실시간 통신과 IoT

(CC533)

경기대학교 컴퓨터과학과

(Department of Computer Science)

Wireless Communication

CONTENTS

OUTLINE

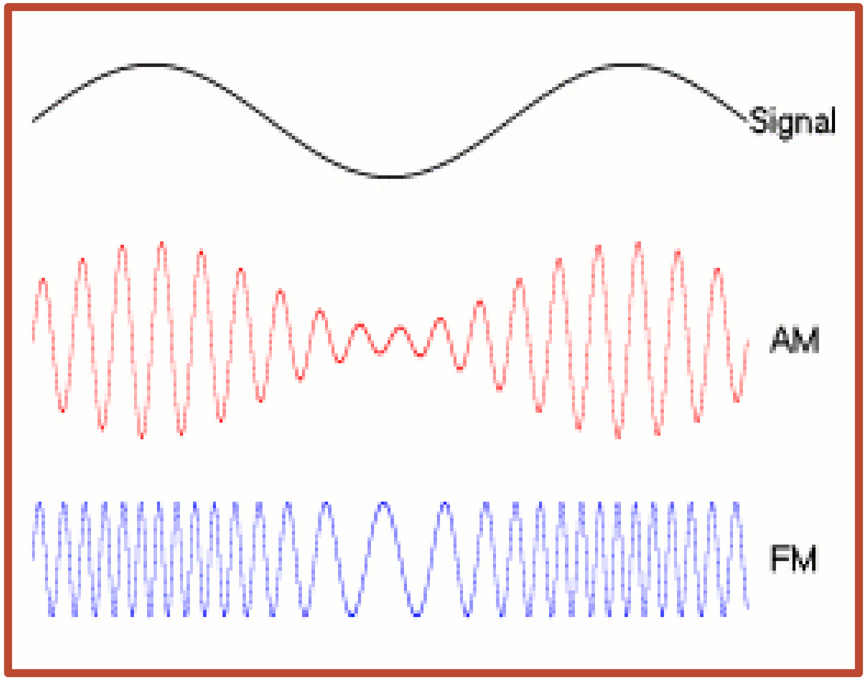
- **What are radios**
  - How do they work?
- **Fundamental characteristics**
  - Design tradeoffs
- **Common radio standards/protocols for indoor applications**
  - Where characteristics fall under (above)
- **Emerging radio standards/protocols for outdoor Internet-of-Things applications**
  - Why the design requirement of IoT radios is different

WHAT ARE RADIOS?

- **A device that enables wireless transmission**
  - Electromagnetic wave
  - Transmitter encodes signal and receiver decodes it

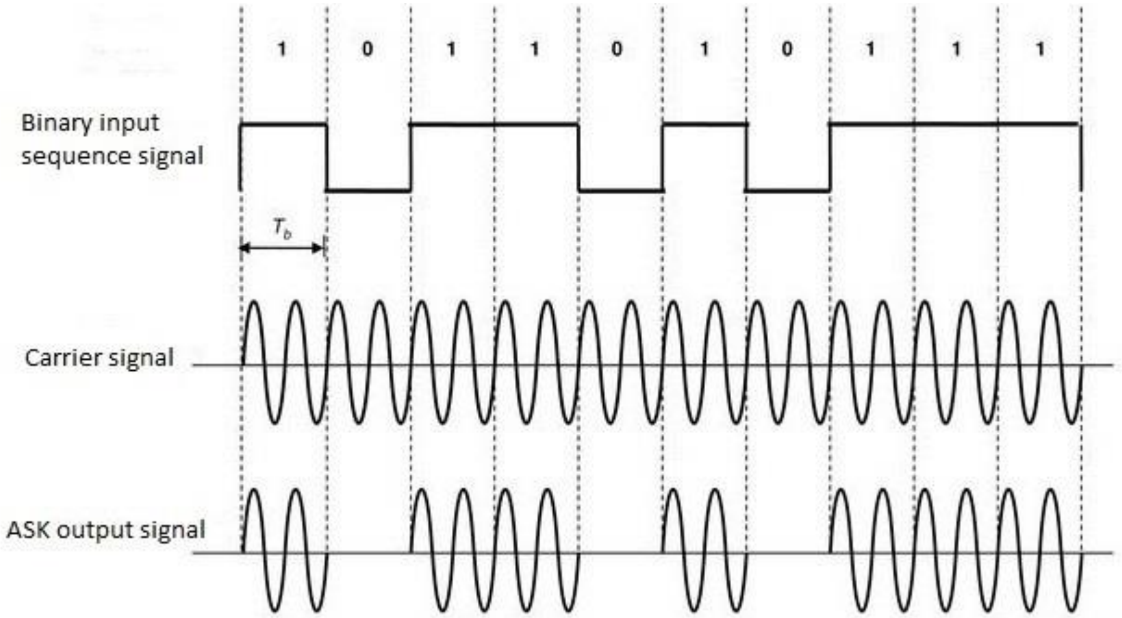
HOW RADIOS WORK - TRANSMITTING

- **Modulation**
  - Converts digital bits to an analog signal
  - Encodes bits as changes in a carrier frequency:
    - Frequency, Amplitude, Phase, ...

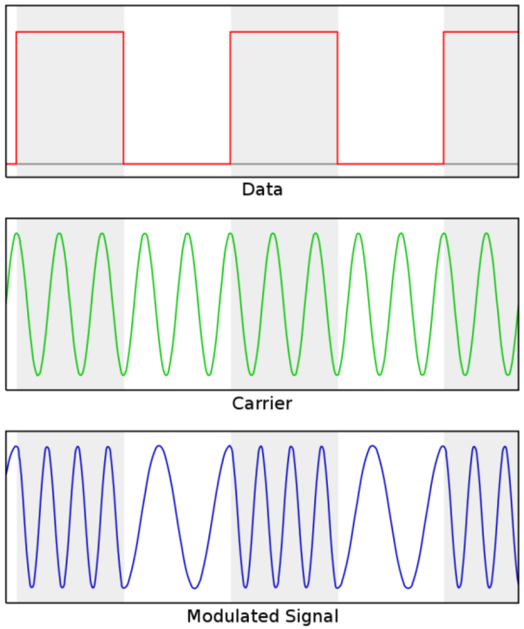


HOW RADIOS WORK - TRANSMITTING

- Example of modulating digital data onto an analog signal



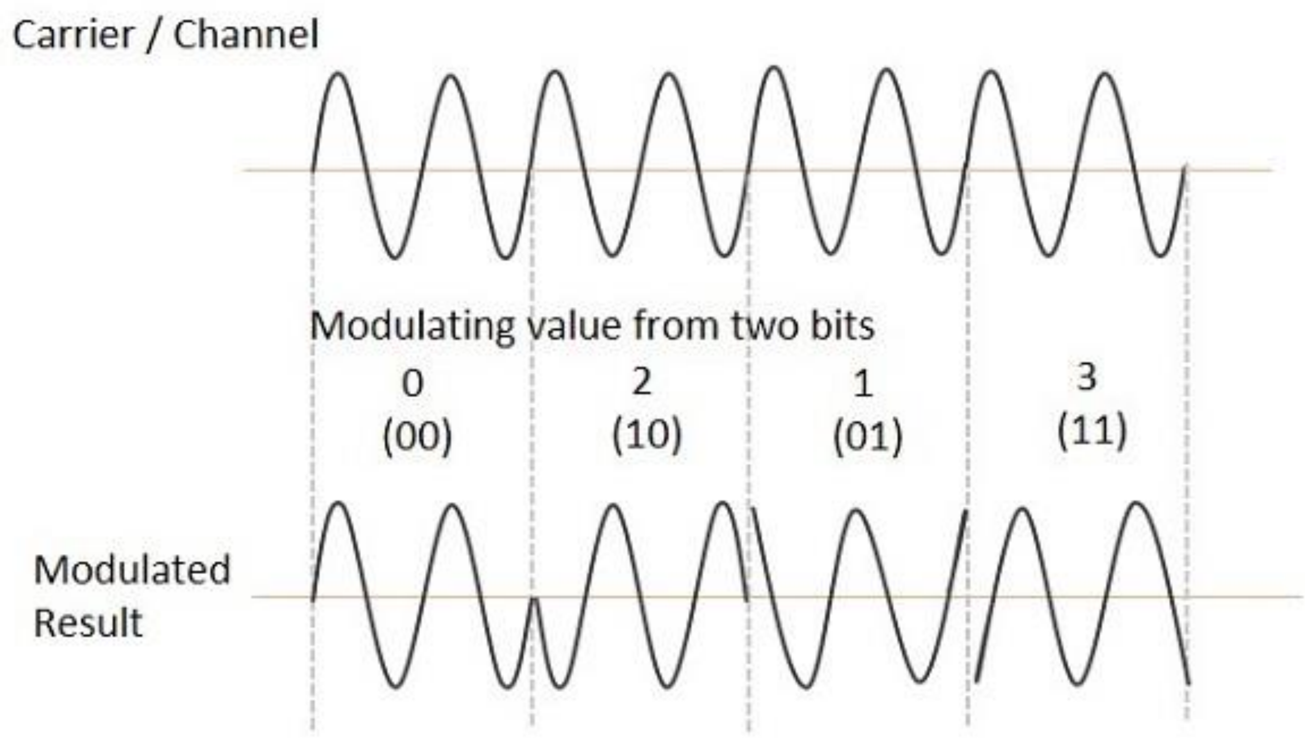
ASK (Amplitude Shift Keying)



FSK (Frequency Shift Keying)

HOW RADIOS WORK - TRANSMITTING

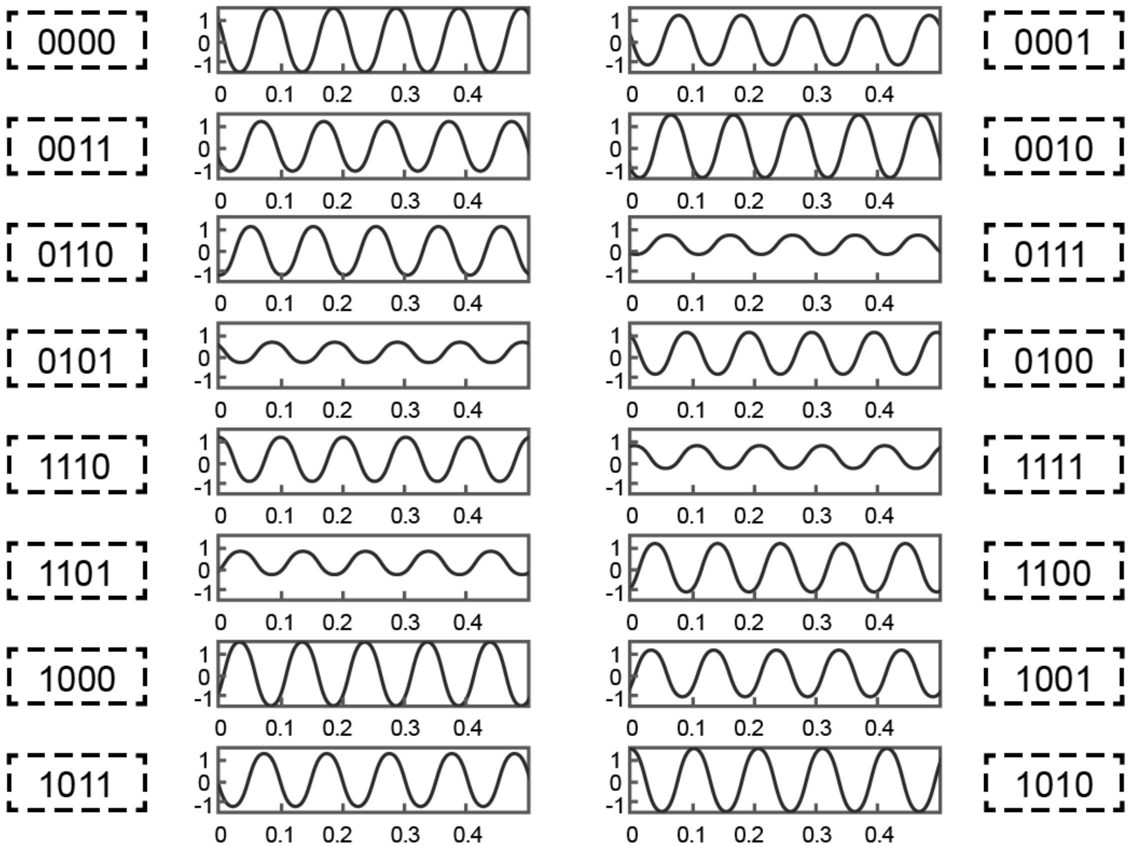
- Example of modulating digital data onto an analog signal



QPSK (Quadrature Phase Shift Keying)

HOW RADIOS WORK - TRANSMITTING

- Example of modulating digital data onto an analog signal



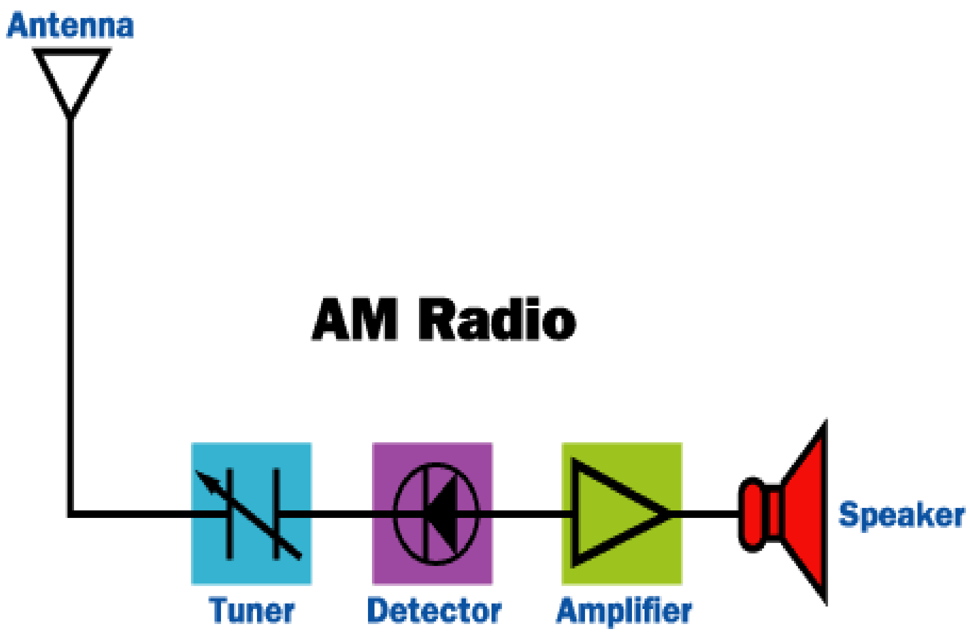
QAM (Quadrature Amplitude Modulation)

HOW RADIOS WORK - RECEIVING

- **Receiving**
  - Simplest is envelope detection
    - Detect changes in carrier freq.
    - Complex require synchronization
  - All require filtering
  - Signals must be demodulated

HOW RADIOS WORK - RECEIVING

- **Example of receiving AM radio**
  - Antenna picks up modulated radio waves
  - Tuner filters out specific frequency ranges
  - Amplitude variations detected with demodulation
  - Amplifier strengthens the clipped signal and sends it through the speaker



RADIO CHARACTERISTICS

Why so many protocols
for indoor and outdoor applications?

- **All radios have to make tradeoffs**
  - Short vs. long distance
  - High vs. low power/energy
  - High vs. low speeds
  - Large vs. small number of devices
  - Device-to-device, device-to-infrastructure
  - Indoor vs. outdoor usages

- **Channel capacity in wireless communications**
  - Shannon–Hartley theorem
    - Additive white Gaussian noise (AWGN) channel

received signal-to-noise ratio

Received power (W)

$$C_{\mathrm{AWGN}} = W \log_2 \left(1 + \boxed{\frac{\bar{P}}{N_0 W}} \right) \text{ [bits/s]}$$

AWGN channel capacity (bits/s)

Bandwidth (Hz)

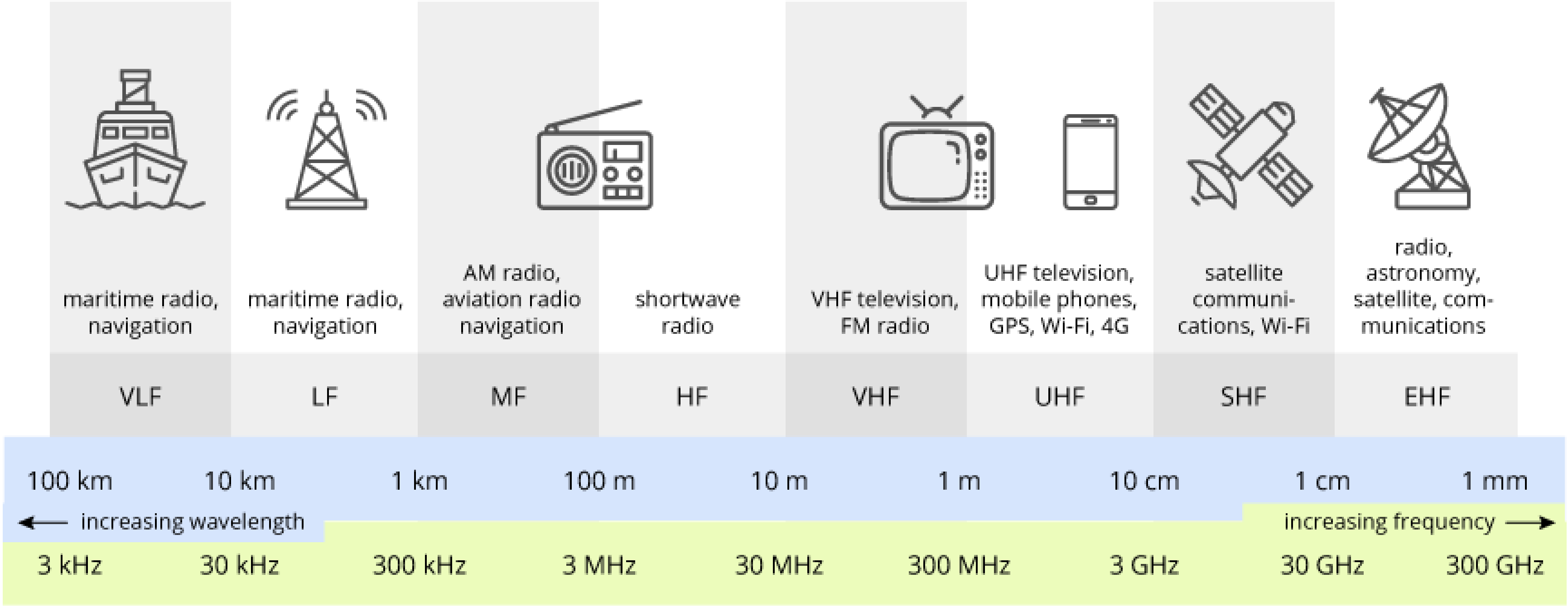
Bandwidth (Hz)

Noise power spectral density (W/Hz)

  - Capacity depends on
    - Bandwidth of the channel, received power, noise

RADIO CHARACTERISTICS

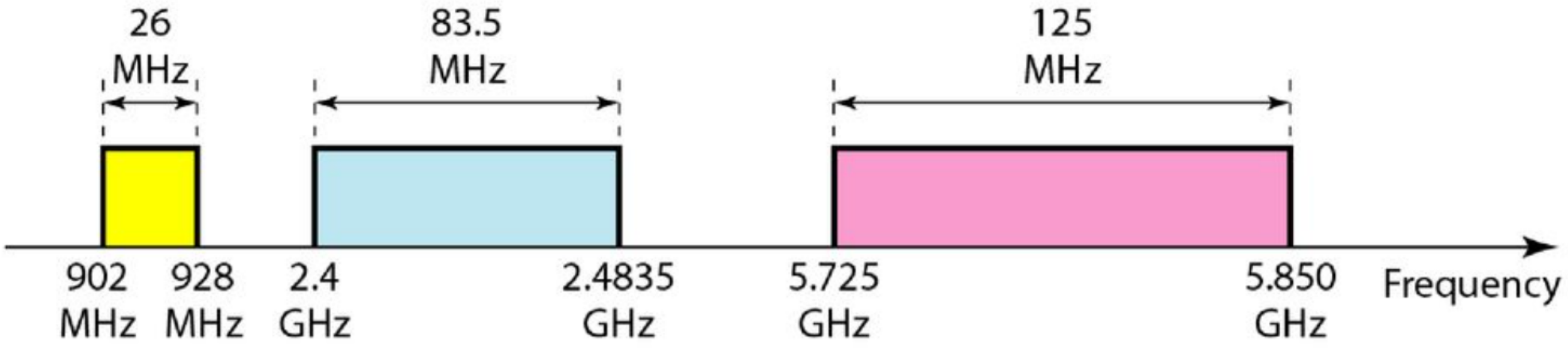
Radio Frequency Bands



https://terasense.com/terahertz-technology/radio-frequency-bands/

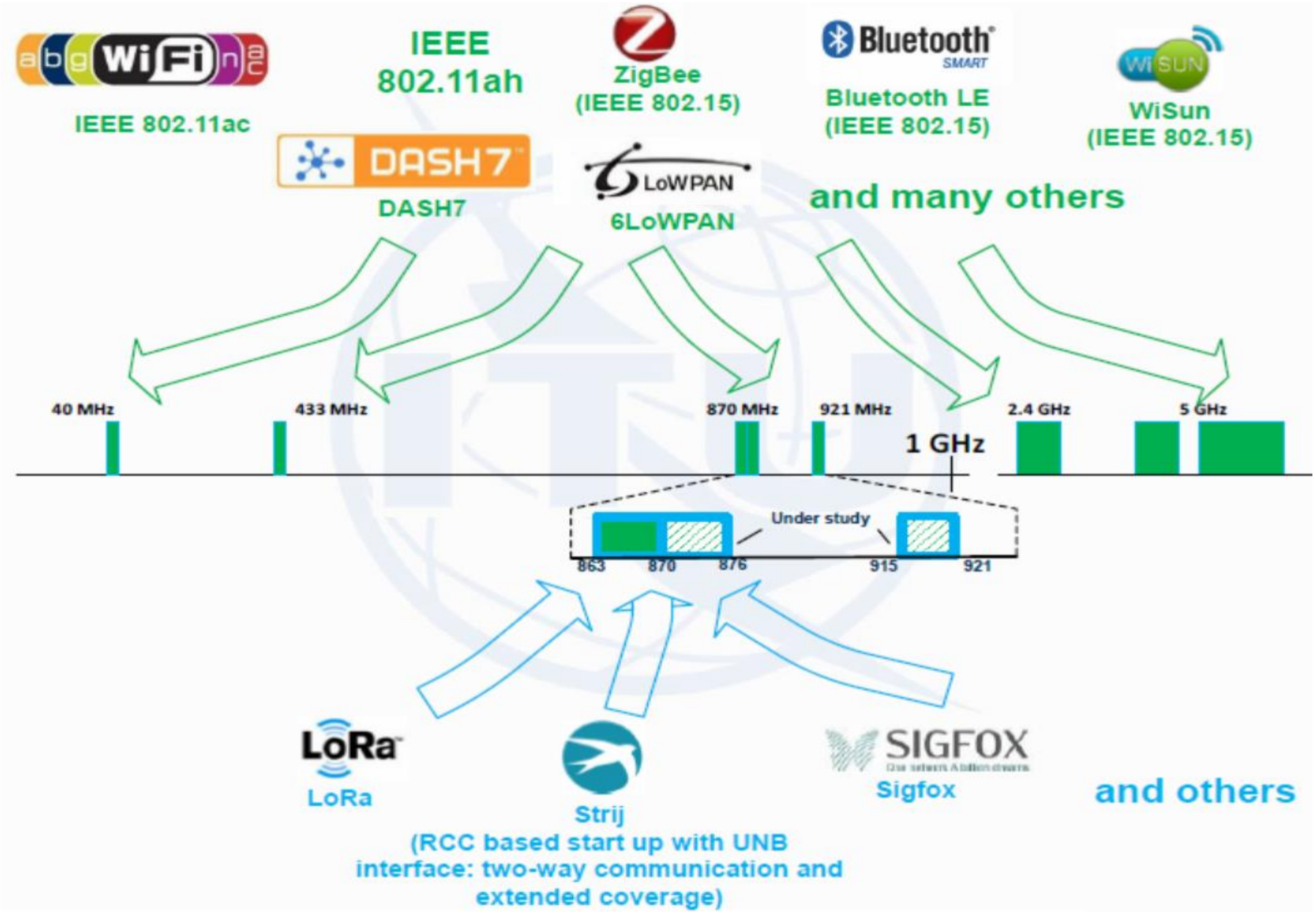
RADIO CHARACTERISTICS

- **ISM bands**
  - Radio spectrum reserved internationally for industrial, scientific and medical (ISM) purposes
  - Unlicensed frequency bands



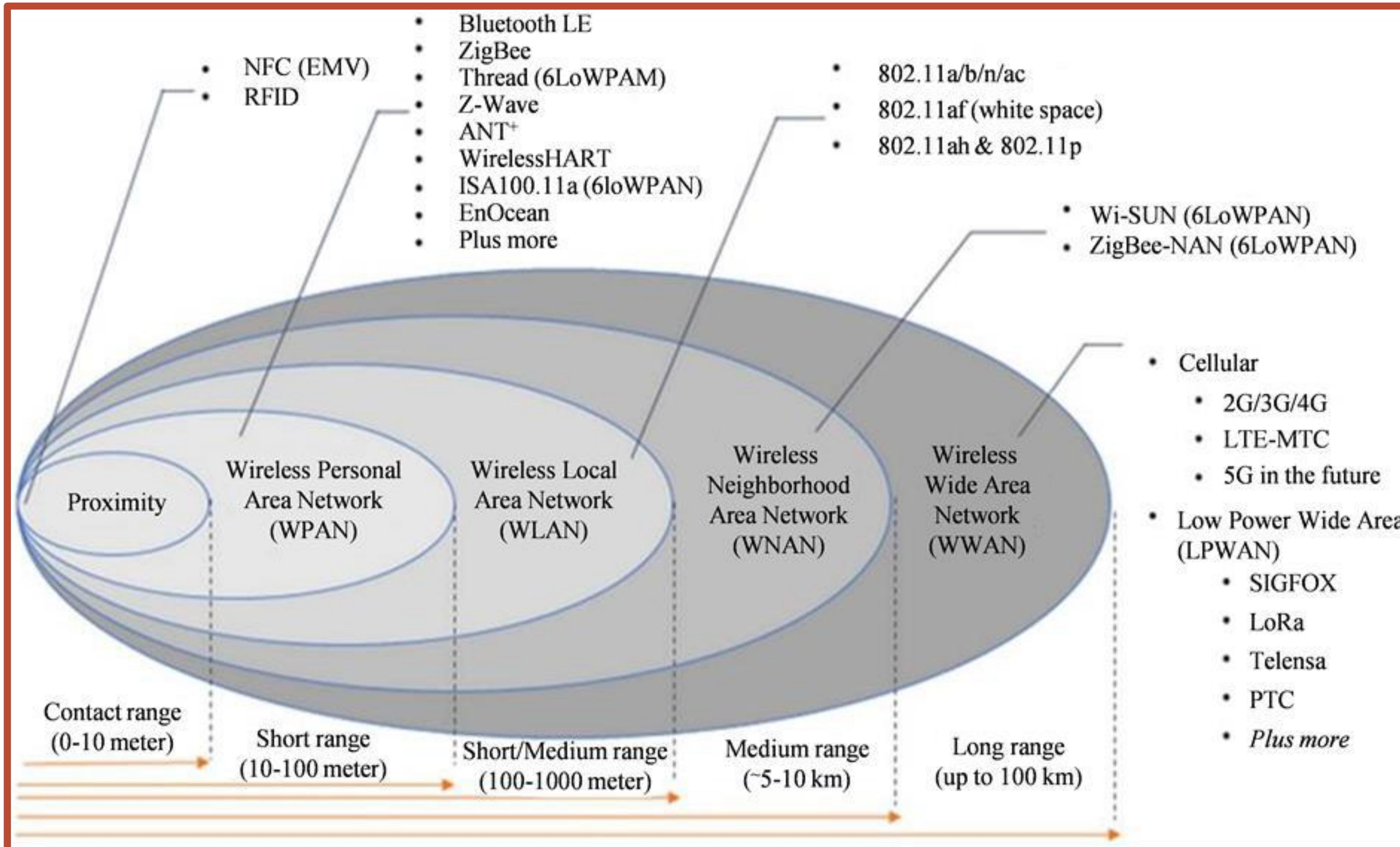
IoT NETWORK CONNECTIVITY

- **Spectrum usage for IoT**



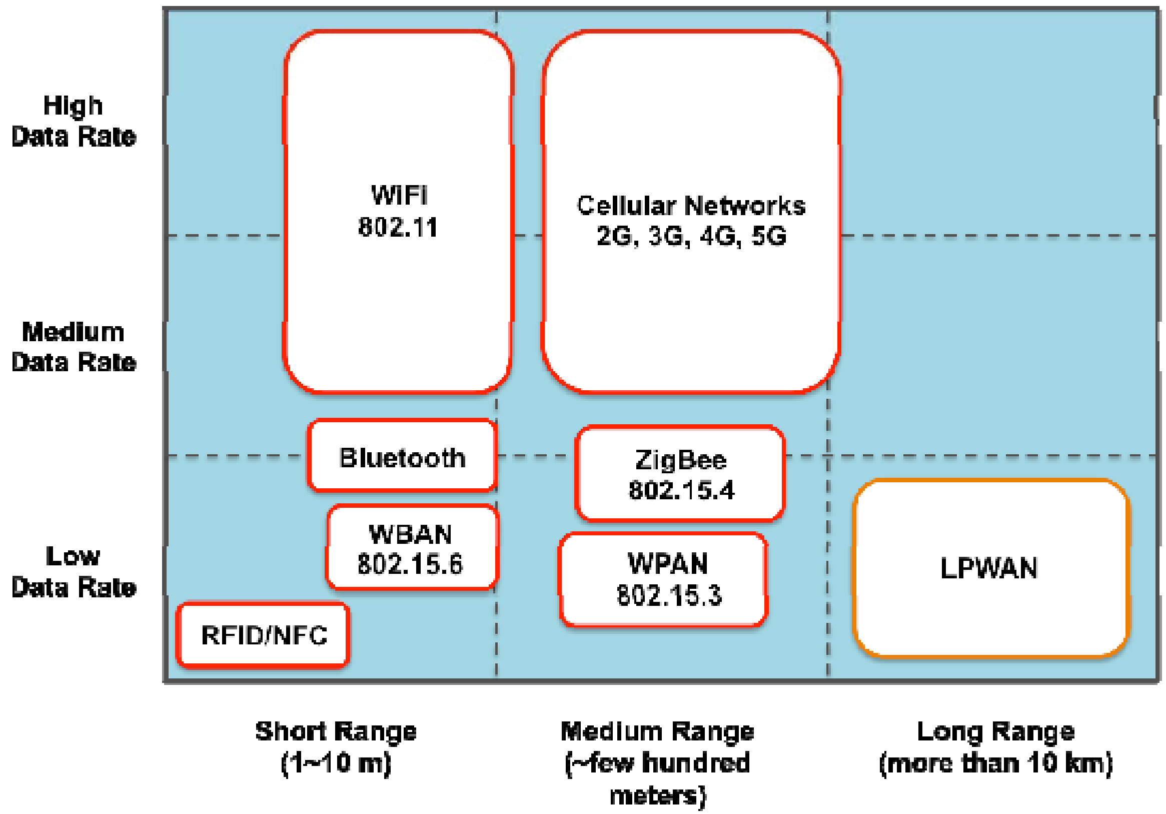
IoT NETWORK CONNECTIVITY

Communication protocols



IoT NETWORK CONNECTIVITY

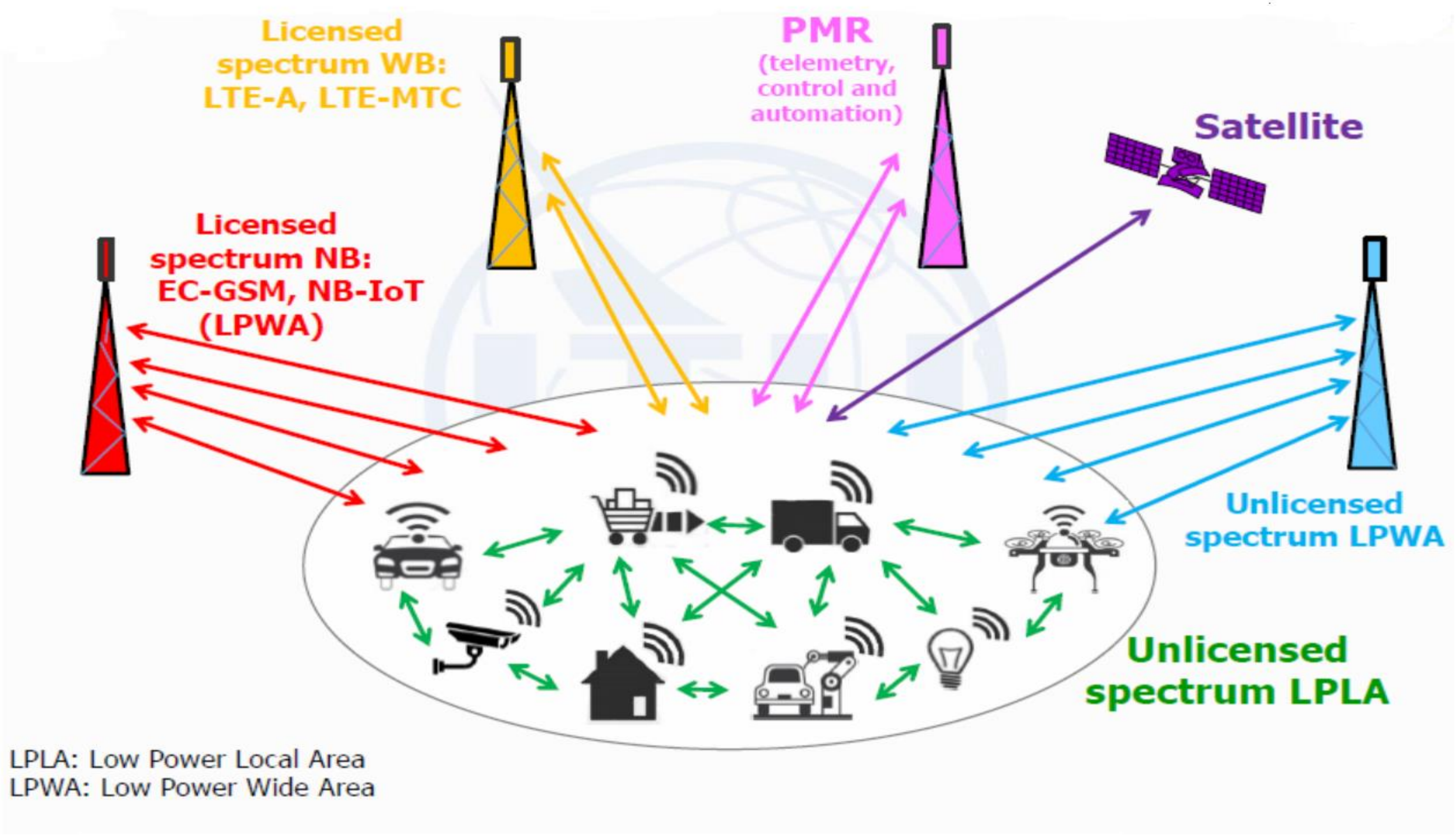
- **Range vs. data rate**



Source: M.Dohler "Machine-to-Machine in Smart Grids & Smart Cities Technologies, Standards, and Applications"

IoT NETWORK CONNECTIVITY

- **IoT connectivity options**



IoT NETWORK CONNECTIVITY REQUIREMENTS

Requirements

IoT Network	Impact on IoT Systems Design
Resource-constrai ned endpoints	**Severely resource constrained (memory, compute)** Cost motivation: compute/memory several orders of magnitude lower, limited remote SW update capabili ty, light protocols, security
Low Power	**Some end-point types may be mostly 'sleeping' and awakened when required** • Sensors cannot be easily connected to a power source • Reduced interaction time between devices and applications (some regulations state duty cycle of no more than 1%) • Idle mode most of the time (energy consumption of around 100 µW). Connected mode just for transmission (mA) • < 100 MHz clock frequency • Embedded memory of few Mb
Embedded	**Smart civil infrastructure, building, devices inside human beings** Sensors deployed in secure or hostile operating conditions, difficult to change without impacting system, S ecurity
Longevity	**Deployed for life typically, have to build-in device redundancy** Very different lifetime expectancy, rate of equipment change in IoT business domains much lower than ICT Industry
High Sensitivity on reception	**Gateways and end-devices with a high sensitivity around** -150 dBm/-125 dBm with Bluetooth lower than -95 dBm in in cellular

COMMON RADIO PROTOCOLS

- **Radios for indoor applications**
  - Design requirements
    - Short range
    - High data rate
    - Small number of devices
  - Common protocols
    - Bluetooth/Low Energy
    - ZigBee
    - Ant
    - Wi-Fi

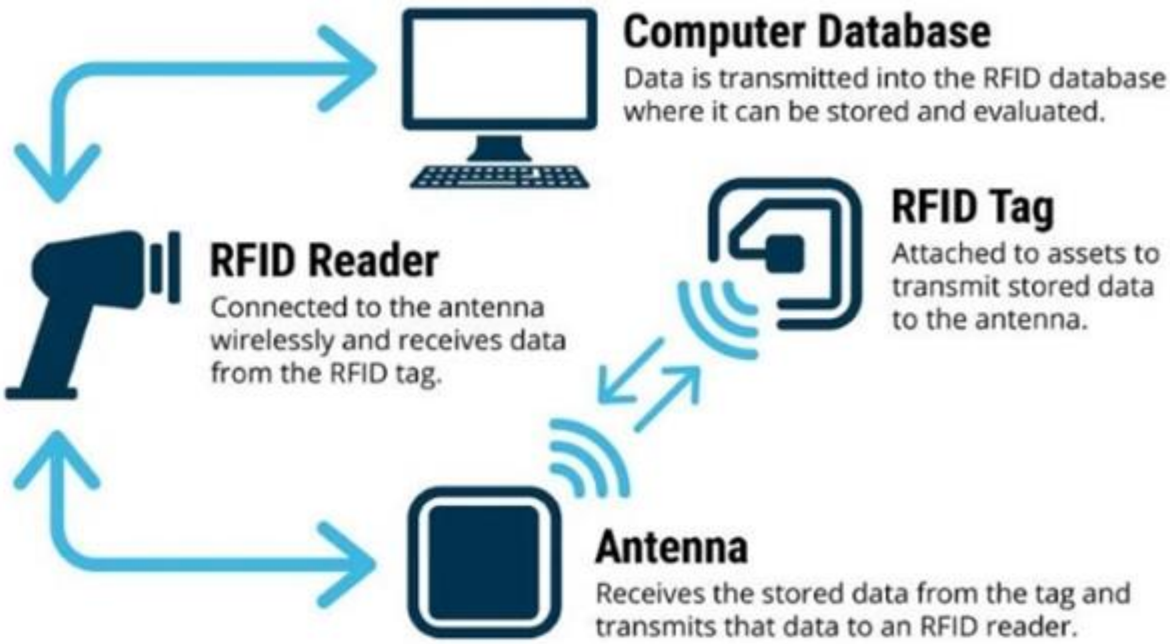
- **Radios for outdoor IoT applications**
  - Design requirements
    - Long range
    - Low data rate
    - Large number of devices
    - Low energy consumption
  - Common protocols
    - GSM/GPRS
    - LTE
  - Emerging protocols
    - Sigfox/LoRa
    - Narrow band LTE
    - Backscatter

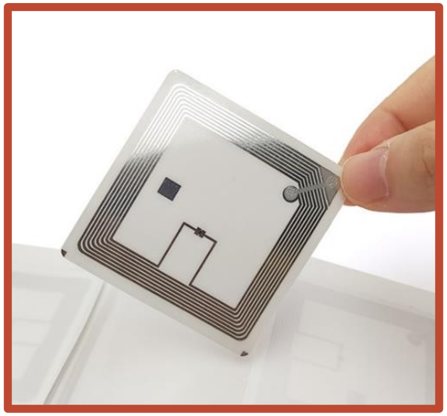
Short Range IoT Solutions

IoT SHORT RANGE COMMUNICATION

- **Short range IoT solutions**
  - RFID
  - Bluetooth
  - Zigbee
  - Wi-Fi

- **RFID**
  - Radio Frequency IDentification
  - Appeared first in 1945

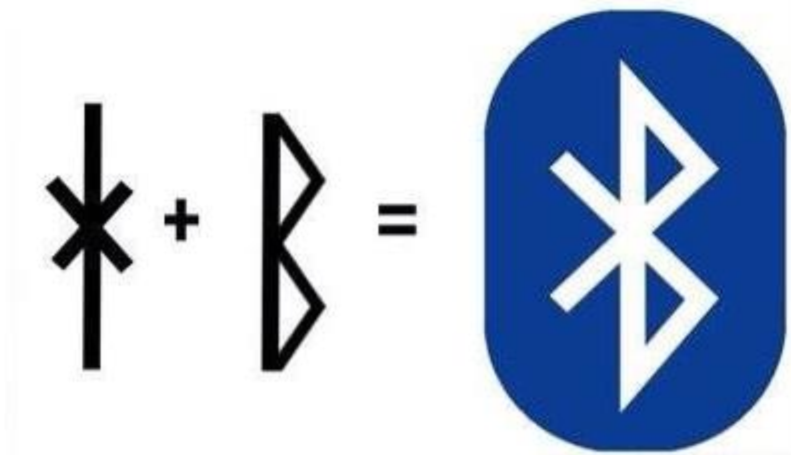




RFID

- Features:
  - Identify objects, record metadata or control individual target
  - Radio frequencies from 100 kHz to 10 GHz
  - Range : < 2 m
  - Transmission rate : 30 kbps
- Operations:
  - Reading device called reader
    - Connected to backend network and communicates with tags using RF
  - One or more tags
    - Embedded antenna connected to chip based and attached to object

- **Bluetooth**



Harald "Bluetooth" Gormsson was a Danish king who lived around 950 CE. He united dissonant Danish tribes and is believed to have been the first Viking king who converted to Christianity. His nickname was suggested for the present-day Bluetooth wireless standard by Jim Kardach, who at the time of his involvement in a related program was reading Frans Bengtsson's book "The Long Ship."

https://www.konkankatta.in/2017/11/did-you-know-origin-of-bluetooth-name.html

BLUETOOTH

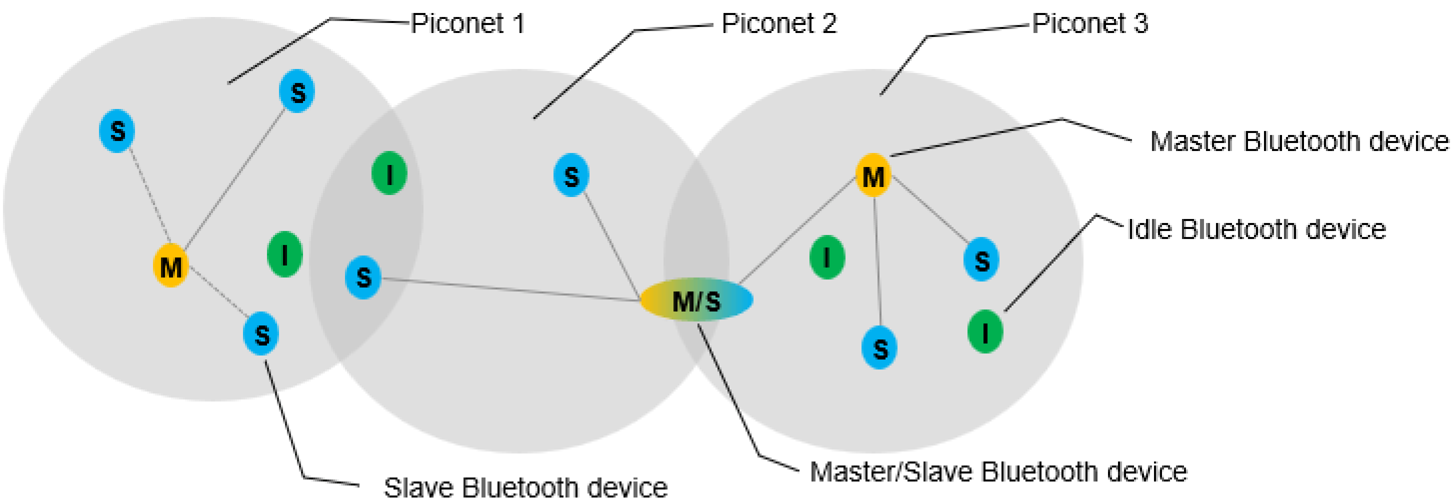
- **Bluetooth**
  - Wireless PAN
  - Low power wireless technology
  - Wireless alternative to wires
  - Based on IEEE 802.15.1
  - Radio band
    - 2.4-2.48 GHZ (79 channels 1 MHz wide) ISM band
  - Average 1 Mbps (Up to 3 Mbps)
  - Supports point-to-point and point-to-multipoint
    - Creates personal area networks (PANs/Piconets)
    - Connects up to 8 devices simultaneously
  - Minimal interference between devices
    - Frequency hopping
      - Devices alter frequencies arbitrarily after packet exchanges -up to 1600 times/second
  - Main applications
    - Speakers, health monitors and other short range applications

Piconet

- 8 stations - 1 master (primary), 7 slaves (secondary)

Scatternet

- Consists of multiple piconets

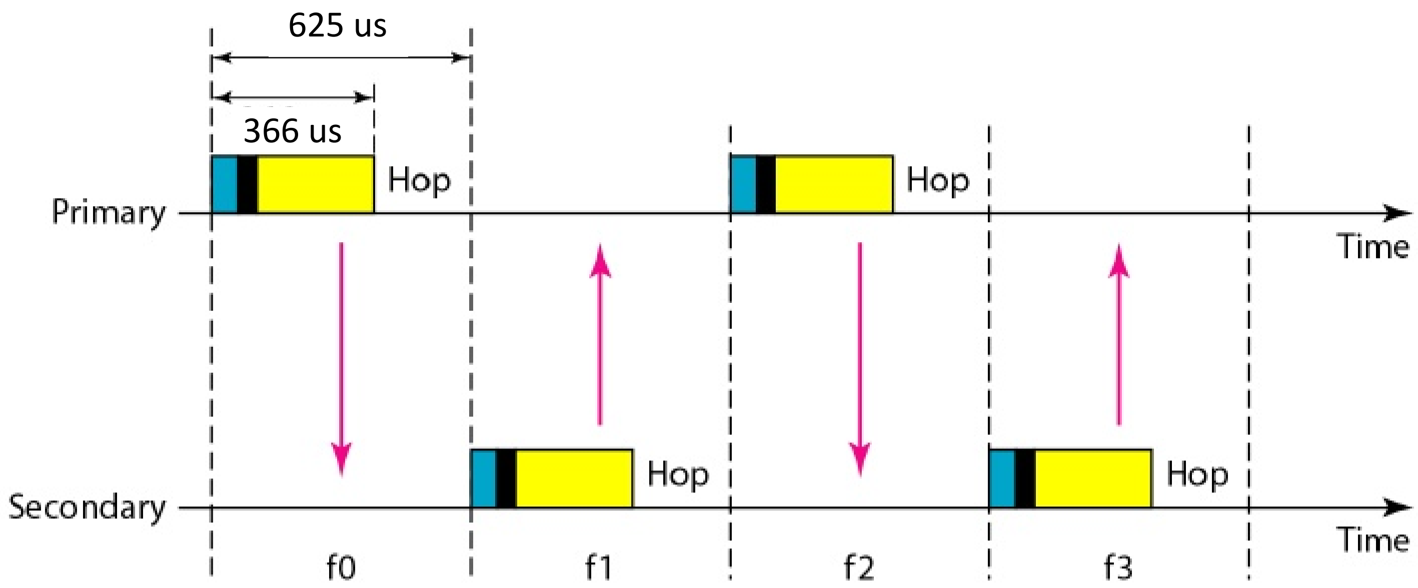


https://kr.mathworks.com/help/comm/ug/what-is-bluetooth.html

Bluetooth MAC

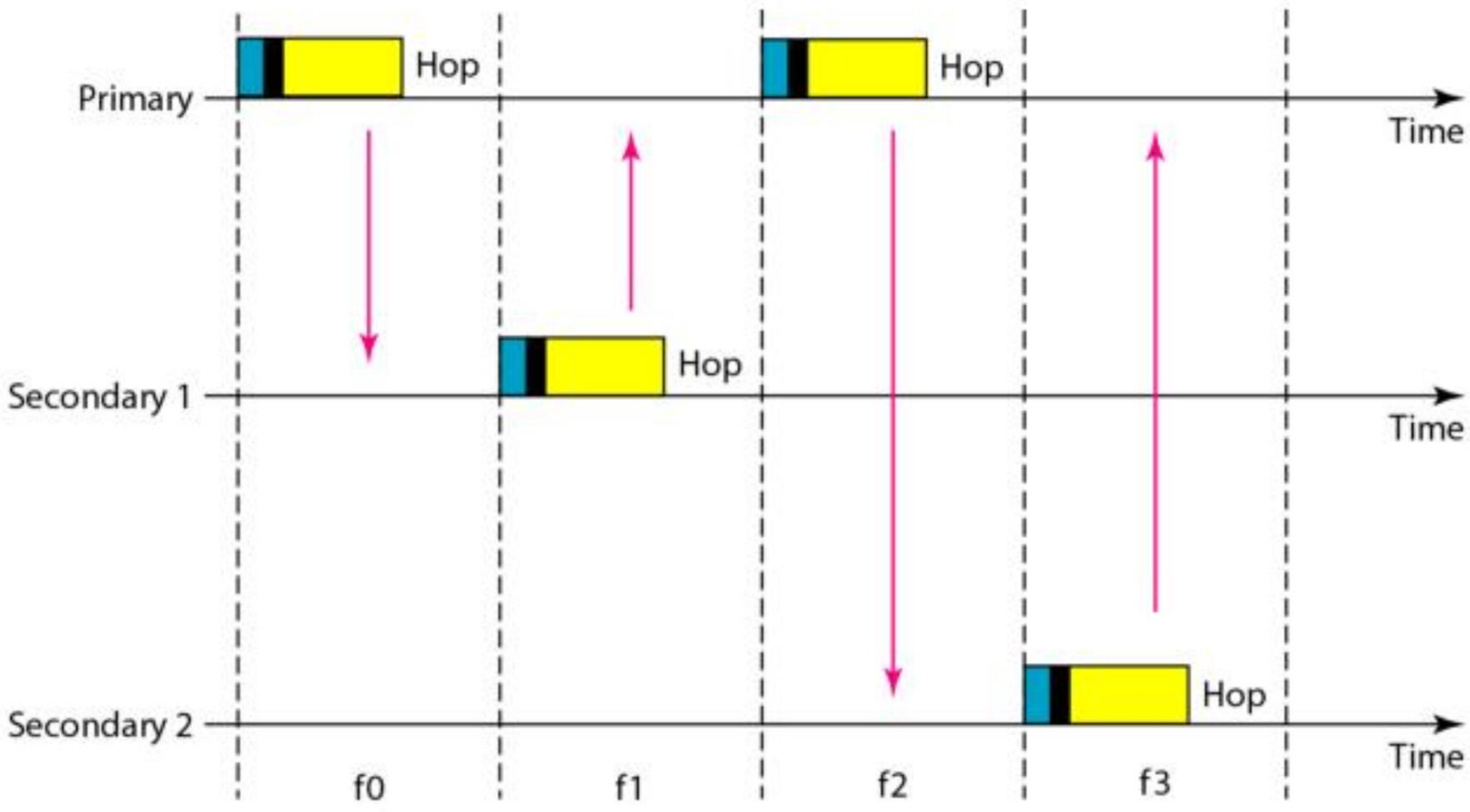
- TDD-TDMA (Time division duplex TDMA)
- Half-duplex (polling)

ex) Single-secondary communication



BLUETOOTH

ex) Multiple secondary communication



BLUETOOTH

- 3 classes of Bluetooth transmit power

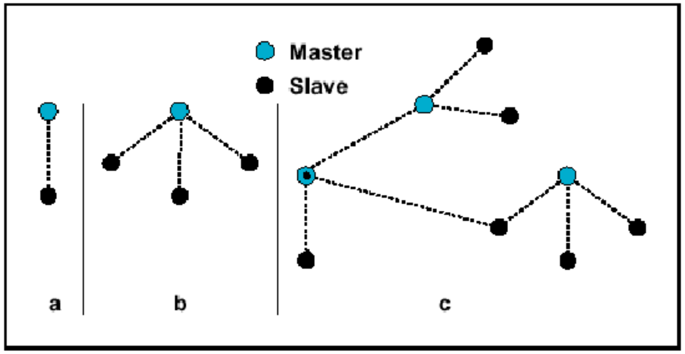


Figure 1.2: Piconets with a single slave operation (a), a multi-slave operation (b) and a scatternet operation (c).

Class	Maximum Power	Operating Range
Class 1	100mW (20dBm)	100 meters
Class 2	2.5mW (4dBm)	10 meters
Class 3	1mW (0dBm)	1 meter

BLUETOOTH

- **Frequency hopping**
  - by actress Hedy Lamar

UNITED STATES PATENT OFFICE

2,292,387

SECRET COMMUNICATION SYSTEM

Hedy Kiesler Markey, Los Angeles, and George Antheil, Manhattan Beach, Calif.

Application June 10, 1941, Serial No. 397,412

6 Claims. (Cl. 250—2)

This invention relates broadly to secret communication systems involving the use of carrier waves of different frequencies, and is especially useful in the remote control of dirigible craft.

Fig. 2 is a schematic diagram of the apparatus at a receiving station;

Fig. 3 is a schematic diagram illustrating a starting circuit for starting the motors at the

Bluetooth Applications

- Wireless communication between devices
  - Mobile phones, laptops, cameras, gaming controllers, computer peripherals, etc
- Short range sensor transmission
- Share multimedia - pictures, video, music
- A2DP - Advanced Audio Distribution Profile
  - Stream audio wirelessly

BLUETOOTH LOW ENERGY

From 2001 – 2006 Nokia asked:

How do we design a radio that can transmit short bursts of data for months or years only being powered by a coin cell battery?

The answer is: ***Keep the radio asleep mode most of the time!***

1. Advertise on only one of three channels
2. Transmit quickly at 1 Mbps
3. 40 channels 2 MHz wide
4. Make the minimum time to send data only 3 msec
5. Limit the max transmit power to 10 mW
6. However, don’t sacrifice security: AES 128-bit

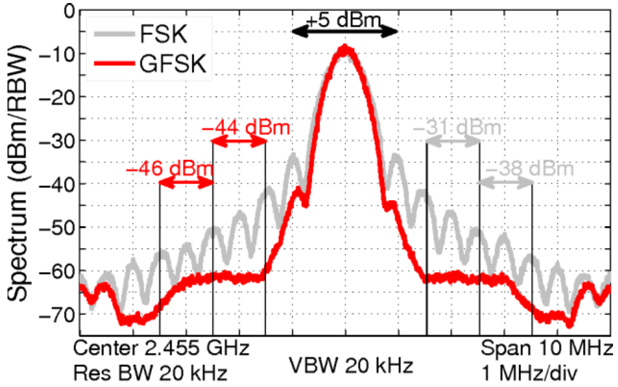
BLUETOOTH LOW ENERGY

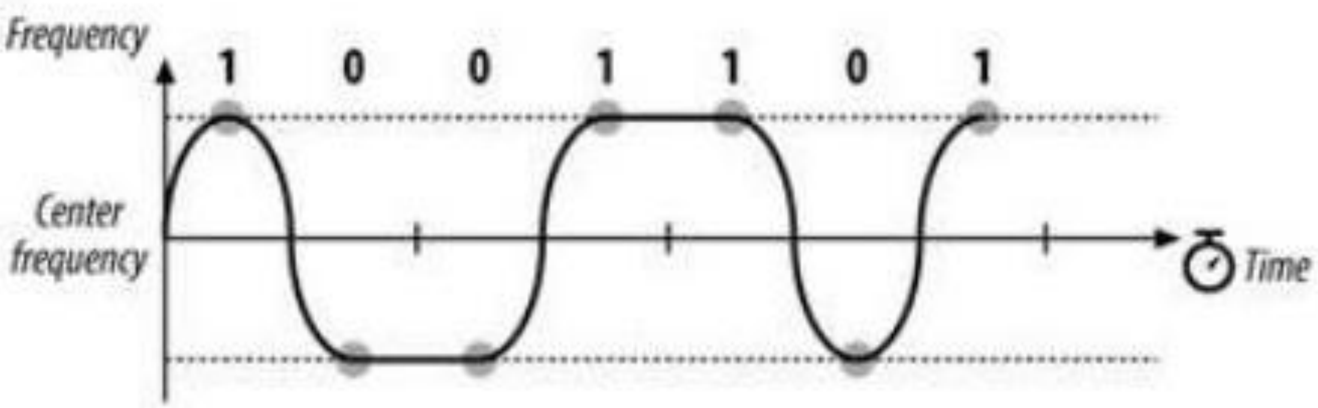
- **Features**
  - GFSK modulation for low power operation
  - Transmission power : 10 ~ 20 dBm
  - Range : 10 ~ 30 m
  - Channels
    - 3 advertising channels
    - 37 data channels
  - Power consumption : 0.01 ~ 0.5 W

- **GFSK (Gaussian frequency-shift keying)**
  - Filters the data pulses with a Gaussian filter
    → To make the transitions smoother
  - Advantages
    - Reducing sideband power
    - Reducing interference with neighboring channels
  - Disadvantage
    - The cost of increasing inter-symbol interference

BLUETOOTH LOW ENERGY

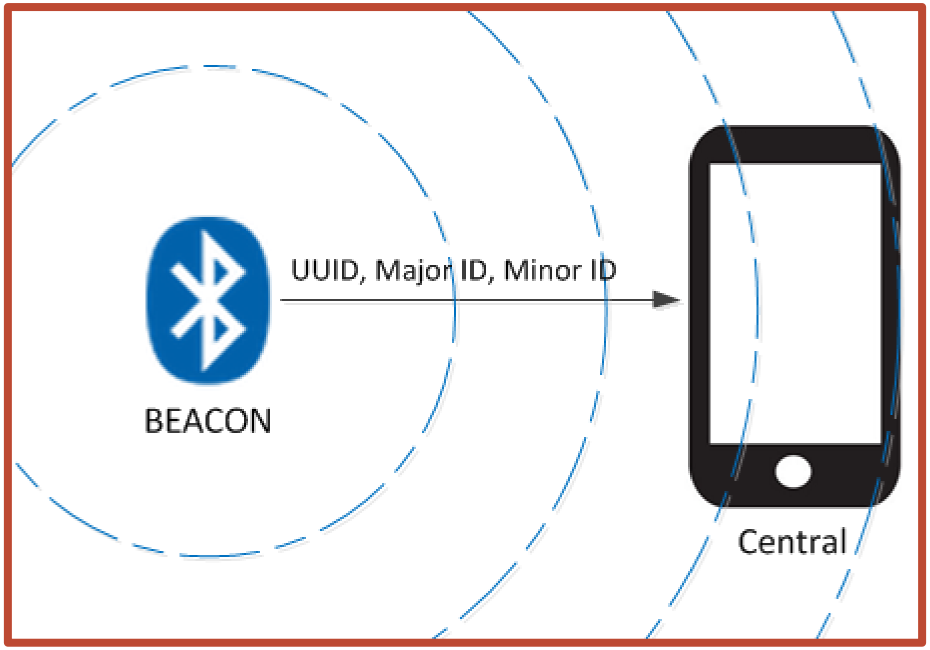
- 2-level GFSK Example





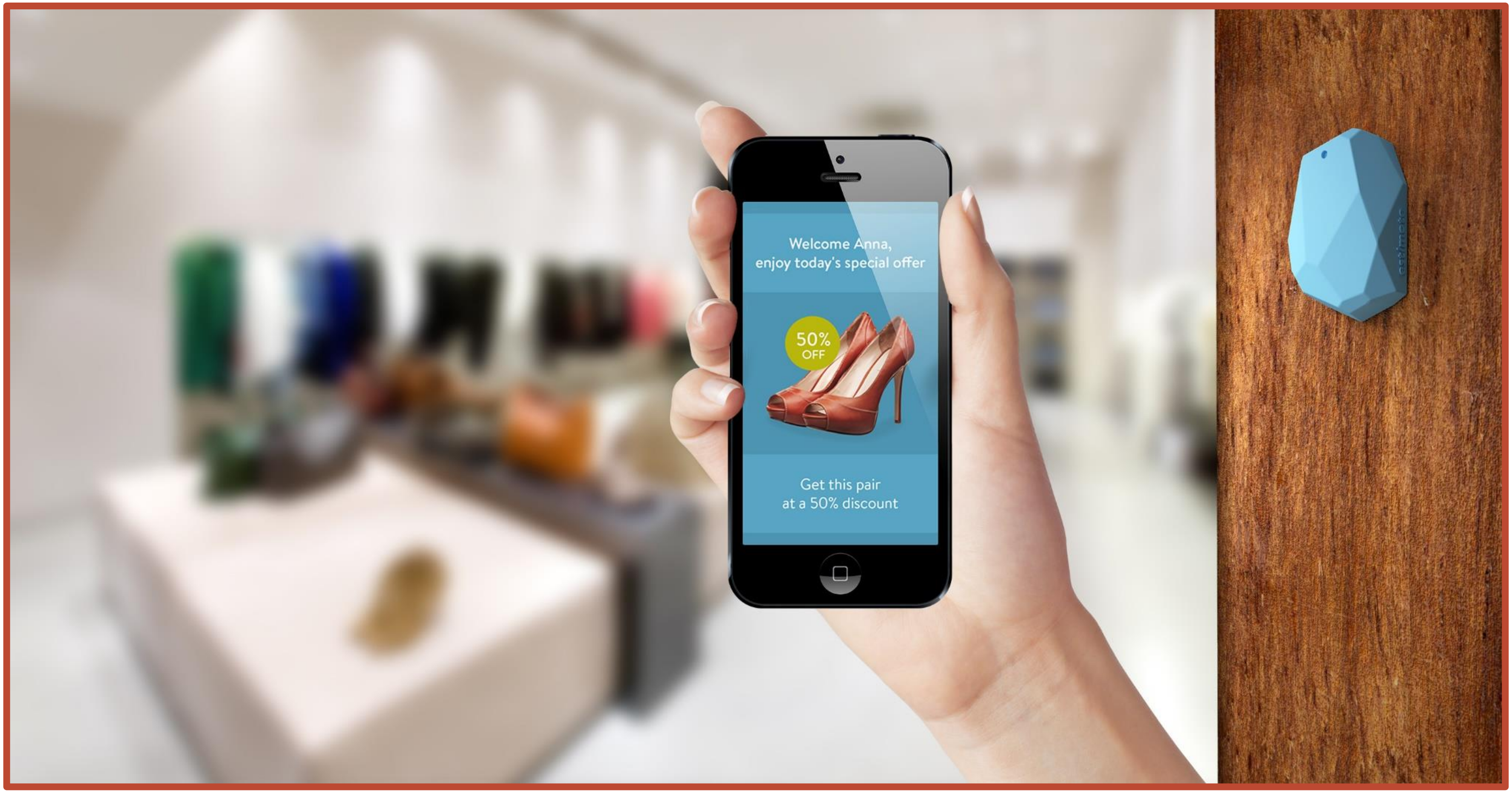
BLUETOOTH LOW ENERGY

- **Bluetooth beacon**
  - Broadcasts information periodically
  - Uses BLE to reduce energy consumption
  - Unidirectional communication
  - Small and cheap modules ($1 ~ $2)



BLUETOOTH LOW ENERGY

- **Beacon examples**



BLUETOOTH LOW ENERGY

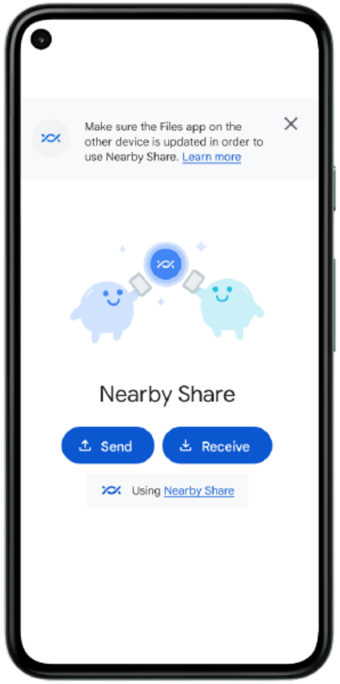
- **Beacon examples**
  - Apple - iBeacon

https://zealousweb.medium.com/apple-ibeacon-to-bring-sweeping-changes-in-retail-9540d6c85c2

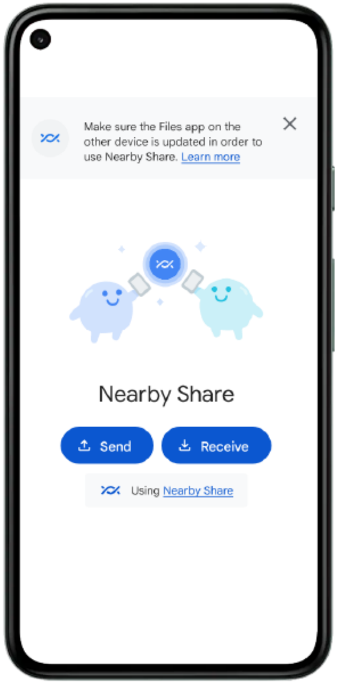
BLUETOOTH LOW ENERGY

- Google - Nearby

Make sure both devices are using Android Nearby Share



Sender



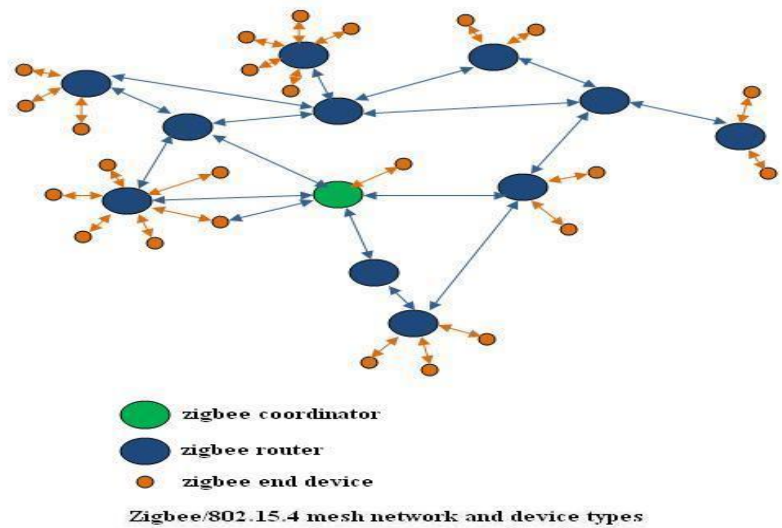
Reciever

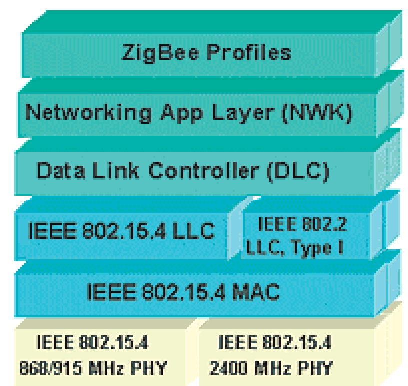
BLUETOOTH LOW ENERGY

- PayPal - PayPal Beacon

ZigBee

- **ZigBee**
  - Built on top of 802.15.4
  - Radio bands
    - 868MHz in Europe
    - 915MHz in US and Australia
    - 2.4GHz else worldwide
  - Short range
  - Radio band
    - 2.4 GHz, 915 MHz or 868 MHz
    - 2 MHz channels (DSSS)
  - Low data-rate: 250 kbps
  - Low power: Up to 1000 days
  - Transmits over longer distances through mesh networks
  - Cheaper than Bluetooth



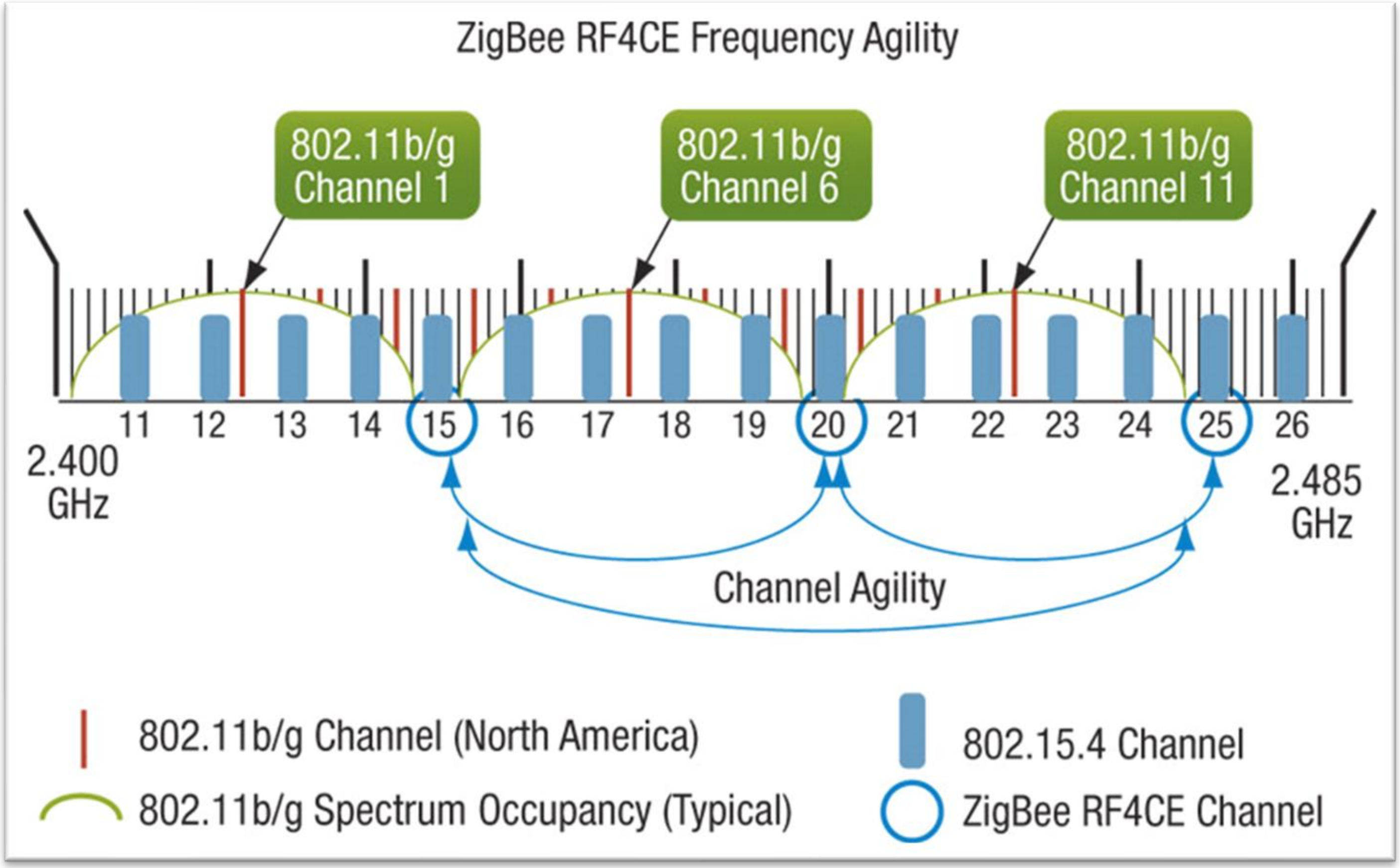


ZigBee

- **Why ZigBee?**
  - Low power, cost, and size
  - Straightforward configuration
  - Good support and documentation
    - Lots of products already on the market
  - Mesh networking
  - Lends itself well to many different applications
  - Very low wakeup time
    - 30 ms (Zigbee) vs. up to 3 s (Bluetooth)

ZigBee

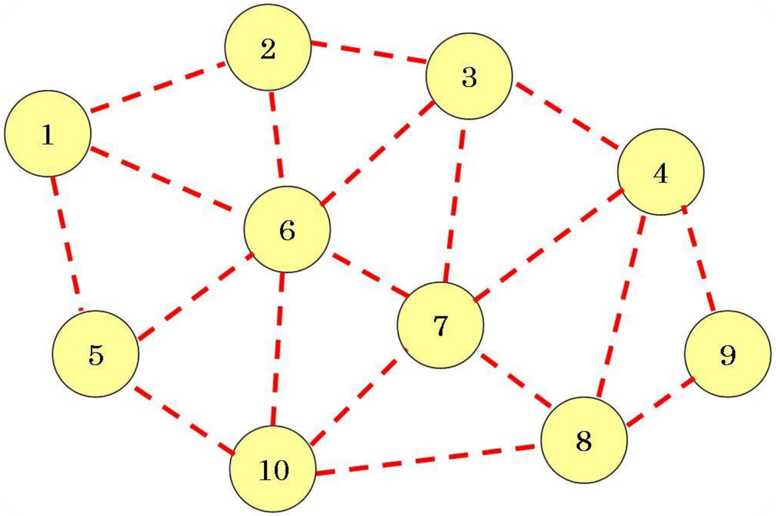
- **Or maybe not...**
  - Competes with Wi-Fi for bandwidth
    - Only 4 usable bands in Wi-Fi intensive scenarios (15, 20, 25, 26)



http://fosiao.com/system/files/misc/zigbee.Wi-Fi_.channel.jpg

ZigBee

- **Mesh networking**
  - Consists of a series of nodes.
  - Each node must acquire and transmit its own data, as well as act as a relay for other nodes to propagate data
  - ZigBee devices often form mesh networks.
  - Examples
    - wireless light switching, Music school practice rooms.



http://kf5czo.blogspot.com/2012/03/ham-radio-and-mesh-networks.html

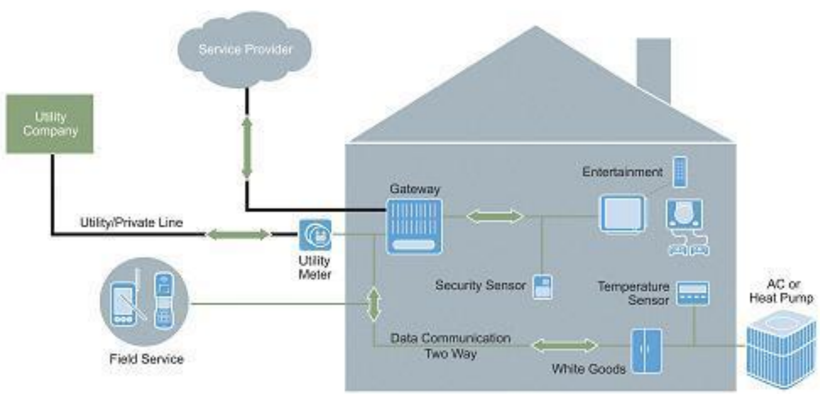
ZigBee

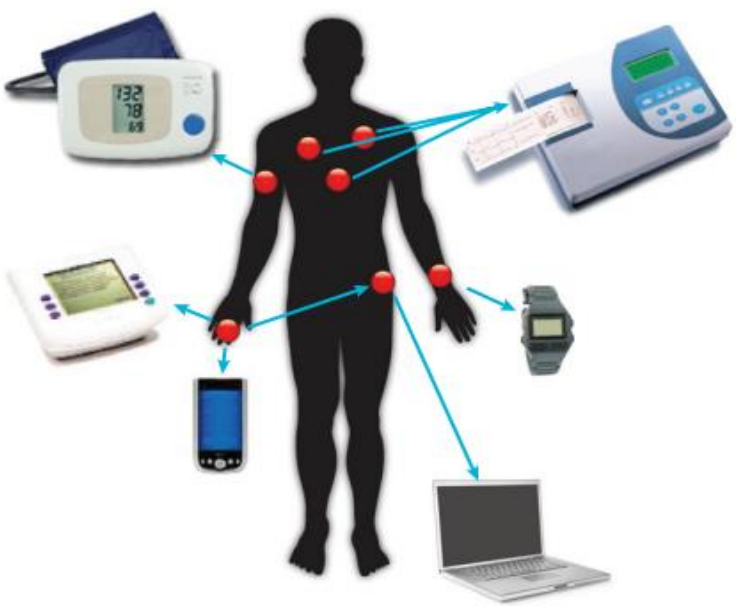
- **Advantages of mesh networking:**
  - Allows devices to communicate to multiple other devices in the network
  - Multiple paths to destination - greater flexibility against interference
  - Allows overall network to grow to larger physical sizes than possible with point-to-point networks.

- **Mesh characteristics**
  - Self-forming
    - ZigBee devices can establish communication pathways when new devices appear
  - Self-healing
    - If a node is removed from the network (either intentionally or not) the remaining network will look to establish alternate routes of communication.

ZigBee

- **ZigBee applications**
  - Wireless environmental sensors
    - Temperature, pressure, sound, luminous intensity
  - Medical devices
    - Glucose meters, heart monitors
  - Household automation
    - Security/temperature controllers
    - Smoke/motion detectors



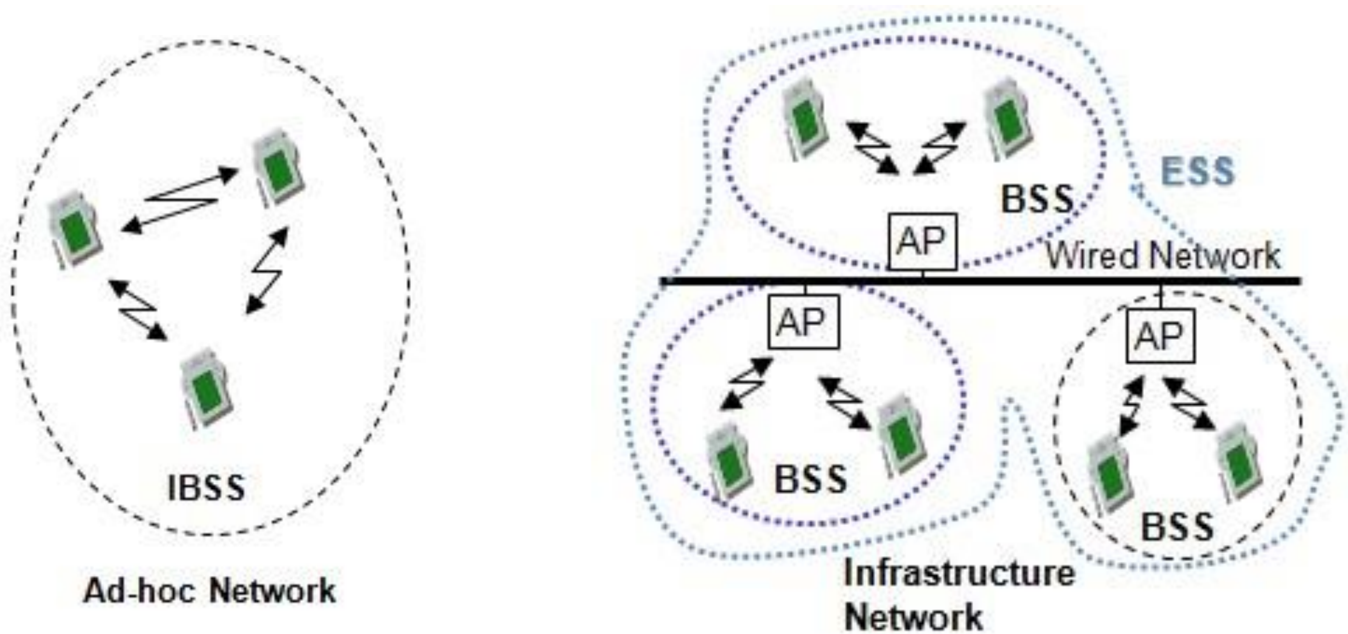


- **Wi-Fi**
  - Wireless alternative to wired technologies
  - Dual Bands: 2.4GHz and 5GHz
  - 802.11a/b/g/n/...
    - Cost vs Speed vs Interference tradeoff
  - Roaming
  - Global standard
  - High speed: Up to 300 Mbps
  - High power consumption
    - Concern for mobile devices
  - Range: Up to 100m

- **Elements of Wi-Fi**
  - Access point
    - Wireless LAN radio transceiver
    - "Base station" that can connect to one or many wireless devices simultaneously to internet
  - Wi-Fi card
    - Accepts wireless signal and relay information

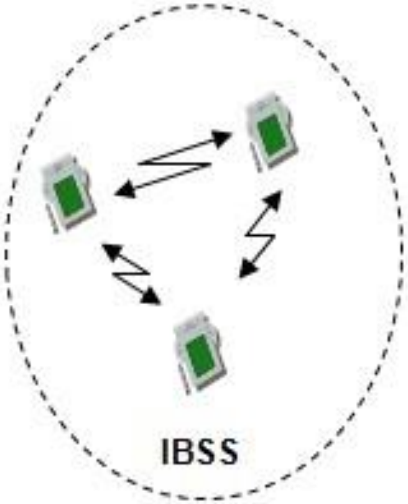
Wi-Fi network topologies

- Peer-to-peer topology (ad-hoc mode)
- AP-based topology (infrastructure mode)



Wi-Fi

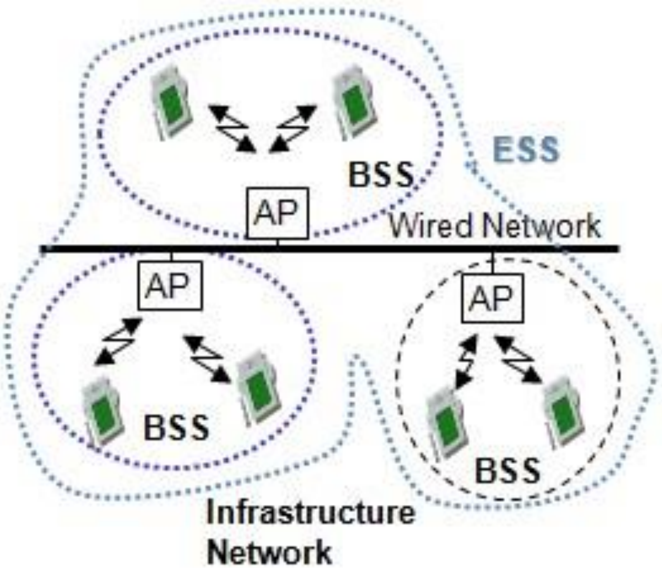
- Peer-to-peer topology (ad-hoc mode)
  - IBSS (Independent Basic Service Set)
  - AP is not required
  - Client devices can communicate with each other directly
  - Useful to create wireless network easily and quickly



Ad-hoc Network

Wi-Fi

- AP-based topology (infrastructure mode)
  - BSS (Basic Service Set)
  - ESS (Extended Service Set)
    - Composed of multiple BSS
  - Any communication has to go through AP
    - Client-to-client communication
      - Must send data to AP first, then AP sends data to destination

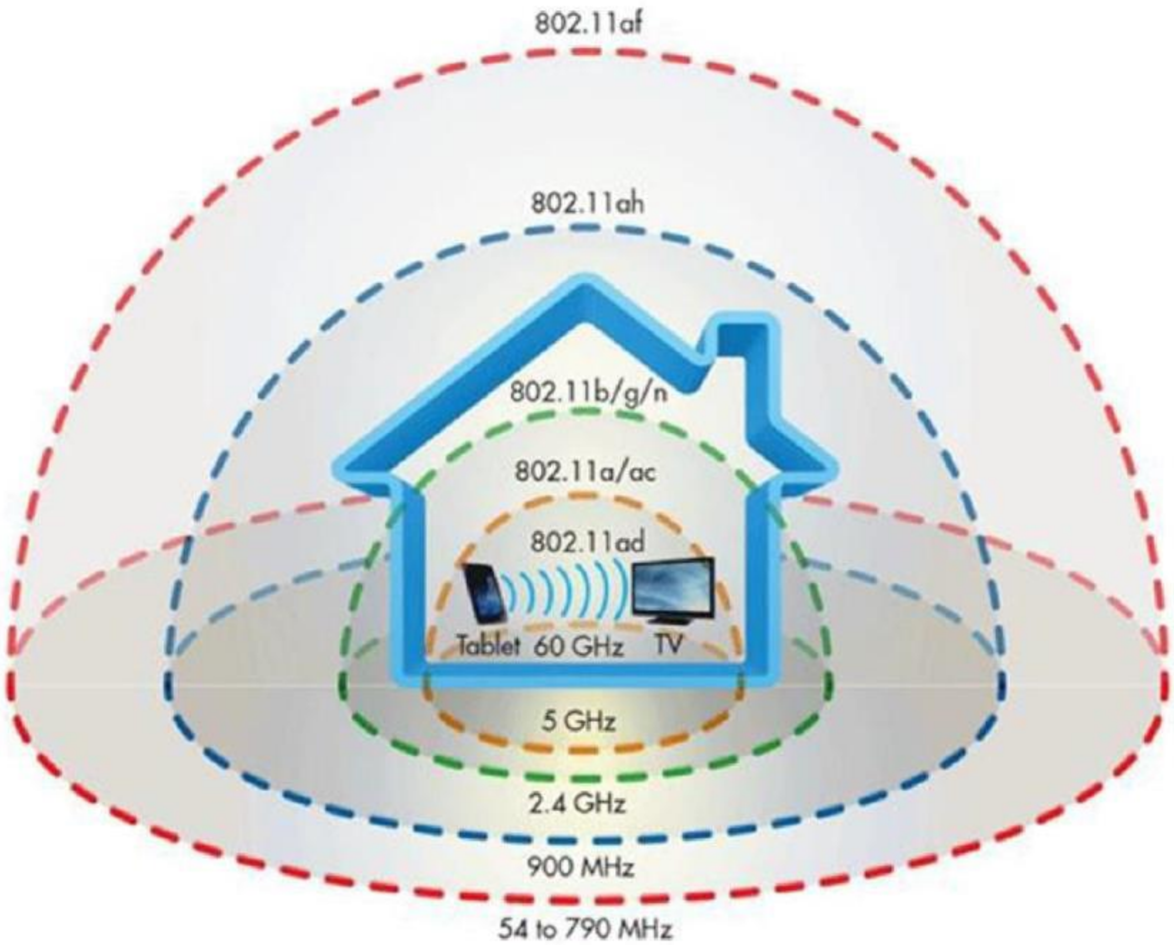


Comparison of Wi-Fi versions

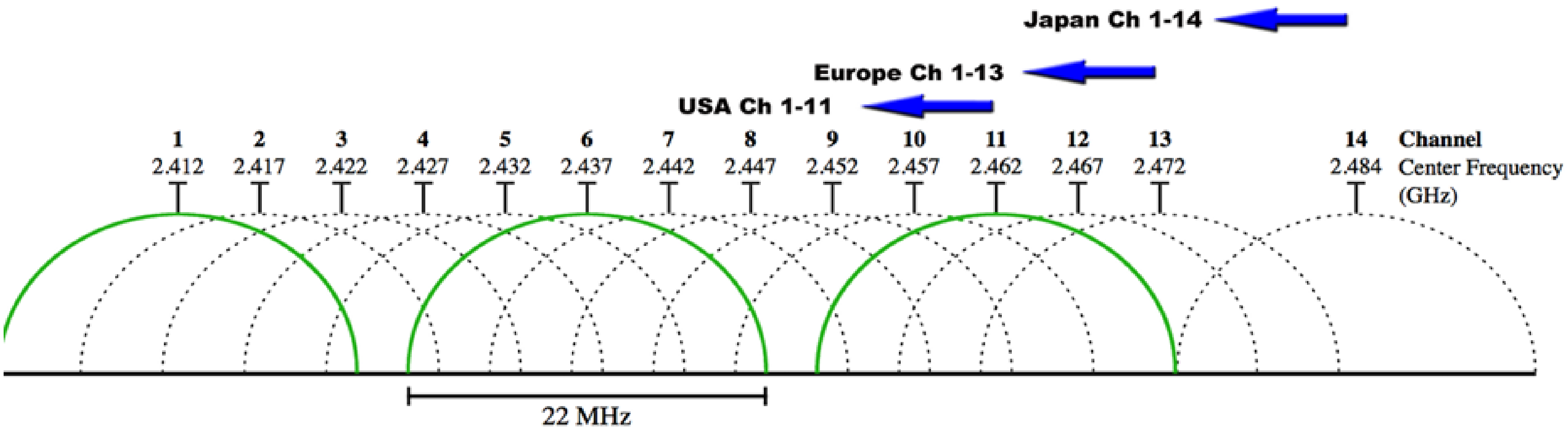
	802.11b	802.11a	802.11g	802.11n	802.11ac
Frequency	2.4 GHz	5 GHz	2.4 GHz	2.4 GHz, 5 GHz	2.4 GHz, 5 GHz
Modulation	DSSS	OFDM	OFDM	OFDM	OFDM
Range	70~100 m	15~35 m	50~80 m	indoor 70 m outdoor 250 m	100 m
Channel bandwidth	20 MHz	20 MHz	20 MHz	20/40 MHz	20/40/80/160 MHz
Max. download	11 Mbps	54 Mbps	54 Mbps	600 Mbps	6.93 Gbps
Pros.	Cheap	Low interference	Compatible with 802.11b	Compatible with 802.11b/g	Compatible with 802.11b/g/n High-speed
Cons.	Interference with Bluetooth	use of satellite frequencies (Not available in some countries)	Interference with Bluetooth	WEP, WPA, TKIP not supported	use of satellite frequencies (Not available in some countries)

Wi-Fi

- **Radio frequency and transmission range**

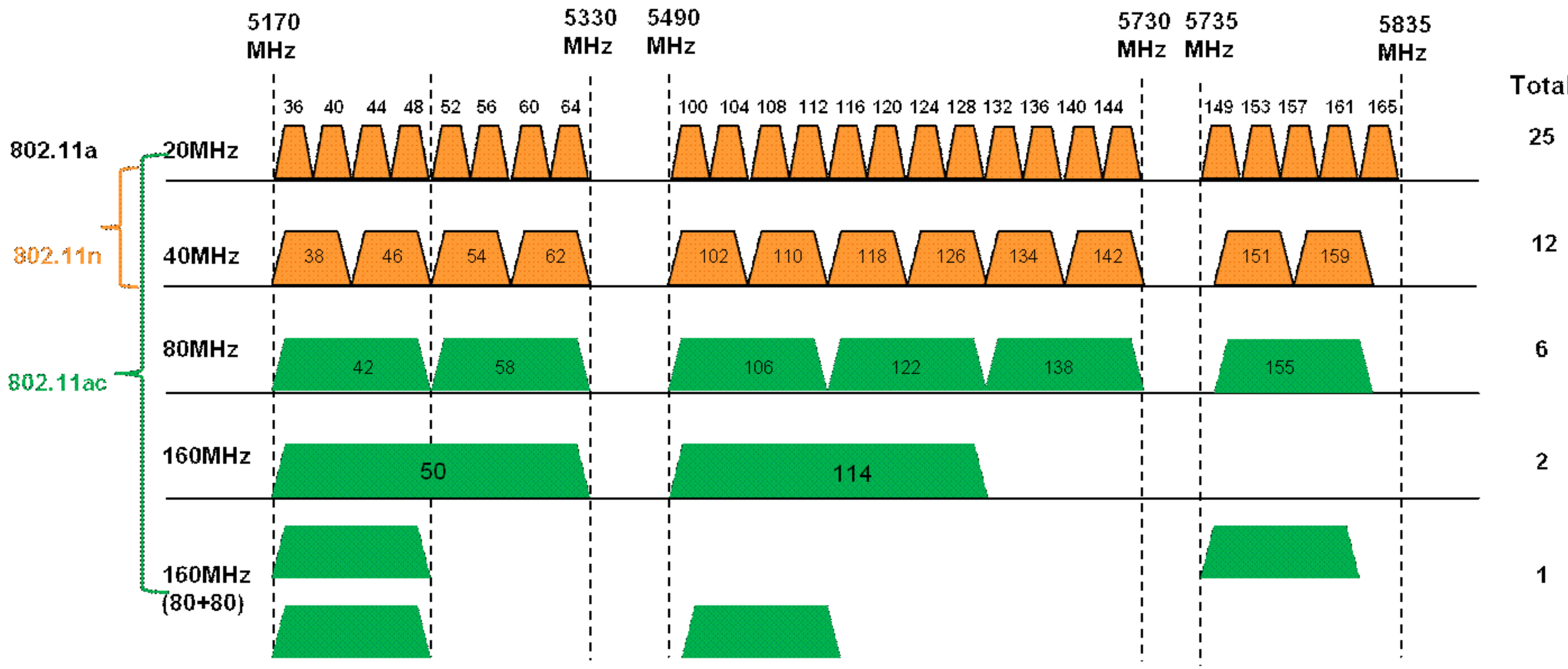


- **802.11 channels (2.4 GHz)**



https://microchipdeveloper.com/Wi-Fi:channels

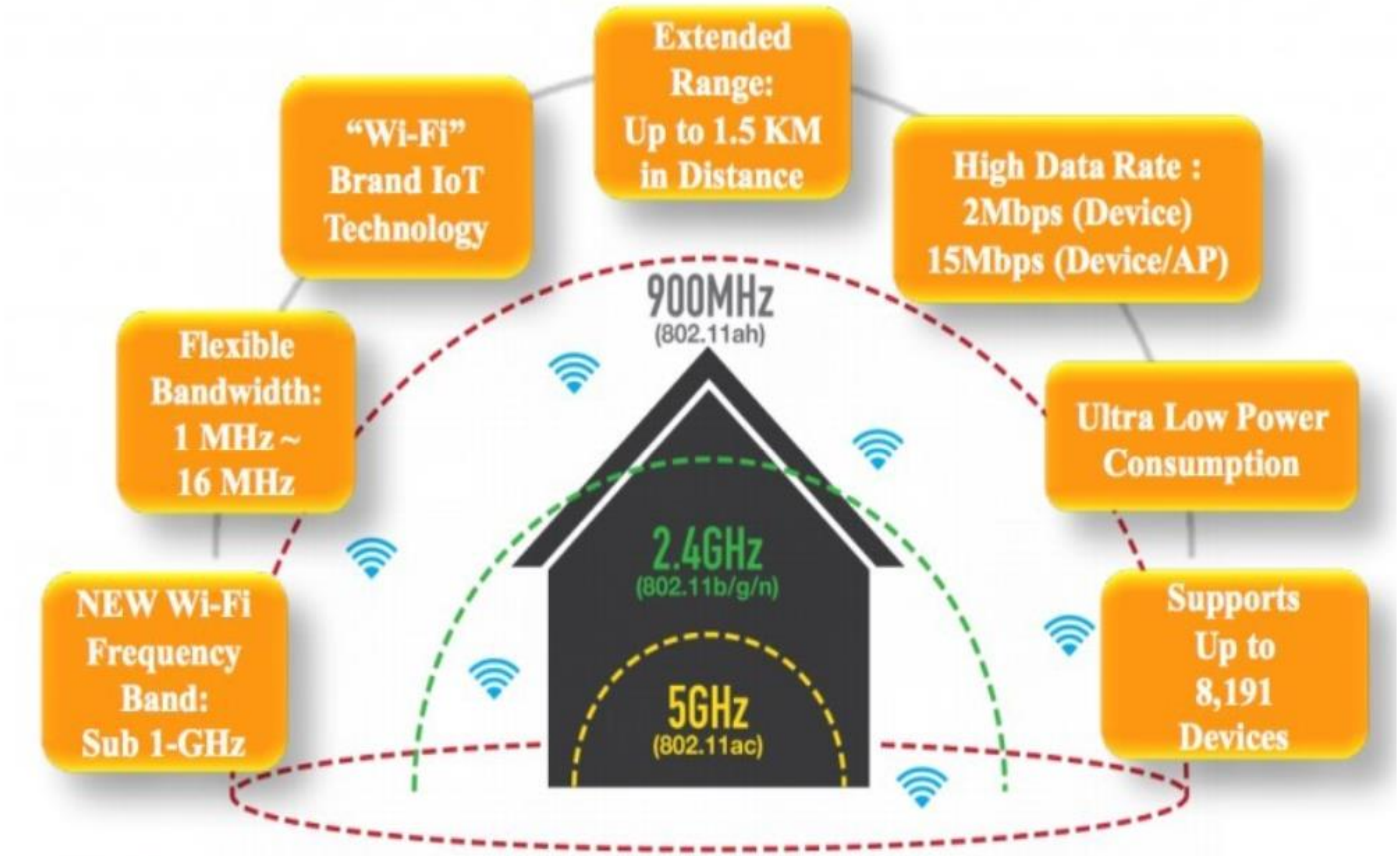
802.11 channels (5 GHz)



https://support.huawei.com/enterprise/en/doc/EDOC1100081215

Wi-Fi HaLow

- 802.11ah



Wi-Fi HaLow

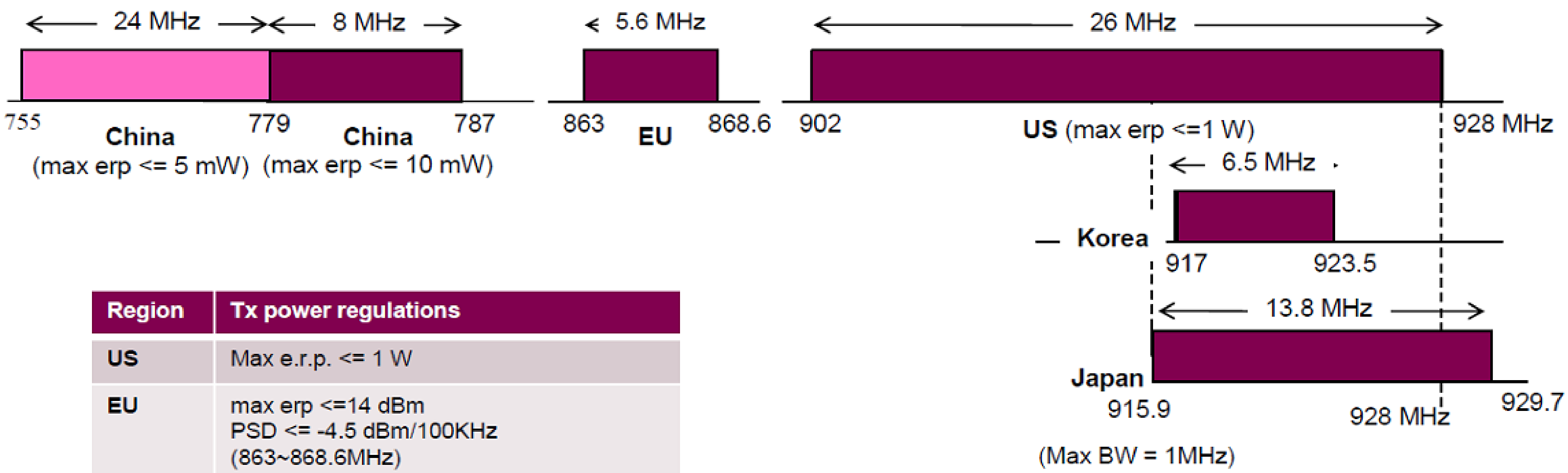
- **802.11ah (Sub 1 GHz) Wi-Fi HaLow at 900 MHz**
  - Wi-Fi consumes too much power, so an IoT customized version was developed
  - Low-power, long-range Wi-Fi
  - Up to 1 km range, lower power consumption thanks to a sleep mode
  - 1, 2, 4, 8 and 16 MHz channels
  - Competes with Bluetooth, 100 kb/s to 40 Mb/s

Wi-Fi HaLow

- **802.11ah use case**
  - Case 1: Sensors and meters
    - Smart grid - meter to pole
    - Environmental monitoring
    - Industrial process sensors
    - Healthcare
    - Home/building automation
    - Smart city
  - Case 2: Backhaul sensor and meter data
    - Backhaul aggregation of sensor networks
    - Long point-to-point wireless links
  - Case 3: Extended range Wi-Fi
    - Outdoor extended range hotspot
    - Outdoor Wi-Fi for cellular traffic offloading

Wi-Fi HaLow

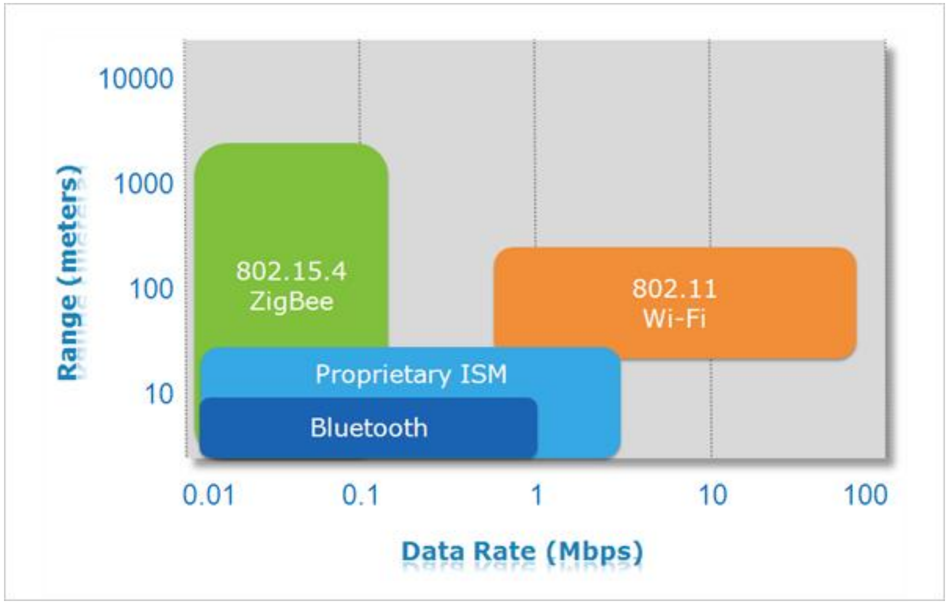
802.11ah channels



Region	Tx power regulations
US	Max e.r.p. <= 1 W
EU	max erp <=14 dBm PSD <= -4.5 dBm/100KHz (863~868.6MHz) PSD <= 6.2 dBm/100KHz (865~868MHz)
Korea	3 mW or 10 mW (920.6~923.5MHz and six 200 KHz channels below 920.6 MHz)
China	Max e.r.p. <= 5 mW (755 – 779 MHz) Max e.r.p. <= 10 mW (779 – 787 MHz)
Japan	1mW , 20 mW or 250 mW (915.9~929.7MHz) Max BW <= 1 MHz

Protocol comparisons

	Bluetooth	Zigbee	Wi-Fi
Speed	Moderate	Low	High
Range	Moderate - High	High	High
Power Consumption	Low - Moderate	Low	High

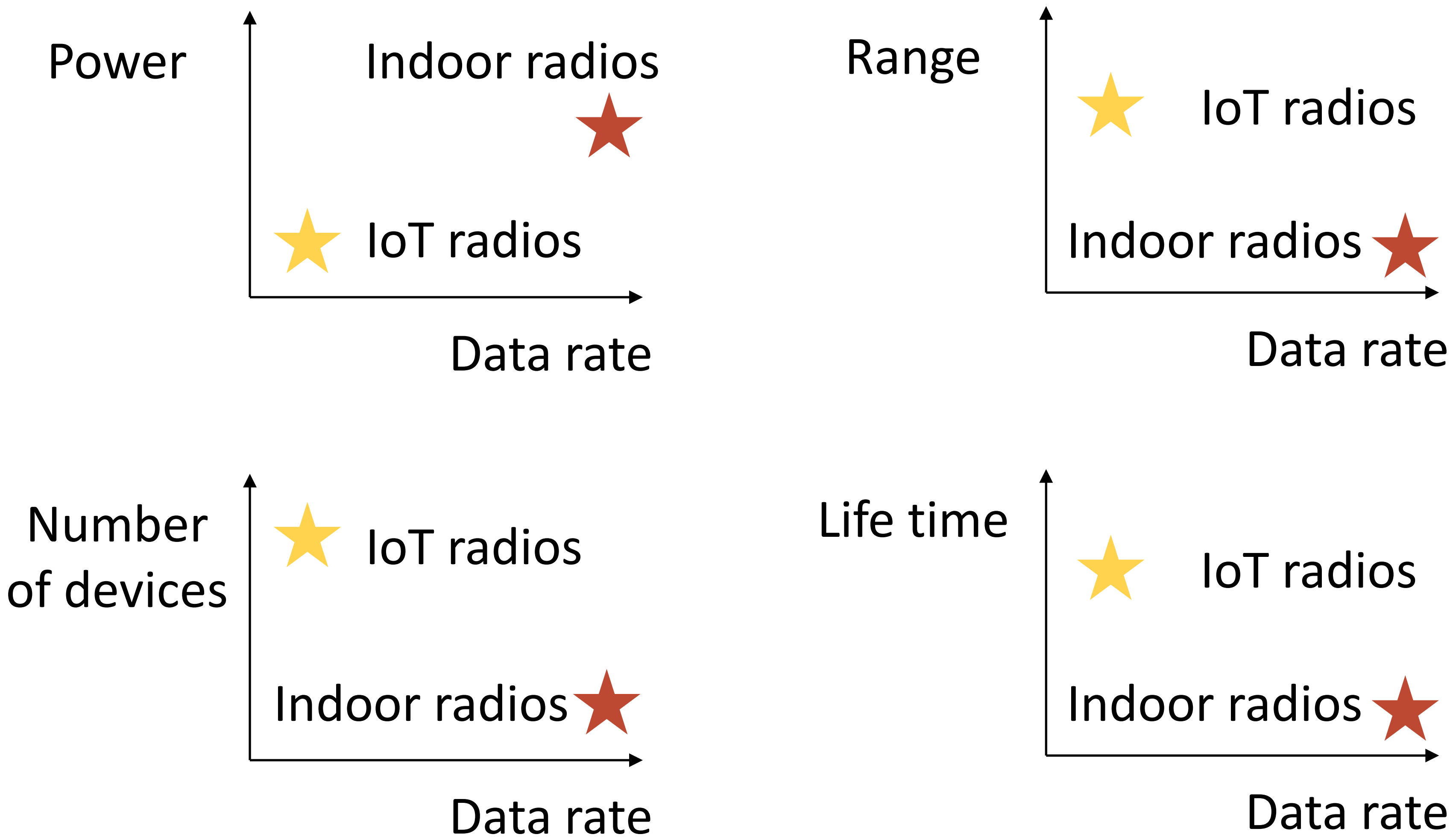


IoT LONG RANGE COMMUNICATION

- **Design requirements**
  - Can we use Wi-Fi/Bluetooth/ZigBee radios to support IoT applications deployed outdoor?
    - Can we achieve kilo meter communication distance?
    - Can we support 3~5 years lifetime with a coin battery?
    - Can we support the communication with thousands of IoT devices with the coverage of a base station?
    - We only need to transmit 100 bits per second data compared to the mega bits per second case in Wi-Fi

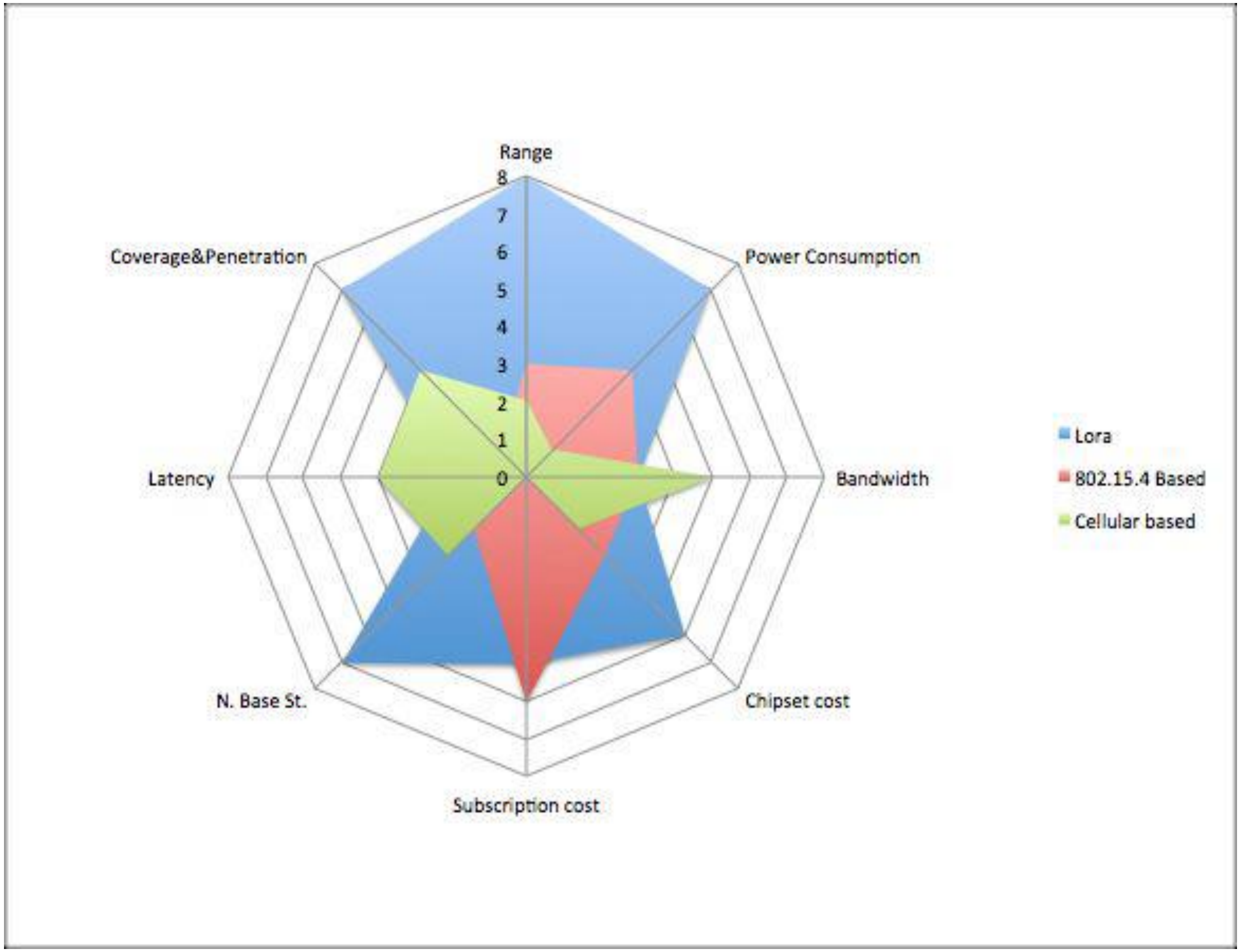
We are wiling to trade data rate
for range, lifetime, and the number of devices supported.

IoT LONG RANGE COMMUNICATION



IoT LONG RANGE COMMUNICATION

- **Comparison of short and long range solutions**



IoT LONG RANGE COMMUNICATION

IoT Long Range Technical Solutions

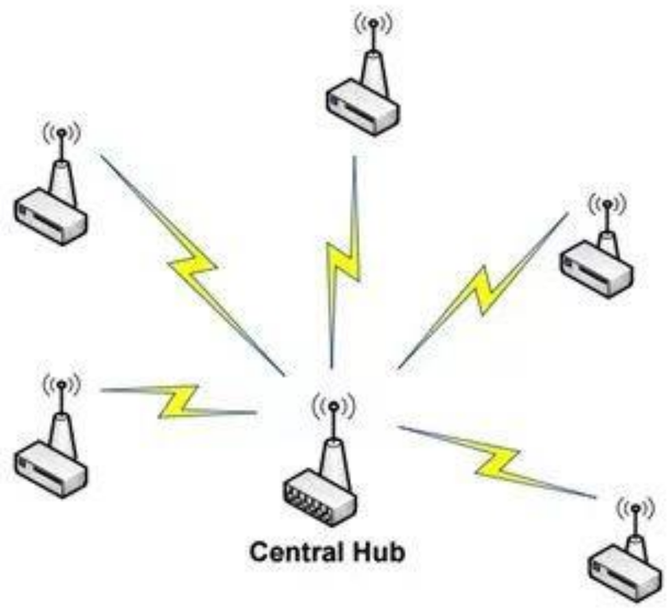
Carrier frequency		Technology	Channel bandwidth	Representative data rate	Link budget target or max. range
Licensed cellular		LTE Cat. 0	20 MHz	DL: 1 Mb/s UL: 1 Mb/s	140 dB
		LTE Cat. M	1.4 MHz	DL: 1 Mb/s UL: 1 Mb/s	155 dB
		NB-IoT	200 kHz	DL: 128 kb/s UL: 64 kb/s	164 dB
		EC-GSM	200 kHz	DL: 74 kb/s UL: 74 kb/s	164 dB
Unlicensed	2.4 GHz	Ingenu RPMA	1 MHz	UL: 624 kb/s DL: 156 kb/s	500 km line of sight
	Sub-1 GHz	LoRa chirp spread spectrum	125 kHz	UL: 100 kb/s DL: 100 kb/s	15 km rural 5 km urban
	Sub-1 GHz	Weightless-N	200 Hz	UL: 100 b/s	3 km urban
	Sub-1 GHz	Sigfox	160 Hz	UL: 100 b/s	50 km rural 10 km urban

Source:

H. S. Dhillon et al., “Wide-Area Wireless Communication Challenges for the Internet of Things,” IEEE Communications Magazine, February 2017

LOW POWER WIDE AREA NETWORK (LPWAN)

- **Low Power Wide Area Network (LPWAN)**
  - Optimized for IoT and Machine to Machine (M2) applications
  - Trade throughput for coverage (up to several kilometers)
  - Star topology



LOW POWER WIDE AREA NETWORK (LPWAN)

- Can accept:
  - Low throughput, application specific
  - Very sparse datagrams
  - Delays
  - Sleeping times

- Range
  - Many kilometers

  cf)
    - 2G typically 3 km, maximum 30 km
    - 802.15.4 less than 100 m
    - Wi-Fi, typically 100m

LOW POWER WIDE AREA NETWORK (LPWAN)

- **Battery duration comparison**
  - LoRa: up to years How?
  - 2G, a few days
  - 802.15.4 months
  - Wi-Fi, a few days

- **Energy scavenging schemes are being investigated**
  - Inductive powering
  - Photovoltaic

LoRa

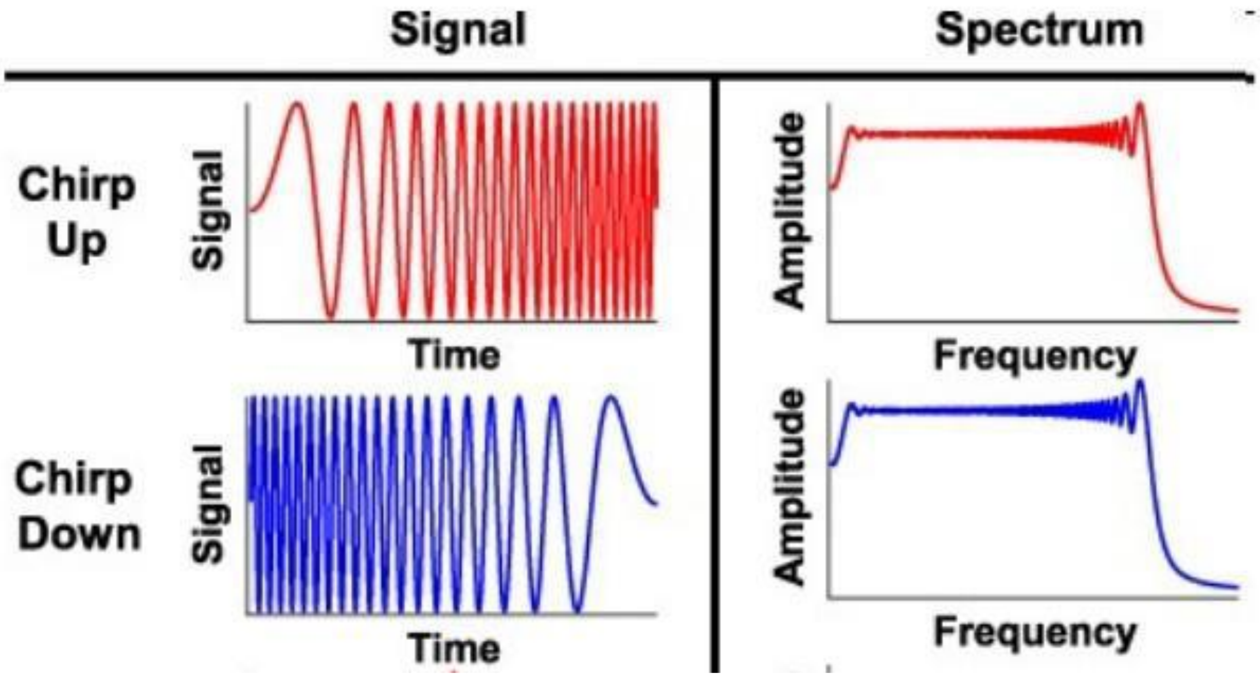
- **Features**
  - Modulation
    - Chirp Spread Spectrum (CSS) with a typical channel bandwidth of 125KHz
  - High Sensitivity
    - End Nodes: Up to -137 dBm, Gateways: up to -142 dBm
  - Long range
    - up to 15 Km
  - Strong indoor penetration
    - With High Spreading Factor, Up to 20dB penetration (deep indoor)
  - Robust to channel noise
    - Occupies the entire bandwidth of the channel to broadcast a signal
  - Resistant to doppler effect multi-path and signal weakening.

LoRa

- **Spectrum usage**
  - Europe
    - 863 to 868 MHz and 434 MHz
    - Duty cycle limitations: 0.1%, 1% and 10%
  - US
    - 902 to 928 MHz
    - 400 ms max dwell time per channel (SF 7 to SF 10 at 125 kHz)

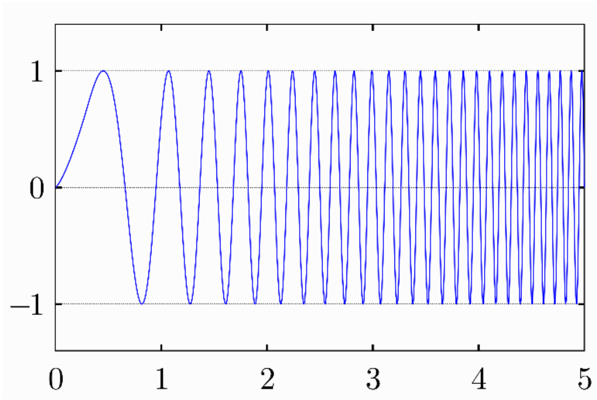
LoRa physical layer

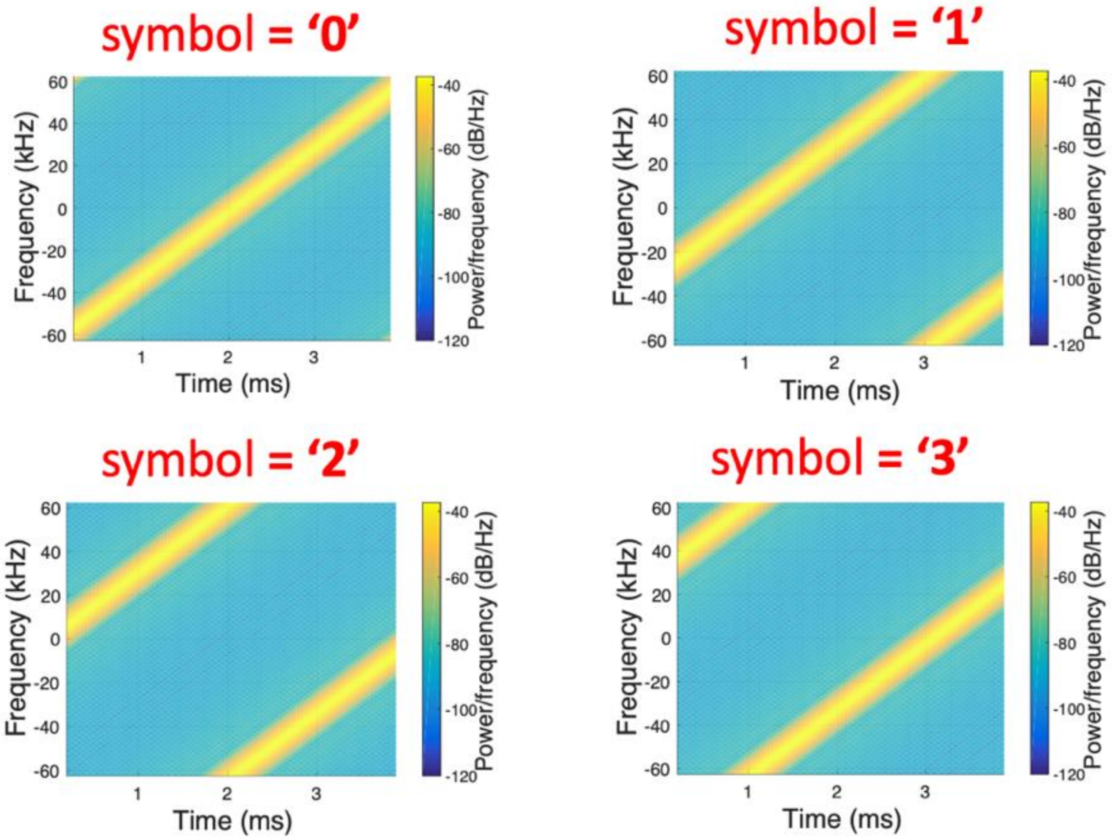
- Modulation - CSS (Chirp Spread Spectrum)



- Upper layers defined in **LoRaWAN**

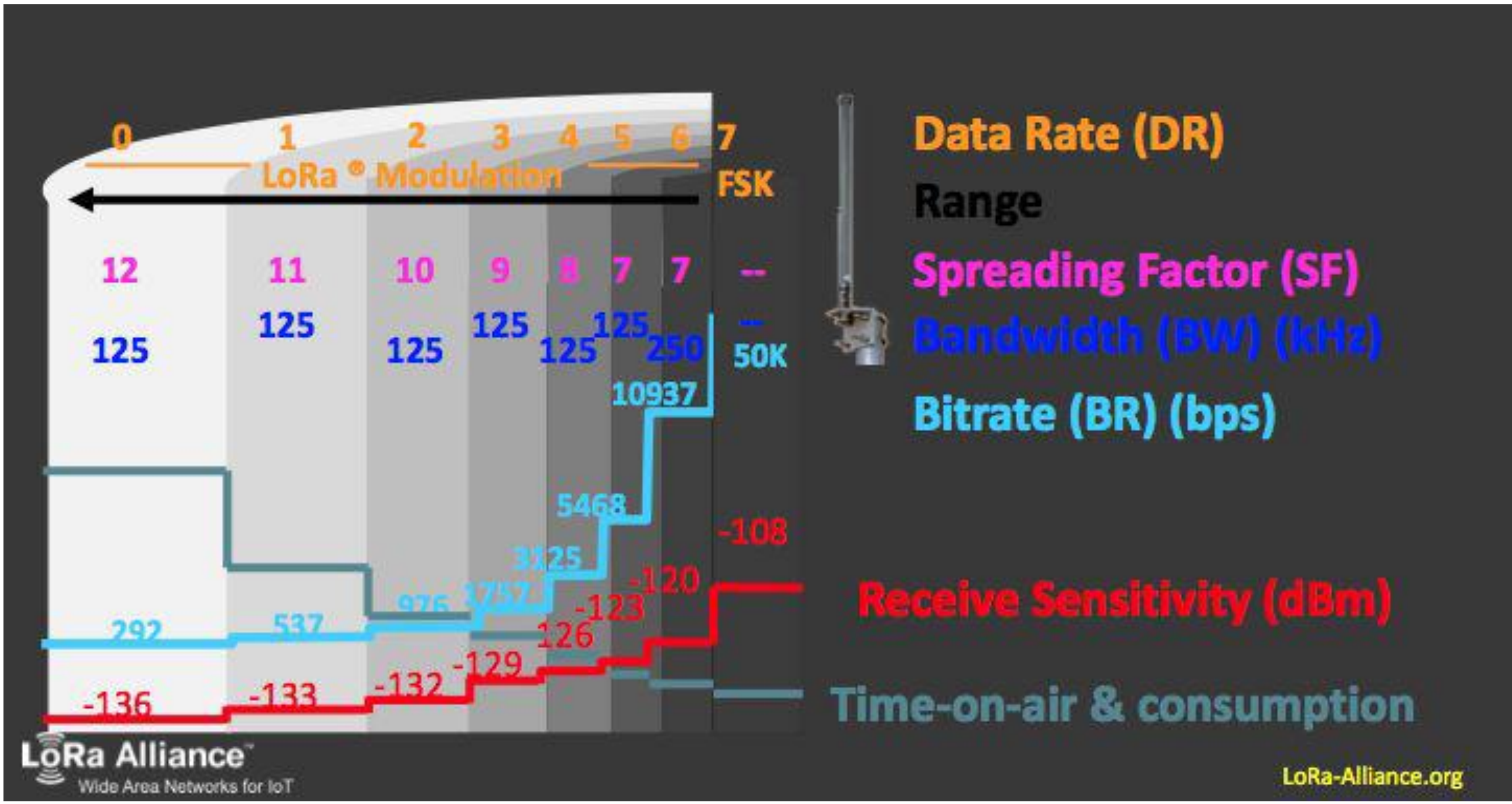
LoRa


1
0
−1
0
1
2
3
4
5


symbol = '0'
symbol = '1'
symbol = '2'
symbol = '3'
Frequency (kHz)
Time (ms)
Power/frequency (dB/Hz)

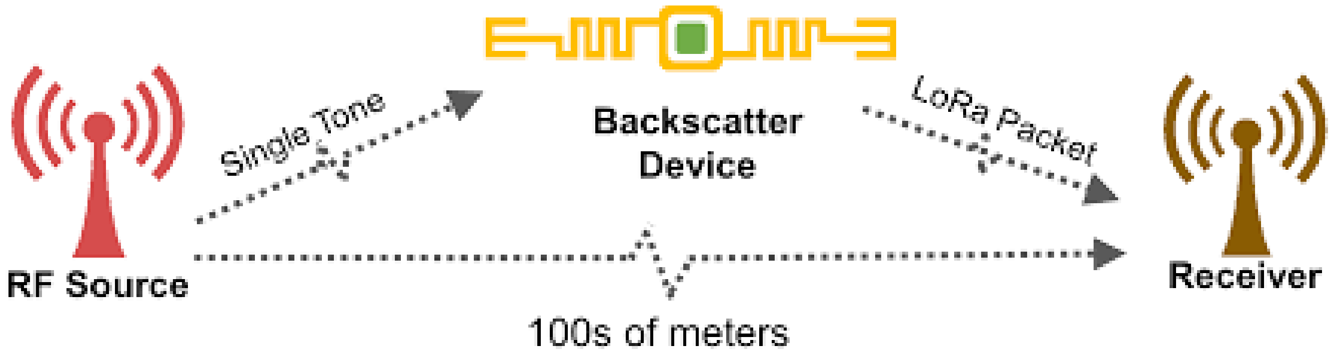
- **Chirp spread spectrum advantages**
  - Long range
  - Great link budget, low power transmission
  - Resistant to multipath and other interference
  - Orthogonality of spreading factors
  - Simplified electronic for receiver synchronization
  - Robust against Doppler shift (mobile applications)

LoRa



0
1
2
3
4
5
6
7
LoRa ® Modulation
FSK
Data Rate (DR)
Range
12
11
10
9
8
7
7
--
Spreading Factor (SF)
125
125
125
125
125
125
250
--
50K
Bandwidth (BW) (kHz)
10937
5468
3125
1757
976
537
292
Bitrate (BR) (bps)
-108
-120
-123
-126
-129
-132
-133
-136
Receive Sensitivity (dBm)
Time-on-air & consumption
LoRa Alliance
Wide Area Networks for IoT
LoRa-Alliance.org

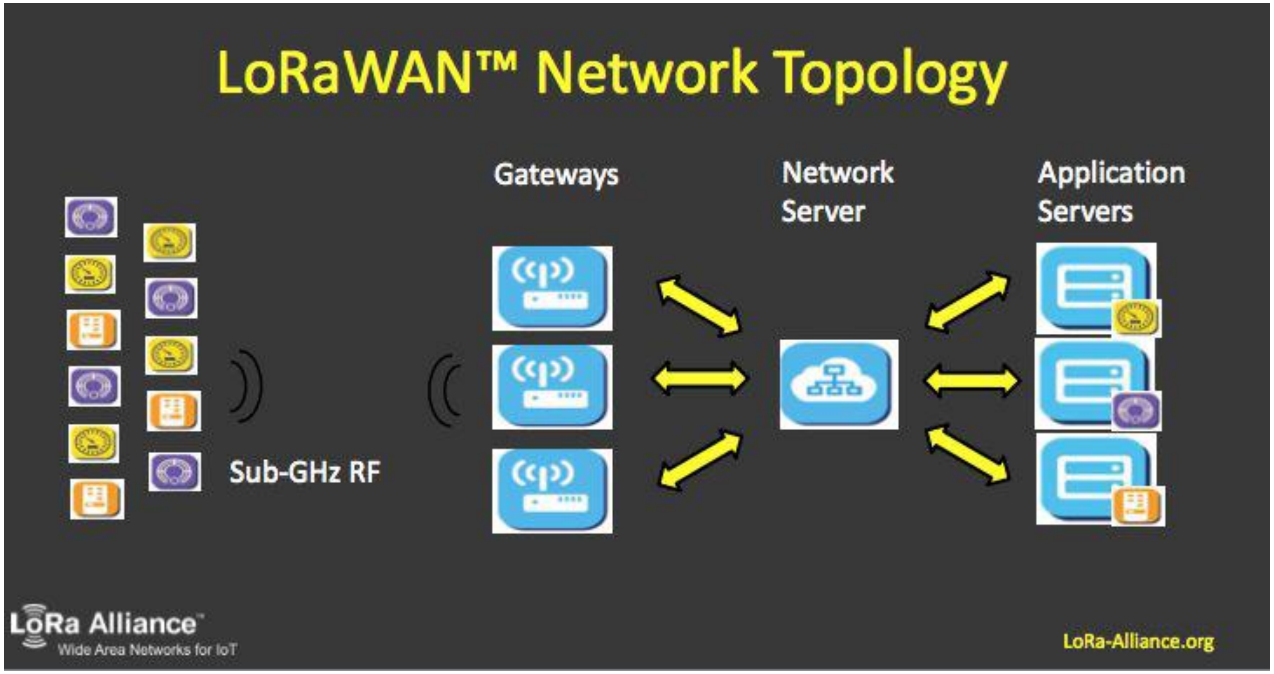
LoRa backscatter



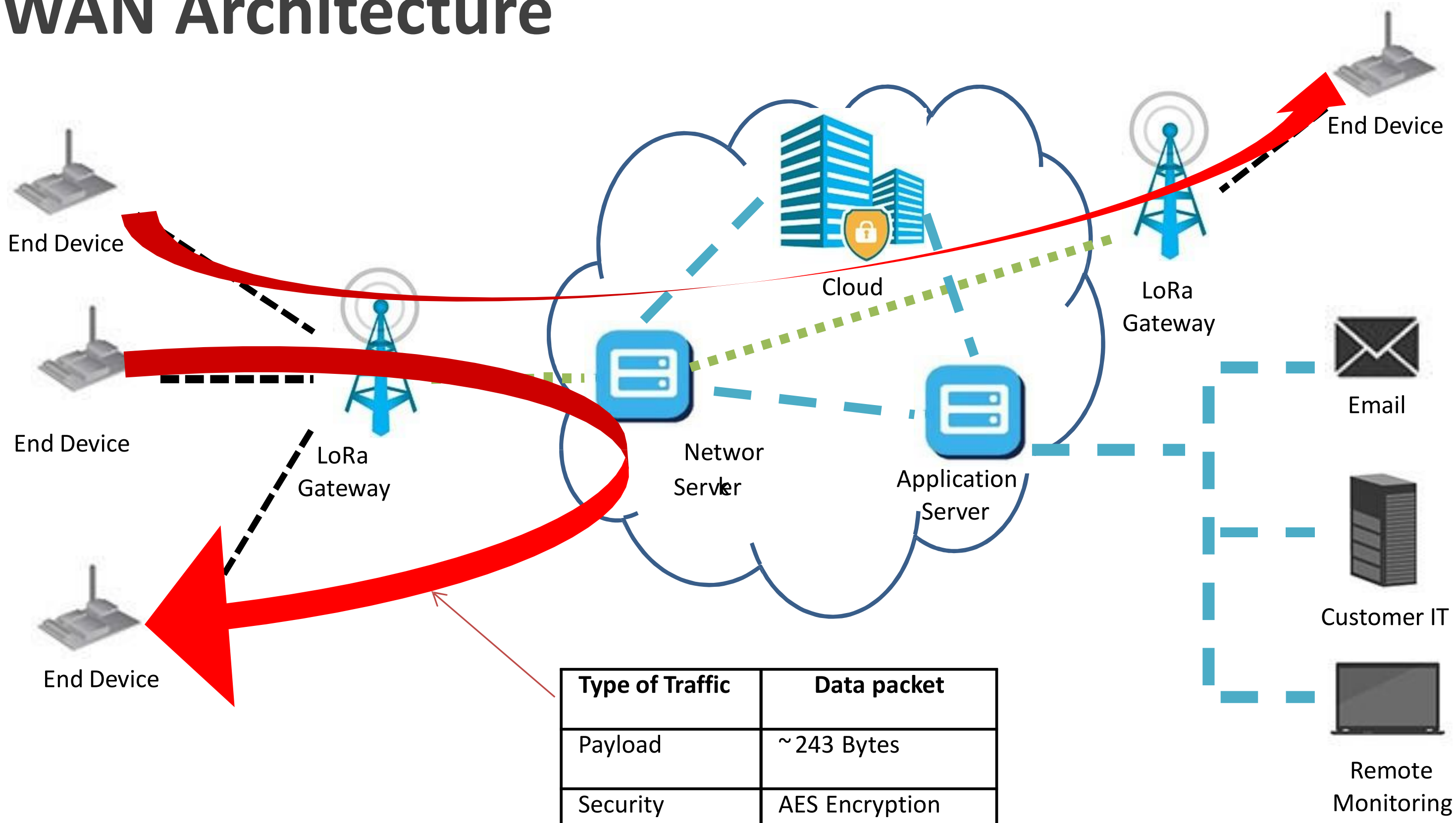
- Piggybacking data on an existing RF signal
- Self interference handled by frequency shifting and harmonic cancellation

LoRaWAN

- Communication protocol that uses LoRa physical layer
- Supports
  - Secure bidirectional traffic
  - Mobility
  - Localization



LoRaWAN Architecture



Type of Traffic	Data packet
Payload	~243 Bytes
Security	AES Encryption

Modulation	LoRa RF (Spread Spectrum)
Range	~15 Km
Throughput	~50 Kbps

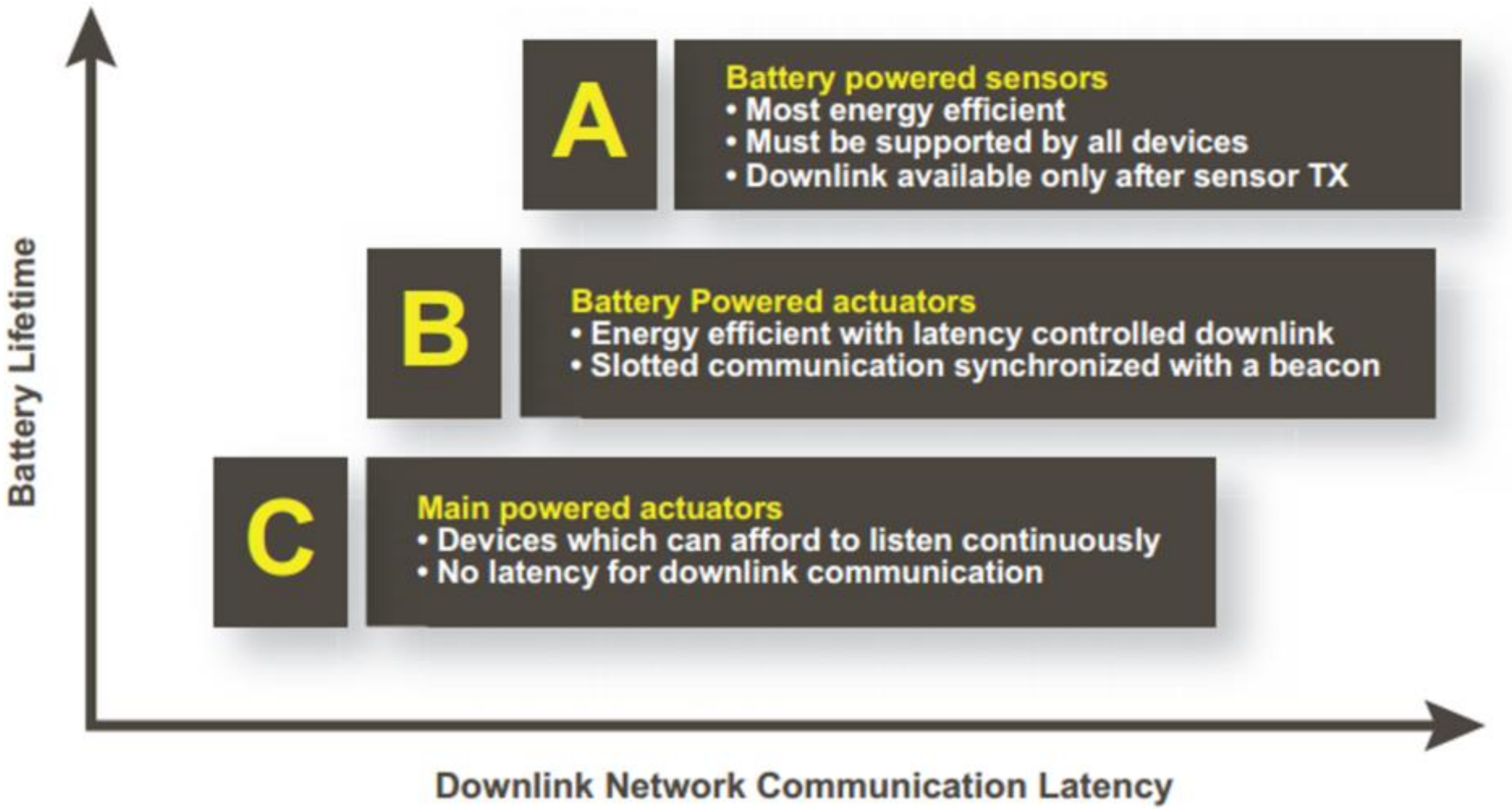
LoRaWAN

- Star-of-stars topology
  - Gateways
    - Relay messages between end-devices and a central network server
    - Connected to the network server via standard IP connections
  - End devices
    - Use single-hop LoRa or FSK communication to one or many gateways.
- All communication is generally bi-directional
  - Uplink communication from an end device to the network server is expected to be the predominant traffic
- To maximize both battery life and overall network capacity, the LoRa network infrastructure can manage the data rate and RF output for each end-device individually by means of an adaptive data rate (ADR) scheme

LoRaWAN Messages

- Uplink message
  - Sent by end-devices to the network server relayed by one or more gateways
- Downlink message
  - Sent by the network server to only one end-device and is relayed by a single gateway
- Confirmed-data message
  - Has to be acknowledged by the receiver
- Unconfirmed-data message
  - Does not require an acknowledgment

- **Down-stream transmission modes**



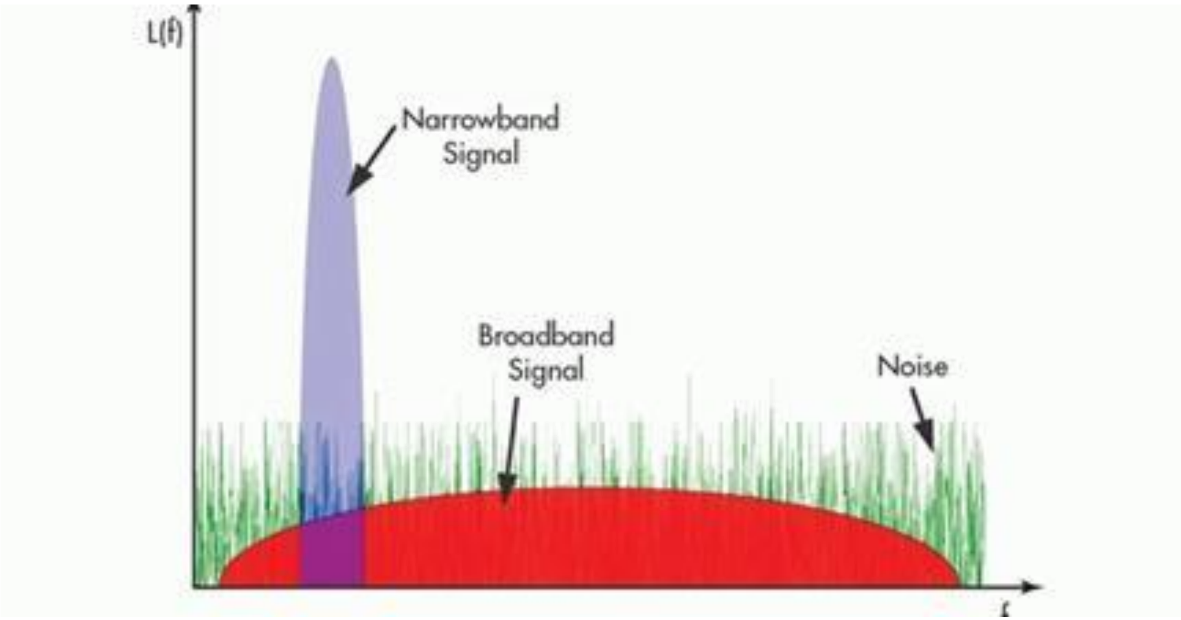
SIGFOX

- **Sigfox**
  - First LPWAN technology
  - Deploy its own base stations to support IoT applications
    - Kilo meter communication distance
    - Connect thousands of devices
    - 868 MHz in Europe, 915 MHz in US
    - Maximum of 140 messages/day, 12 bytes long on a 100 Hz channel, 100 b/s UL
    - Ultra-narrow band, BPSK UP, GFSK DL, 600 b/s
    - Mobility restricted to 6 km/h
    - 5 years lifetime

SIGFOX

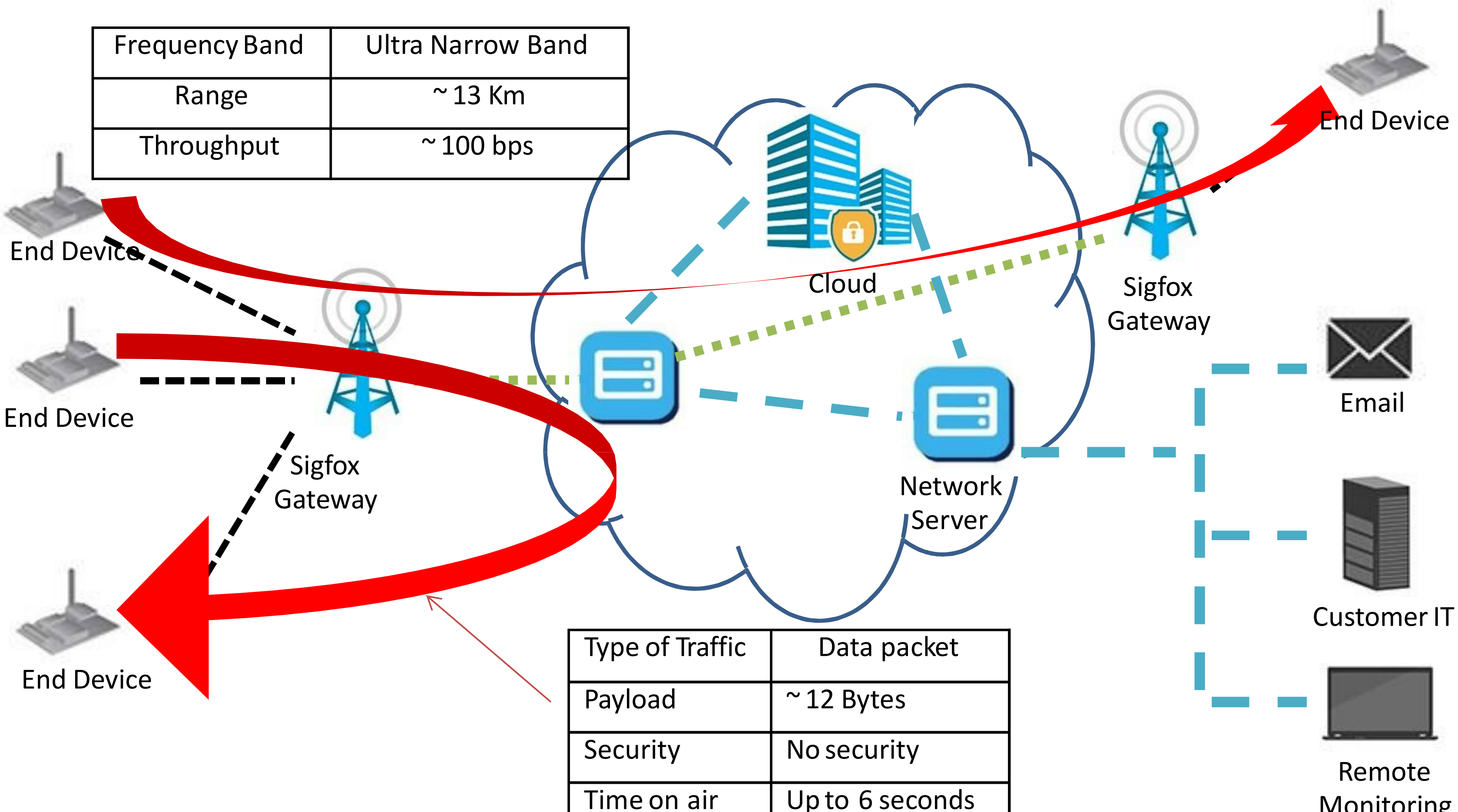
- **Repetition of the message**
  - Each message sent 3 times
  - Repetition at 3 different time slot = time diversity
  - Repetition at 3 different frequencies = frequency diversity
- **Collaborative network**
  - Network deployed and operated to have 3 base stations coverage at all times = space diversity
- **Minimization of collisions**
  - Probability of collisions are highly reduced
  - Ultra Narrow Band
  - 3 base stations at 3 different locations

- **Ultra Narrow Band**
  - Reduce the transmitted signal bandwidth
    - Reduced noise power
    - Therefore, we can reduce the transmission power
    - Therefore, we can reduce the power consumption of radio communication



SIGFOX

Architecture



Frequency Band	Ultra Narrow Band
Range	~ 13 Km
Throughput	~ 100 bps

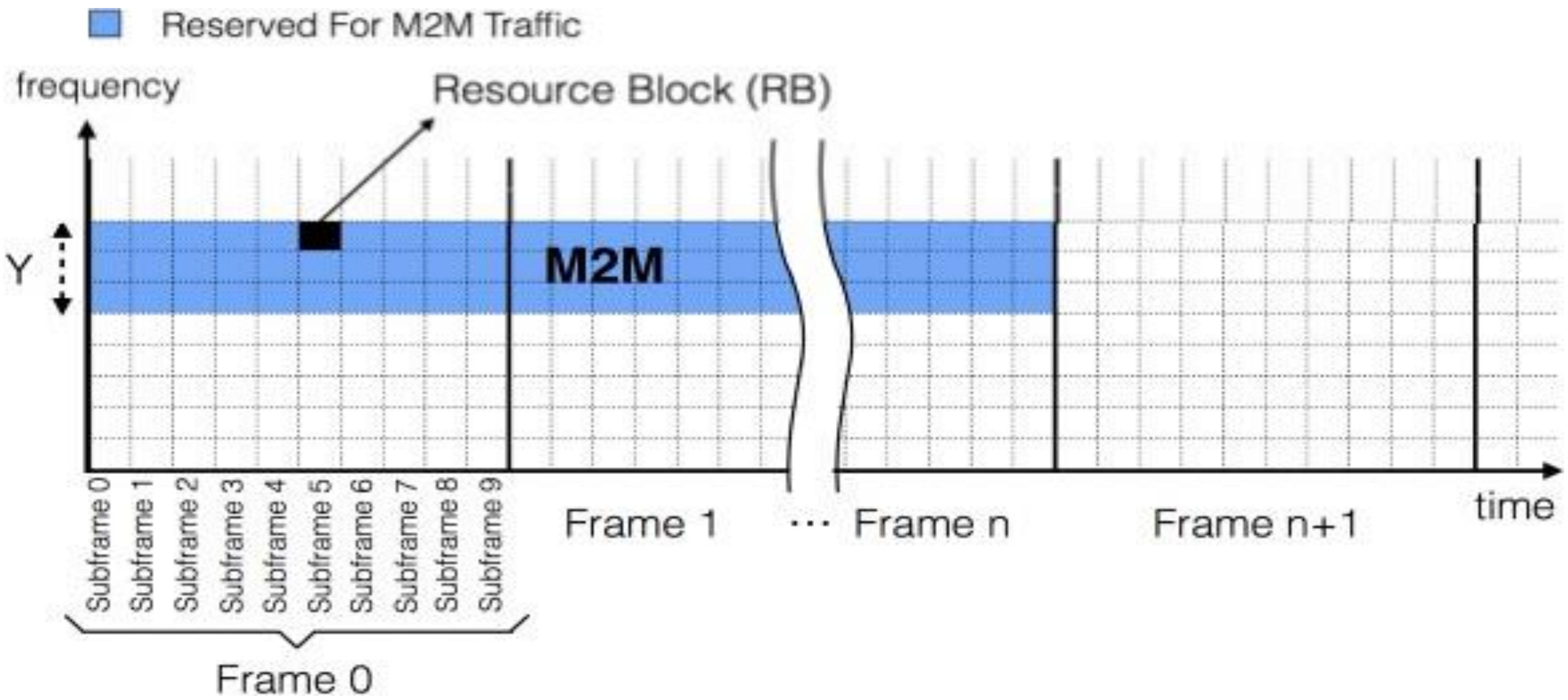
Type of Traffic	Data packet
Payload	~ 12 Bytes
Security	No security
Time on air	Up to 6 seconds

LTE-M

- **Overview**
  - Evolution of LTE optimized for IoT
  - Licensed Spectrum
  - Low power consumption and autonomous
  - Easy Deployment
  - Interoperability with existing LTE networks
  - Coverage up to 11 Km
  - Max Throughput ≤ 1 Mbps
  - Frequency Bands: 700-900 MHz for LTE
  - Some resource blocks are allocated to IoT on LTE bands

LTE-M

- Some resource blocks are allocated to IoT on LTE bands



LTE to LTE-M

3GPP Releases	8 (Cat.4)	8 (Cat. 1)	12 (Cat.0) LTE-M	13 (Cat. 1,4 MHz) LTE-M
Downlink peak rate (Mbps)	150	10	1	1
Uplink peak rate (Mbps)	50	5	1	1
Number of antennas (MIMO)	2	2	1	1
Duplex Mode	Full	Full	Half	Half
UE receive bandwidth (MHz)	20	20	20	1.4
UE Transmit power (dBm)	23	23	23	20

Release 12

- New category of UE ("Cat-0"): lower com plexity and low cost devices
- Half duplex FDD operation allowed
- Single receiver
- Lower data rate requirement (Max: 1 Mbps)

Release 13

- Reduced receive bandwidth to 1.4 MHz
- Lower device power class of 20 dBm
- 15dB additional link budget: better coverage
- More energy efficient because of its extended disco ntinuous repetition cycle (eDRX)

NB-IoT

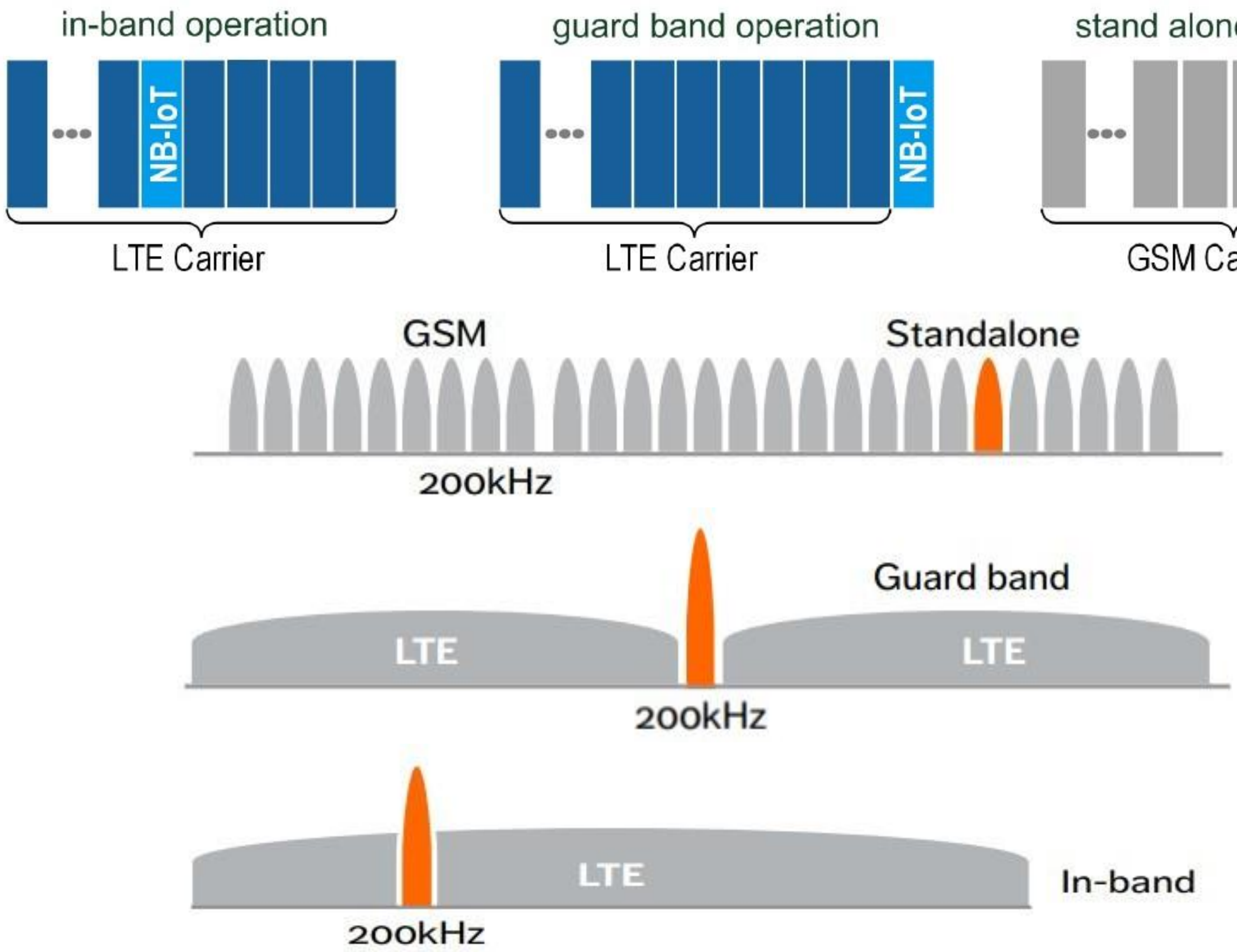
April 2014	May 2014	March 2015	August 2015	November 2015	Jun 2015	2017+
Narrowband proposal to Con nected Living	3GPP 'Cellular IoT' S tudy Item	GSMA Mobile IoT created	3GPP align ment on sin gle standar d	1st ive pre-stand ard NB-IOT mess age NB-IoT	Full 3GPP Standard Released	Commercial rollout

A GLOBAL INITIATIVE

NB-IoT

- **Overview**
  - 3GPP backed, based in LTE
  - Licensed spectrum
    - 180 kHz bidirectional channels, in band or in guard bands
  - Optimized for low end of IoT
  - Excellent indoor coverage
  - Support of a massive number of connections
    - Up to 50,000 devices per NB-IoT network cell
  - Cost efficiency
    - Lower cost than eMTC
  - Low device power consumption
    - 10 years with 5 Wh battery
  - Increasing coverage range
  - Optimized for low end of IoT

- **Spectrum & access**



NB-Iot vs. LTE-M

Comparison of LTE-M and NB-IoT Capabilities

	LTE-M	NB-IoT
Also known as	eMTC, LTE Cat-M1	LTE Cat-NB1
Specification	Based on LTE	Based on a subset of LTE
Bandwidth	1.08 MHz (equivalent to an LTE channel)	180 kHz (fits into a GSM channel)
Max throughput	360 kbps	30/60 kbps
Network deployment	Relatively easy for operators to add to existing LTE networks	Easier for operators with GSM networks to incorporate
Frequency deployment	LTE in-band	LTE in-band, LTE guard band and GSM repurposing
Voice/data support	Voice and data	Data only
Range	Up to 4x	Up to 7x
Mobility/cell reselection	Yes	Limited
Module size	Suitable for wearables	
Power consumption	Up to 10 years of battery lifetime	

qorvo

IoT COMMUNICATION PROTOCOLS

Protocols

Technology	Sensitivity	Data rate	Spectrum Strategy
WiFi (802.11 b,g)	-95 dBm	1-54 Mb/s	Wide Band
Bluetooth	-97 dBm	1-2 Mb/s	Wide Band
BLE	-95 dBm	1 Mb/s	Wide Band
ZigBee	-100 dBm	250 kb/s	100 m
SigFox	-126 dBm	100 b/s	Ultra Narrow Band
LoRa	-149 dBm	18 b/s - 37.5 kb/s	Wide Band
Cellular data (2G,3G)	-104 dBm	Up to 1.4 Mb/s	Narrow Band