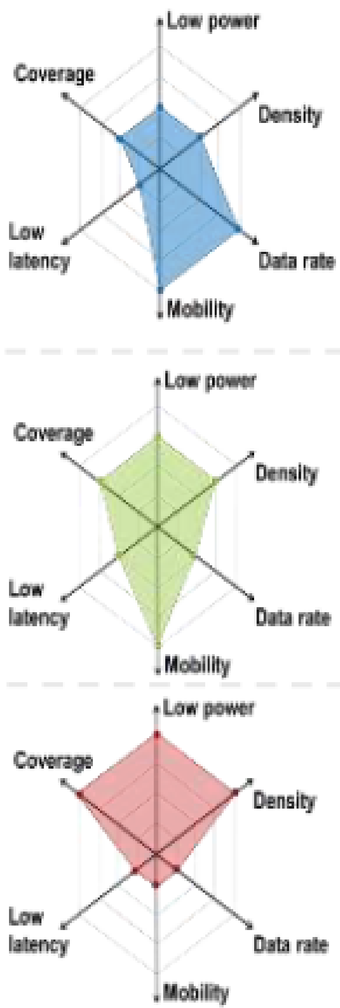
Questions?

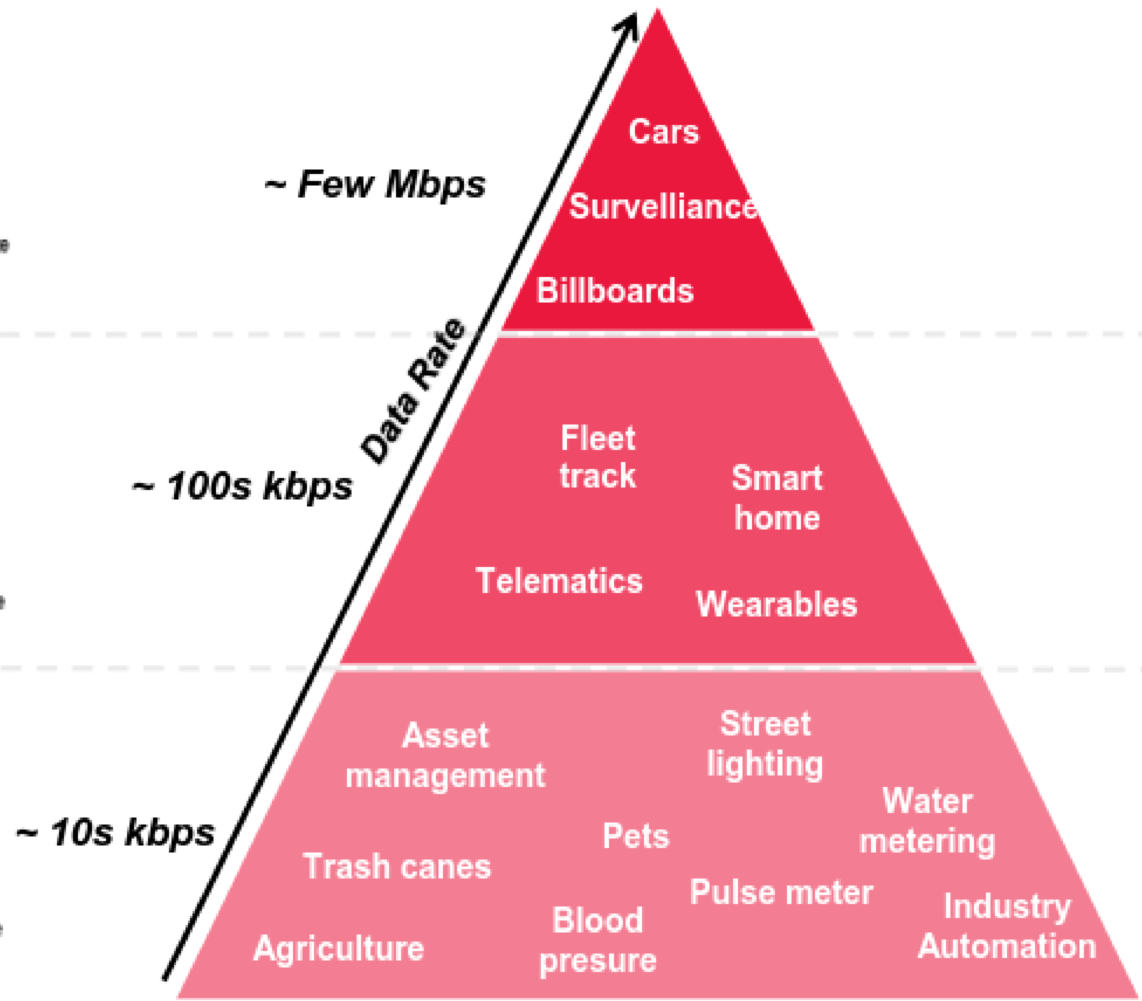
	IEEE 802.11ah	NB-IoT	LoRaWAN
Bands	900 MHz (ISM)	Between 400-2200 MHz (Licensed Frequency)	868/915/433 MHz (ISM)
Topology	Star, Mesh, Cluster-Tree	Star	Star of Stars
Max. Range	1 Km	10 Km in one cell	10 Km in one cell
Max.Power	100 mW	200 mW	25 mW
DIY	Yes	No	Yes
Max. No. of Nodes per cell	8192	100K	50 K
Modulation	OFDM	QPSK	CSS
Channel Access	CSMA/CA + GTS + RAW	HD-FDD TDMA+FDMA	Aloha
Data rates	150 Kbps- 347 Mbps	20-250 Kbps	0.3-50 kbps
Power Saving	Sub-1GHz TWT, Sleep-Wake, BDTO, Short MAC	PSM, low bandwidth, low duty cycle, eDRX	Target Application

Summary: One size does not fit all!

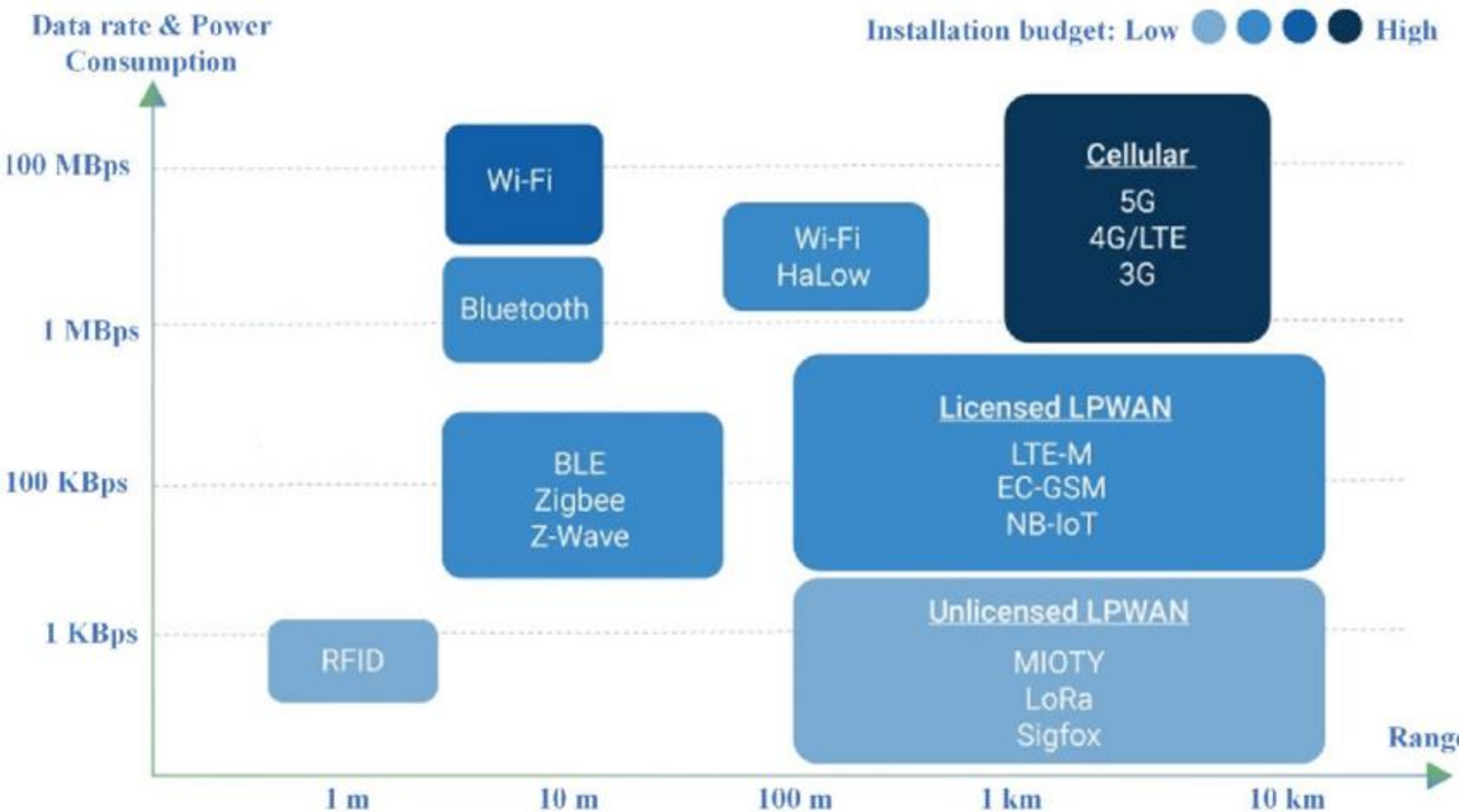
Requirement

Devices per





Competing and Complementing



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

IoT market is diverse and big to accommodate several technologies!

Comparison

- Current trends
  - Indoor: WiFi
  - Outdoor: Cellular, LoRaWAN, WiFi (Halow)
- On-mobile advantage
  - Cellular, WiFi
- Lead advantage
  - WiFi and LoRaWAN
- Ecosystem advantage
  - Cellular
    - Convergence of applications

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