EE-432
Systeme de Telecommunication

Prof. Andreas Burg
Joachim Tapparel, Yuqing Ren, Jonathan Magnin

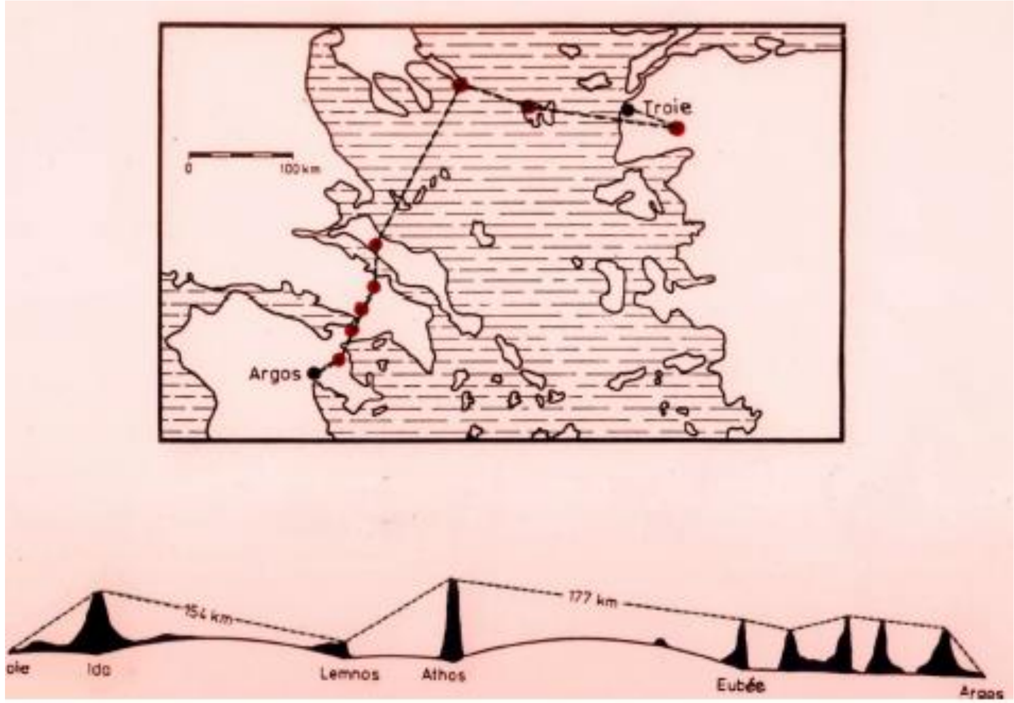
Background

The Earliest Communication Marvels and Fairy Tales

Convey information more rapidly than by physical message transport

Best solution: optical signalling, but with issues

- Distance is relevant, but not the main issue
- Visibility conditions
- Obstacles
- Curvature of the earth



Example: Trojan War Legend

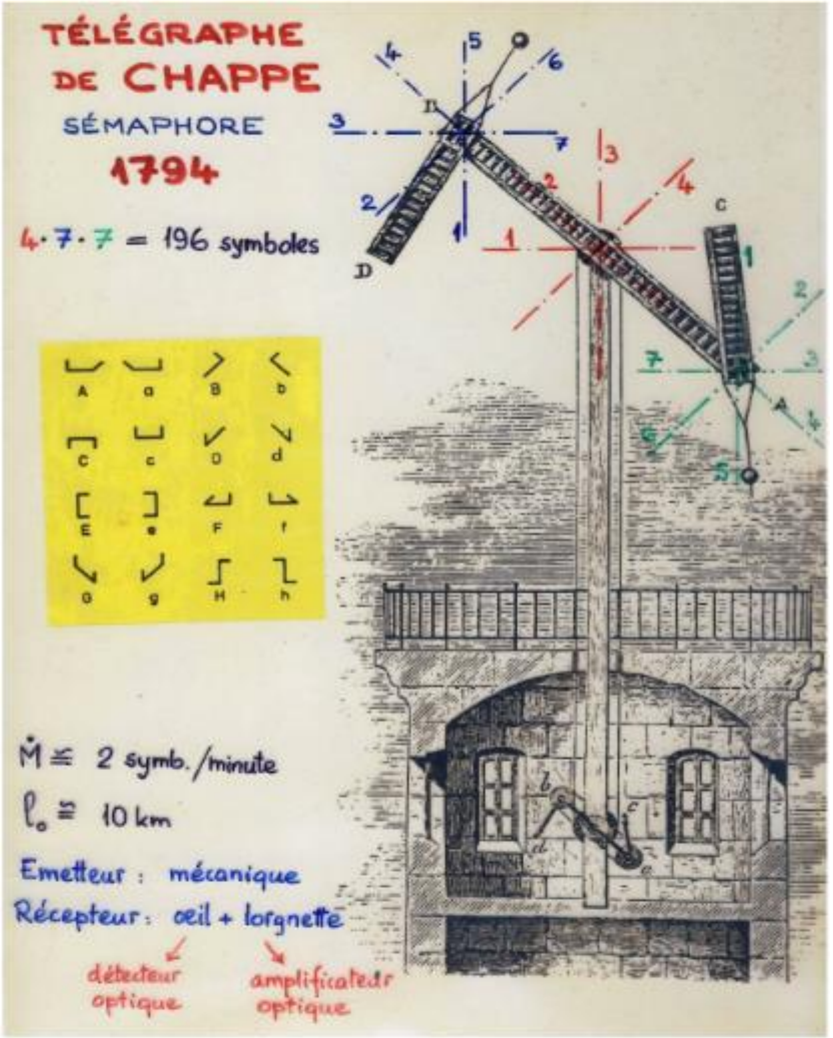
- Mentioned in Greec Mythology, 500 b.c. By Homer in Iliad and Odyssey
- Victory at Troja was aledgetly communicated via 8 light houses (“Fryktories”), some up to 177 km apart
- Surprising: Total energy to be spent on creating light signals > 7 kW or **100 m2** of fire

More Sophisticated Versions into the 18th/19th Century

Idea of conveying messages visually prevailed, as light was the only “signal” that could be “transmitted” without technology

1794: De Chappe Telegraph

- **“Multi-level (multi-dimensional) signalling”, symbols referred to as “semaphore”**
- **First line between Paris and Lille:**
  225 km, 22 stations
- **More lines quickly established**
- **Message latency examples:**
  - Paris – Brest: 7 minutes
  - Berlin – Cologne 10 minutes



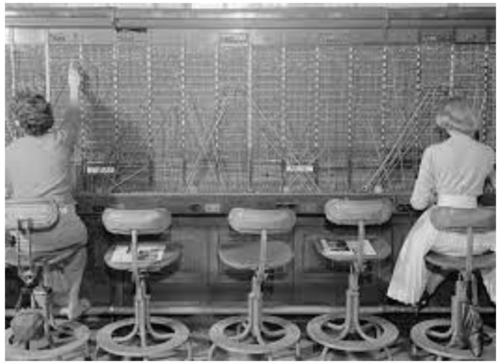
Electricity Revolutionizes the Telegraph Mid 19th Century

- **1833: Gauss, Weber** — **Electromagnetic Telegraph**
- **1836: Morse** — **Ternary "Morse Code"**
- **1857:** — **First Transatlantic telegraph line** (4'000 km, worked 20d)
- **1866:** — **2nd Transatlantic telegraph line**
- **1870:** — **Aerial Line from Calcutta to London** (10'000 km)

Biggest Issue: No means for amplification

- 1876: A. G. Bell — Invention of the Telephone

- 1885 - ... — Rollout of "Telephone Networks"



Foundations of Wireless Communication

Fundamentals based on the research of Maxwell (1865) & Hertz (1886)

Theoretical description of electromagnetic radiation
Heinrich Hertz

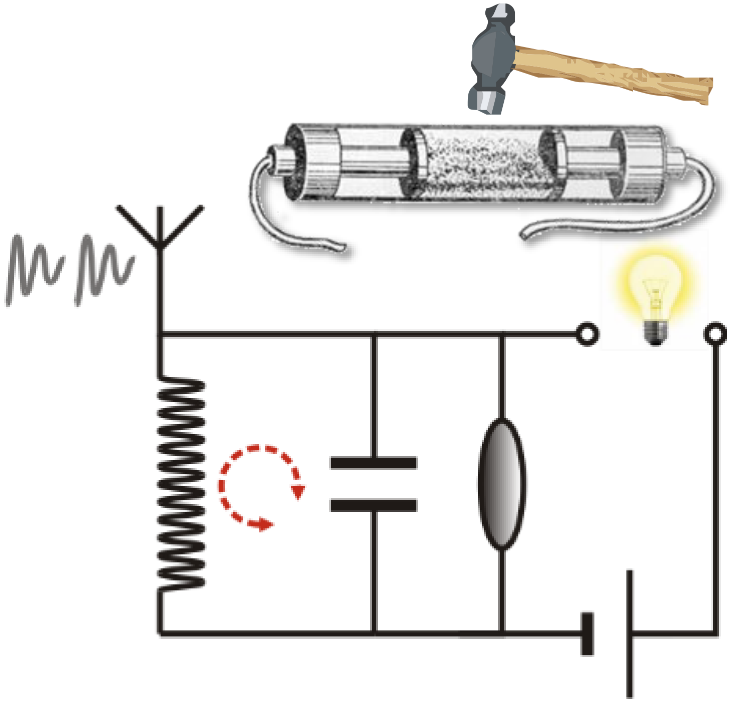
Demonstration of electromagnetic radiation
James Maxwell

„I do not think that the wireless waves I have discovered will have any practical application“

History & Milestones

Wireless systems have come a long way from their first inception

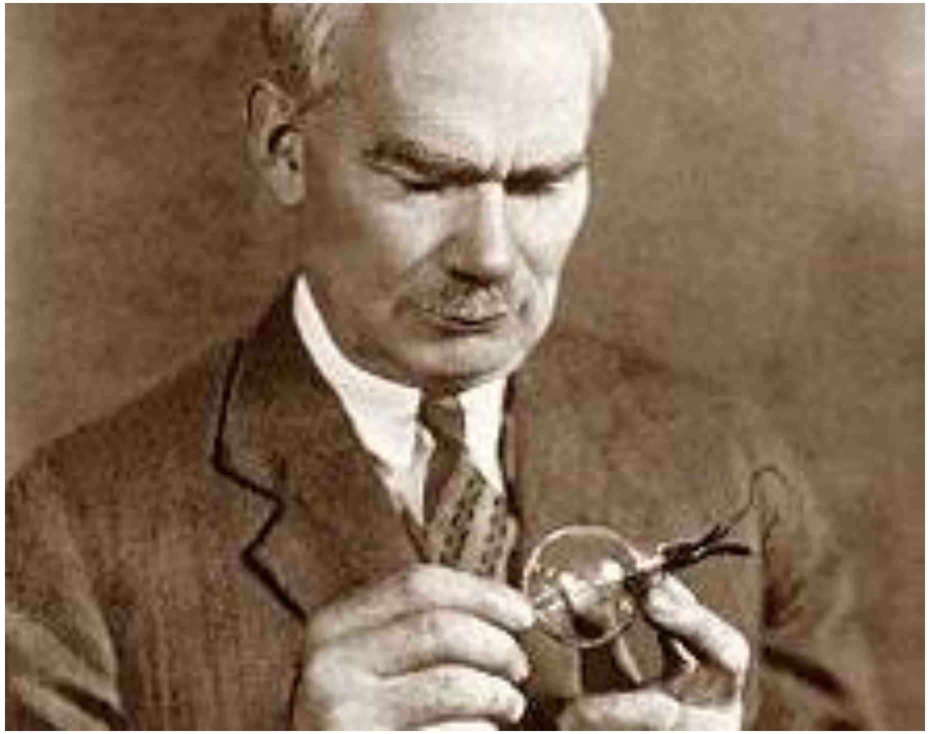
1895 wireless transmitter by Guglielmo Marconi



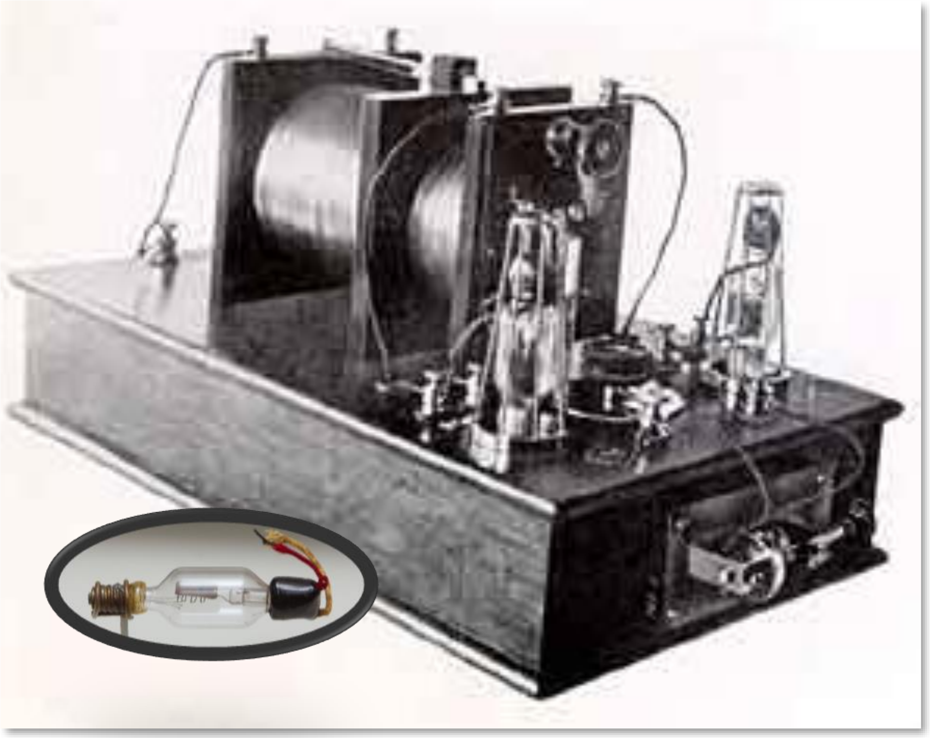
~1906 Primitive receiver without amplifier

History & Milestones

Wireless systems have come a long way from their first inception



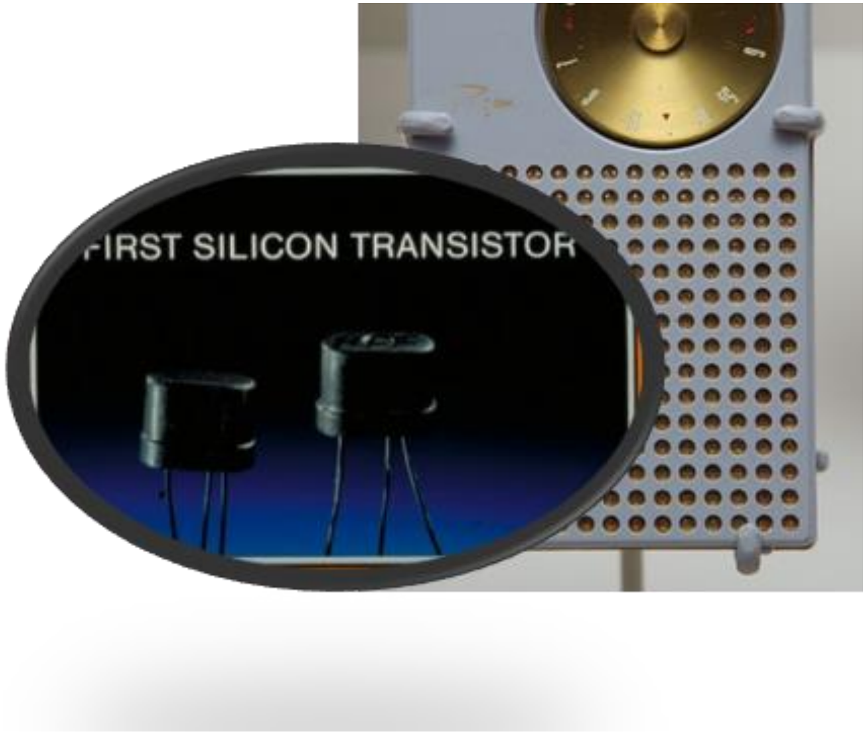
1906 Lee de Forest invented the vacuum tube



De Forest radio enabled by vacuum tubes (amplifiers)

History & Milestones

Wireless systems have come a long way from their first inception



1954 transistor radio
(Texas instruments)

1990s rise of the mobile phone
(2007 Apple iPhone)

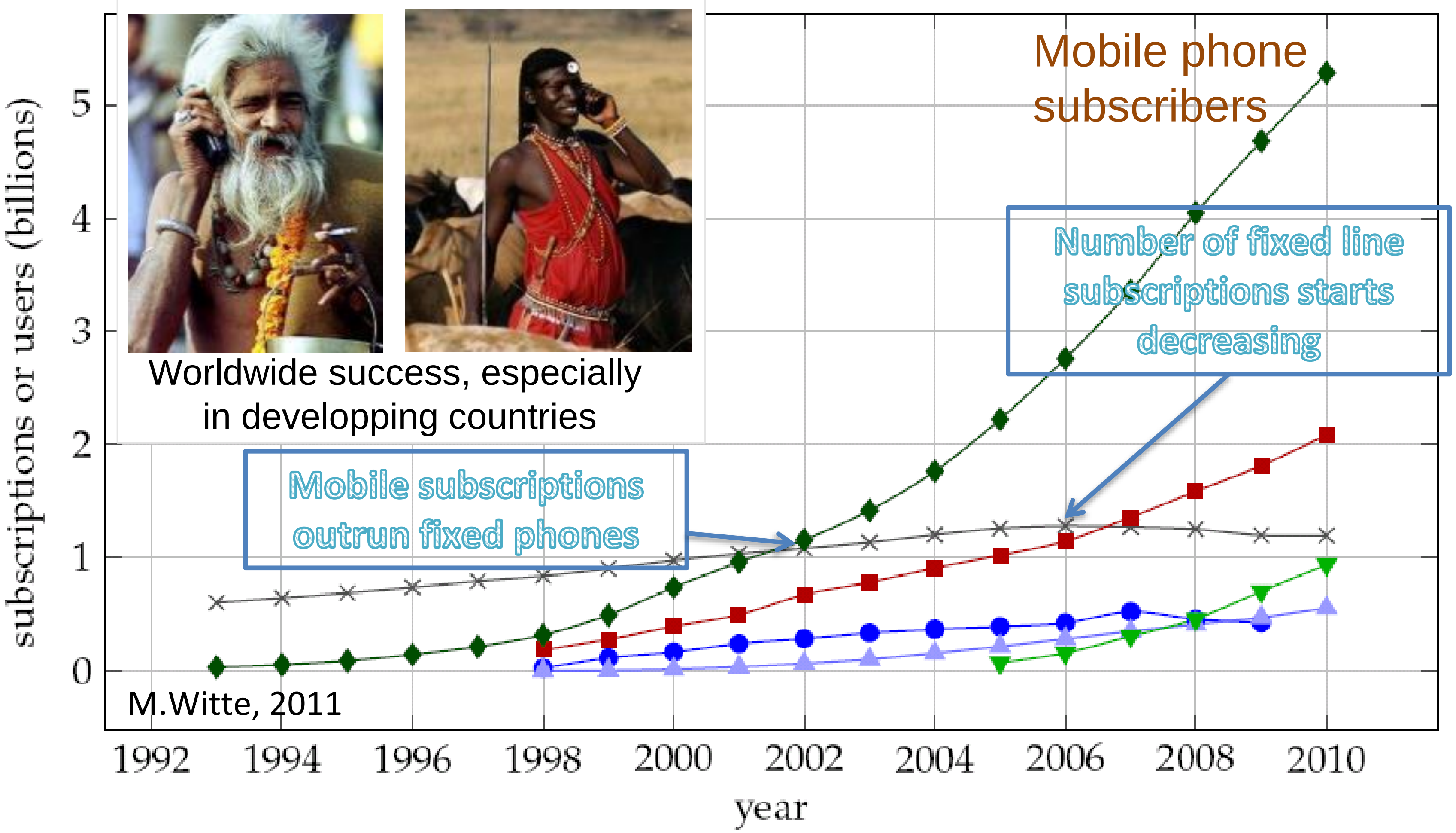
The Death of the Wire?

First true success of mobile communication (2G) was voice

1G

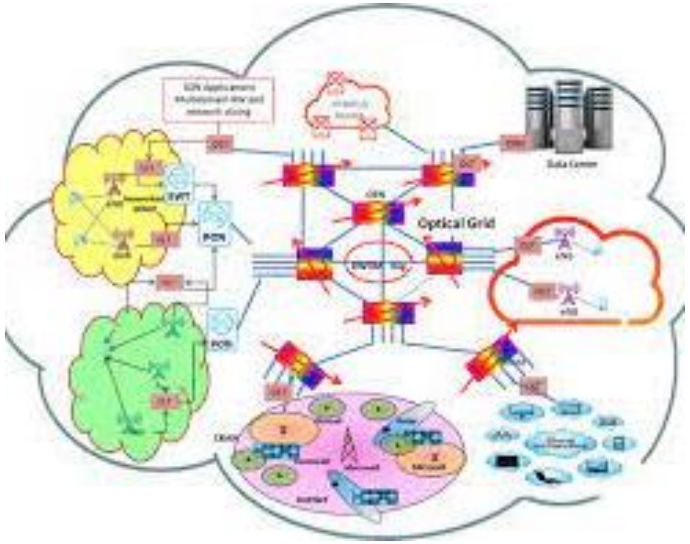
2G

1991



Under the Hood: “Fast Wires” More than Ever Needed

Wired links form the backbone of wireless systems and enable long distance and ultra-high speed communication



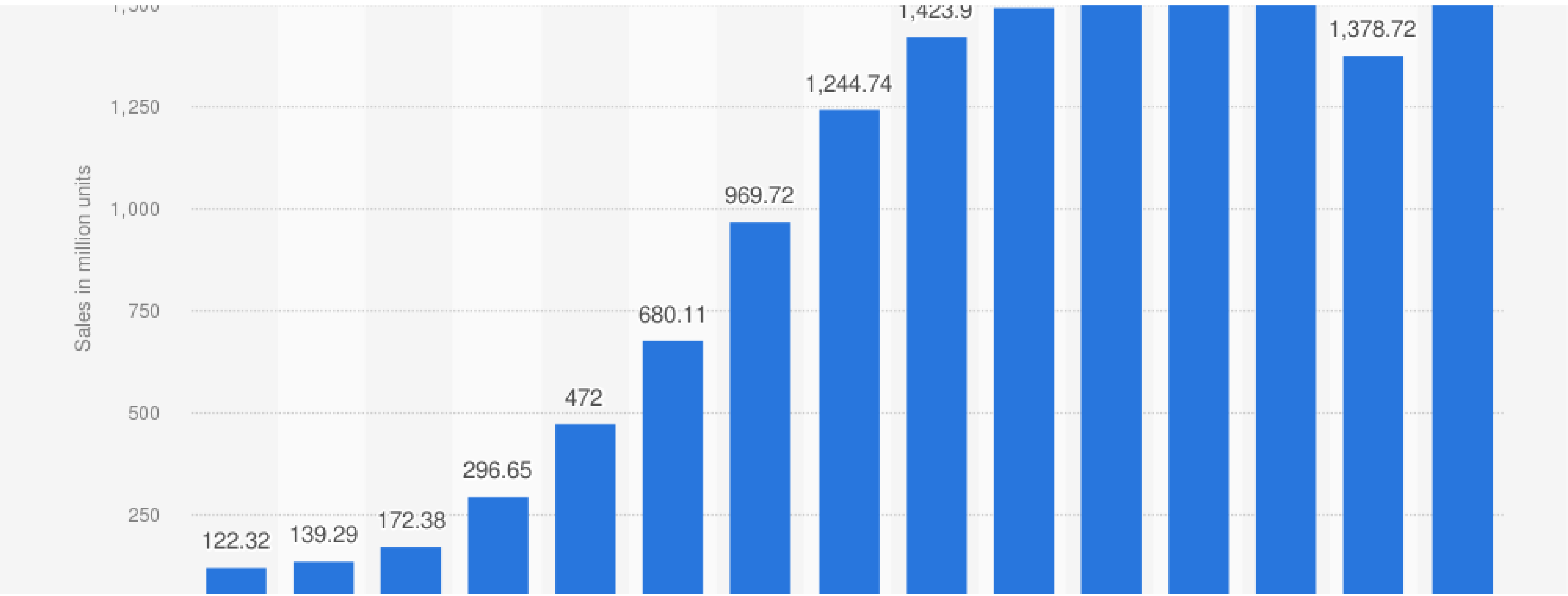
Connecting Sites in Cellular Networks

Internet Backbone

Data center/chip-to-chip links for very high speed

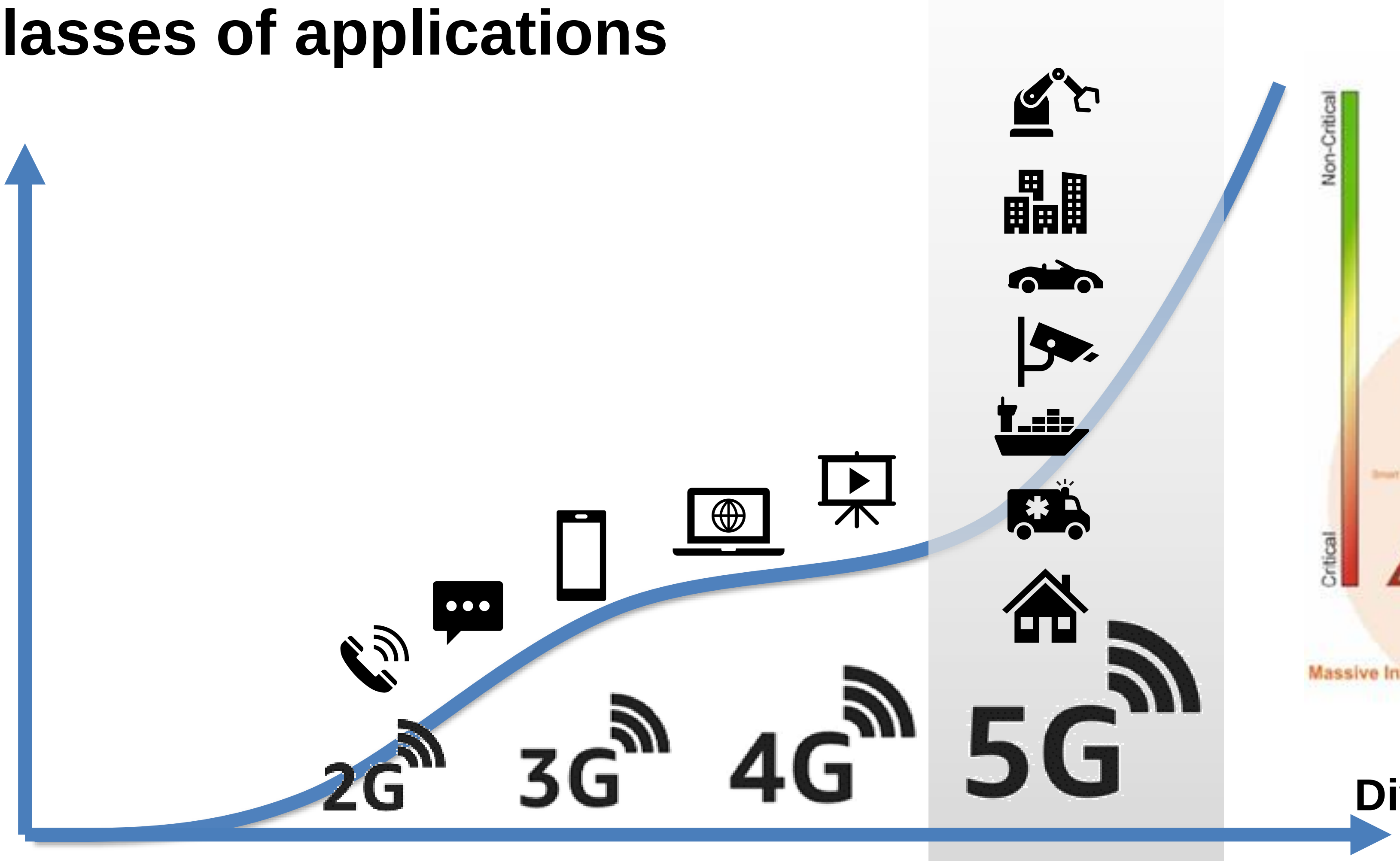
Huge Market

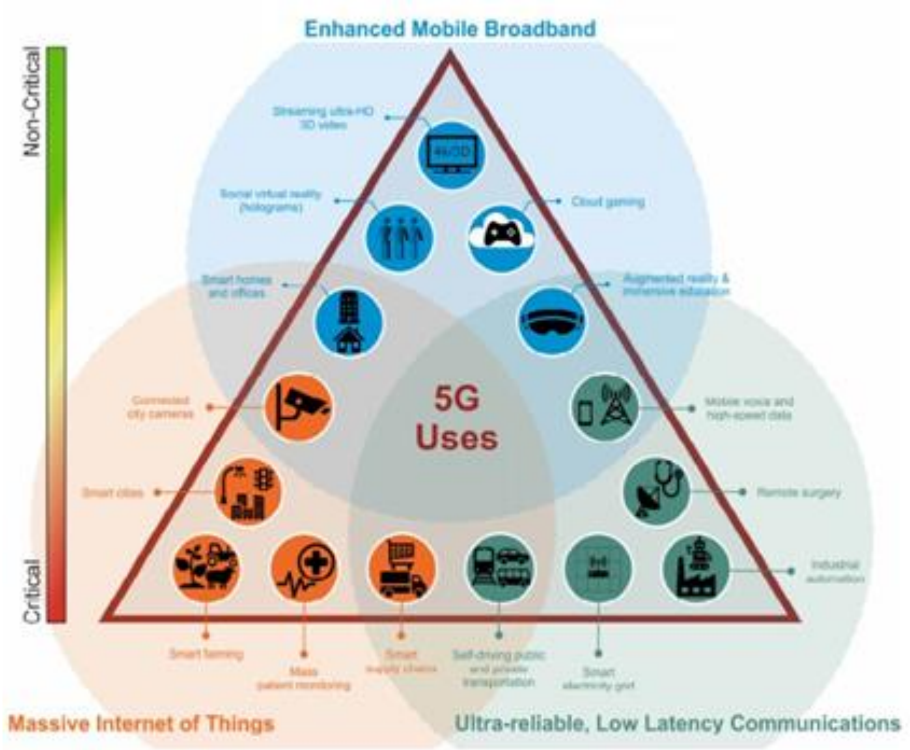
Annual sales of mobile phones alone is **in** the **billion units**



Evolution of 40 Years and 5 Generations

Continuous addition of new services tied to emergence of new classes of applications

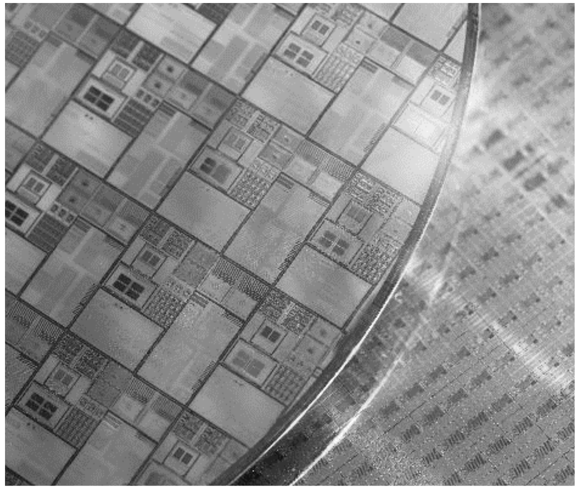




5G Recognizes Need for Diversification due to Conflicting Requirements

Technology Evolves and New Technologies Emerge

Evolution → **Revolution**

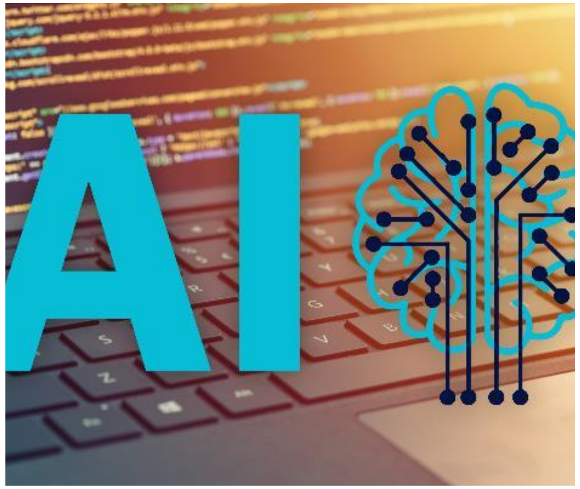


Semiconductor Technology

Nanometer CMOS, FinFET, EUV Lithography, 3D integration, …

Wireless Connectivity

Advanced signal processing, modulation and RF systems



Artificial Intelligence

Brian-inspired approach to computation

6G is on the horizon (planned for 2o3o)

Autonomous Mobility
Connecting ground-based and air-born vehicles to support autonomy and safety

Industry 4.0 and Industrial Robotics
Provide feedback and control for fully coordination between factory elements with ultra-high reliability and low latency

Immersive experience: AR/VR
Massive data rates and tactile latencies for seamless experience

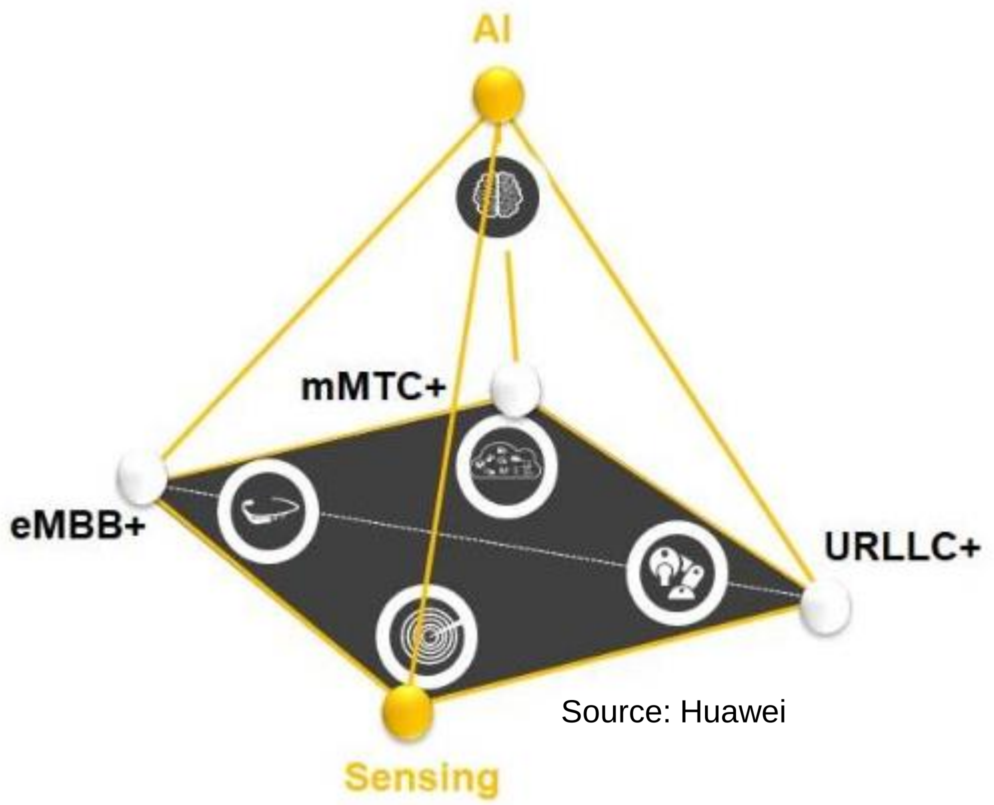
Intelligent and Autonomous Machines
Diverse requirements for an unexplored field with many, yet unknown applications

What to Expect from 6G

Evolution
improvements in familiar KPIs

KPIs	6G Objectives
User Experience	Gbps to 10s of Gbps (10x – 100x)
Peak Data Rates	10s of Gbps to Tbps (10x – 1000x)
Latency (PHY)	0.1ms – 1ms (10x)
Jitter	Micro seconds
Mobility	1’000 km/h (2x)
Reliability	99.9999% (100x)
Availability	Truly global
Spectrum efficiency	1.5x – 3x
Energy efficiency	10x – 20x

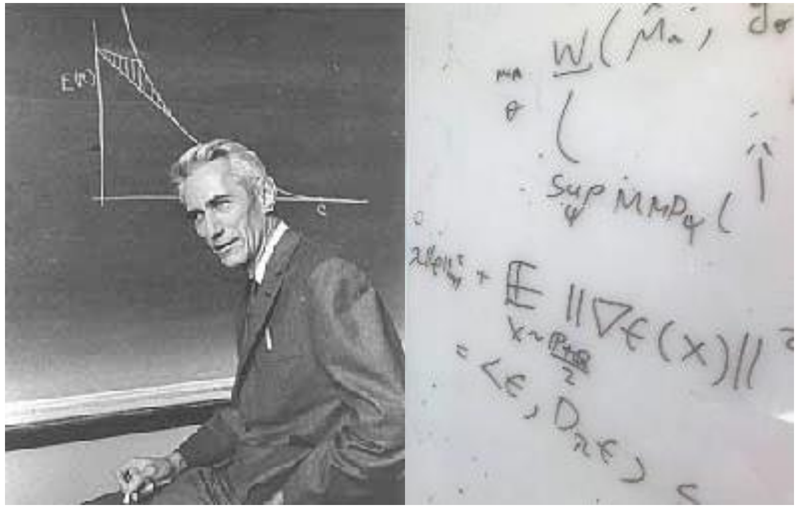
Revolution
new capabilities



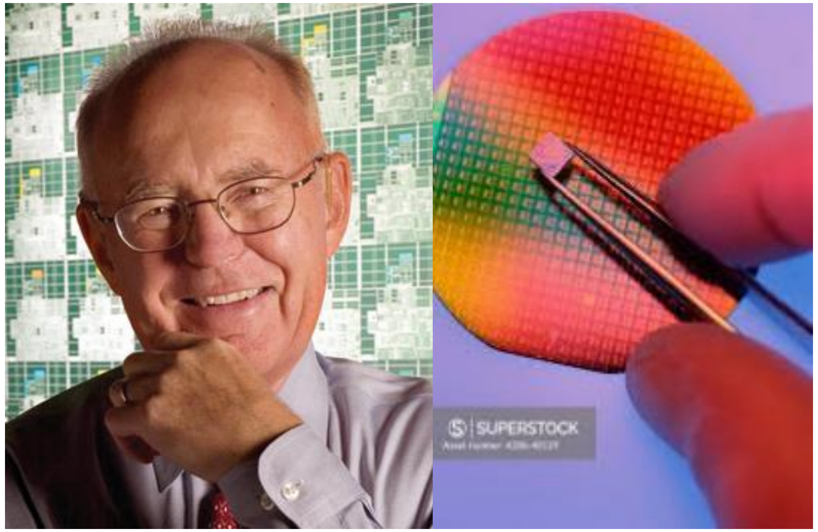
Source: Huawei

Enabling Technologies

Modern communication is built on a precise communication theory (Shannon) & dense integrated circuits (Moore's law)



A **precise mathematical** theory enables a systematic development



Dense integrated circuits allow for integration of complex algorithms

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Key Technology Components

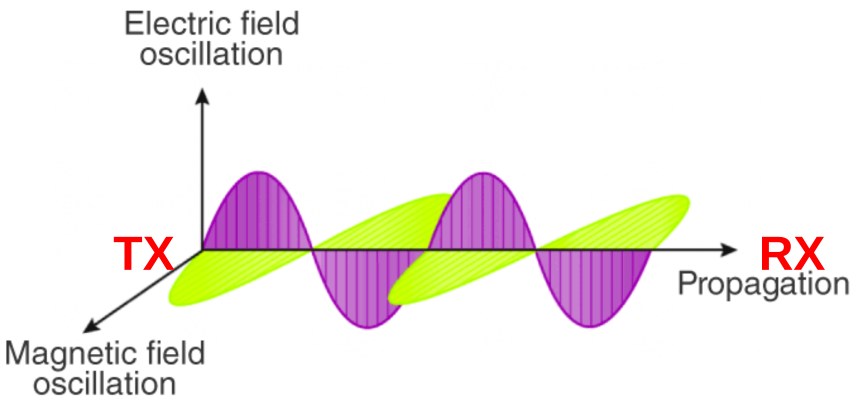
Radio Waves

Wireless communication is enabled by electromagnetic fields

- Think of a “field” as the “water level in a lake”

Electromagnetic waves: rapidly alternate the field in one place (TX)

- Waves propagate through the medium and can be sensed (“felt”) in another place (RX)



Radio Wave Propagation

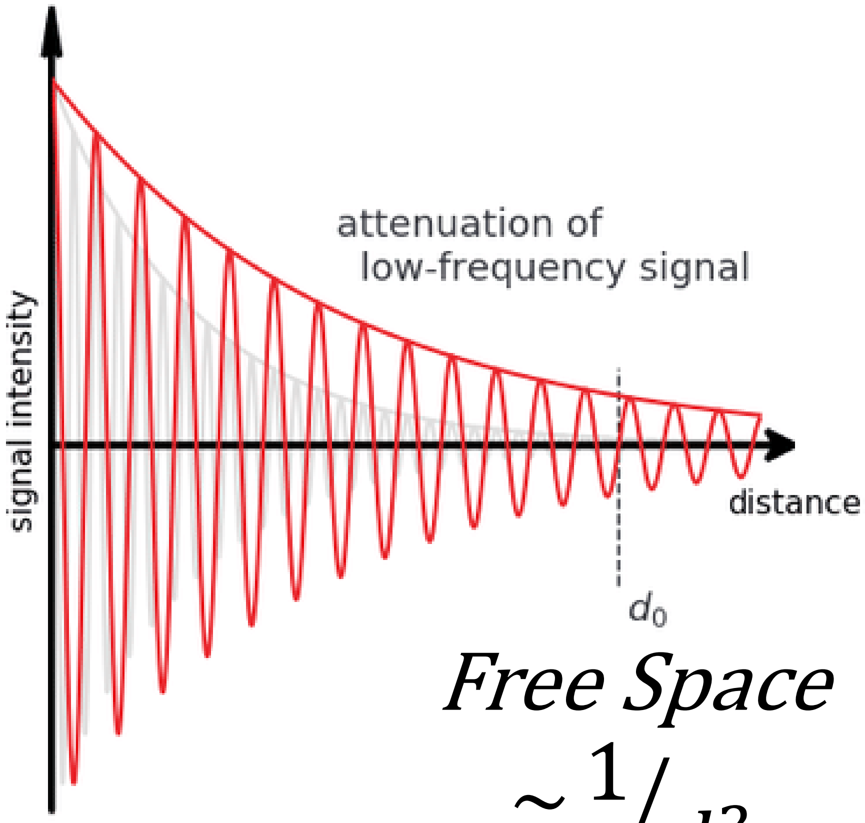
Radio waves propagate at the speed of light: 300’000 km/second

<0.15 seconds

0,000000003 seconds (3 ns) **for 1 meter**

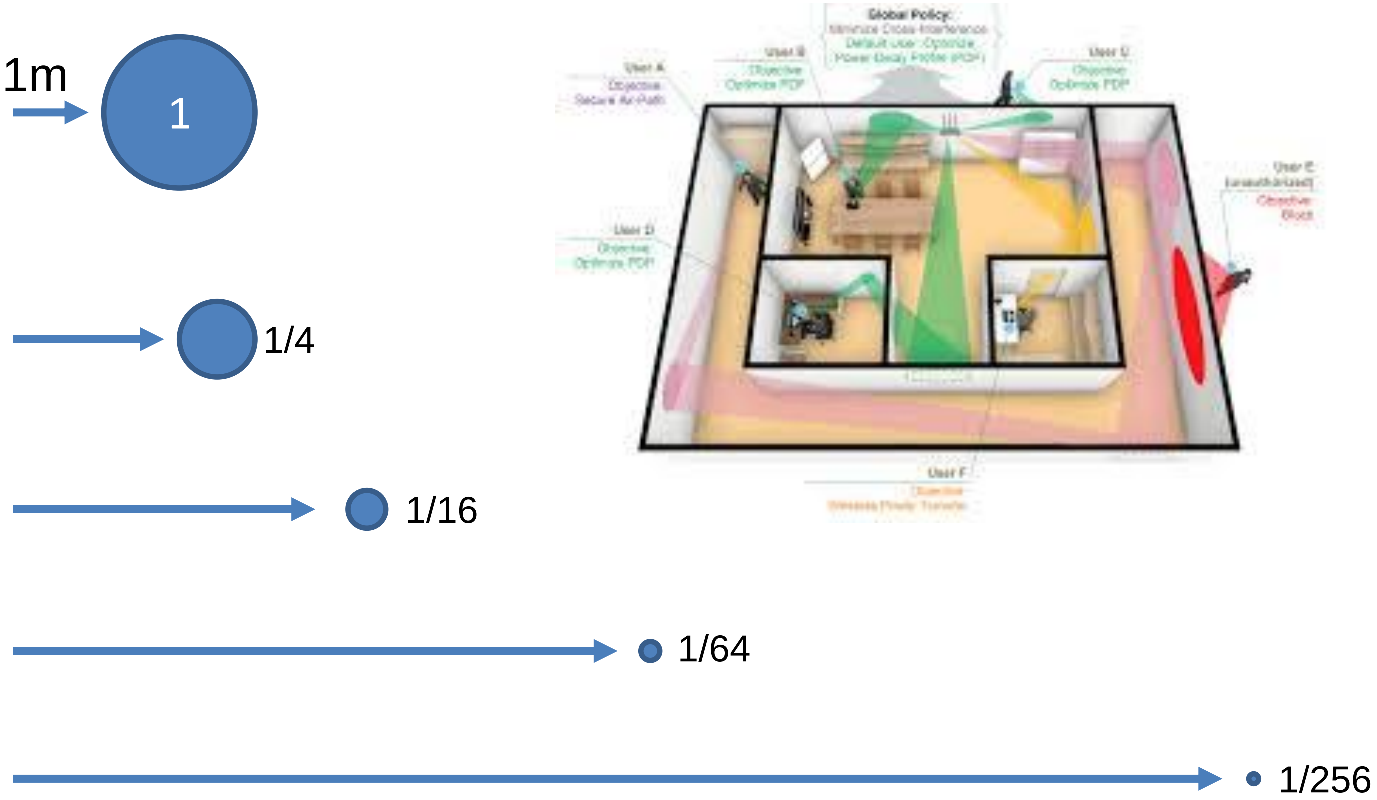
Radio Wave Propagation

Radio waves are also rapidly attenuated (become weaker) as they propagate



Free Space

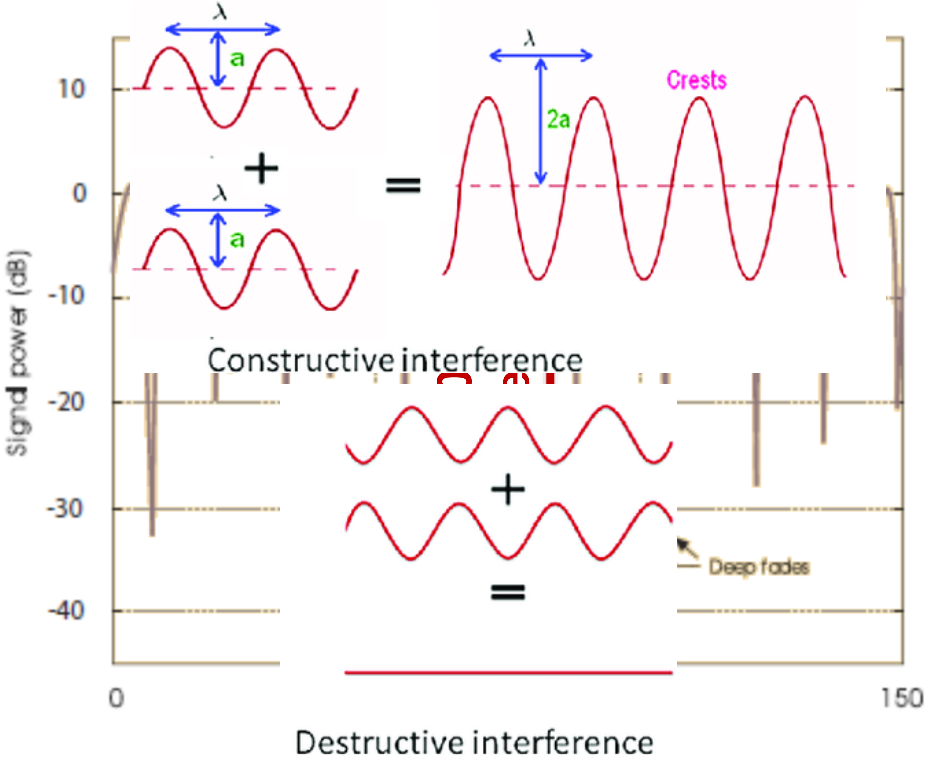
$$\sim {}^{1}/_{d^2}$$



Fading Channels

In complex (real) environments (especially indoor), radio signals strength often even fluctuates randomly by orders of magnitude!

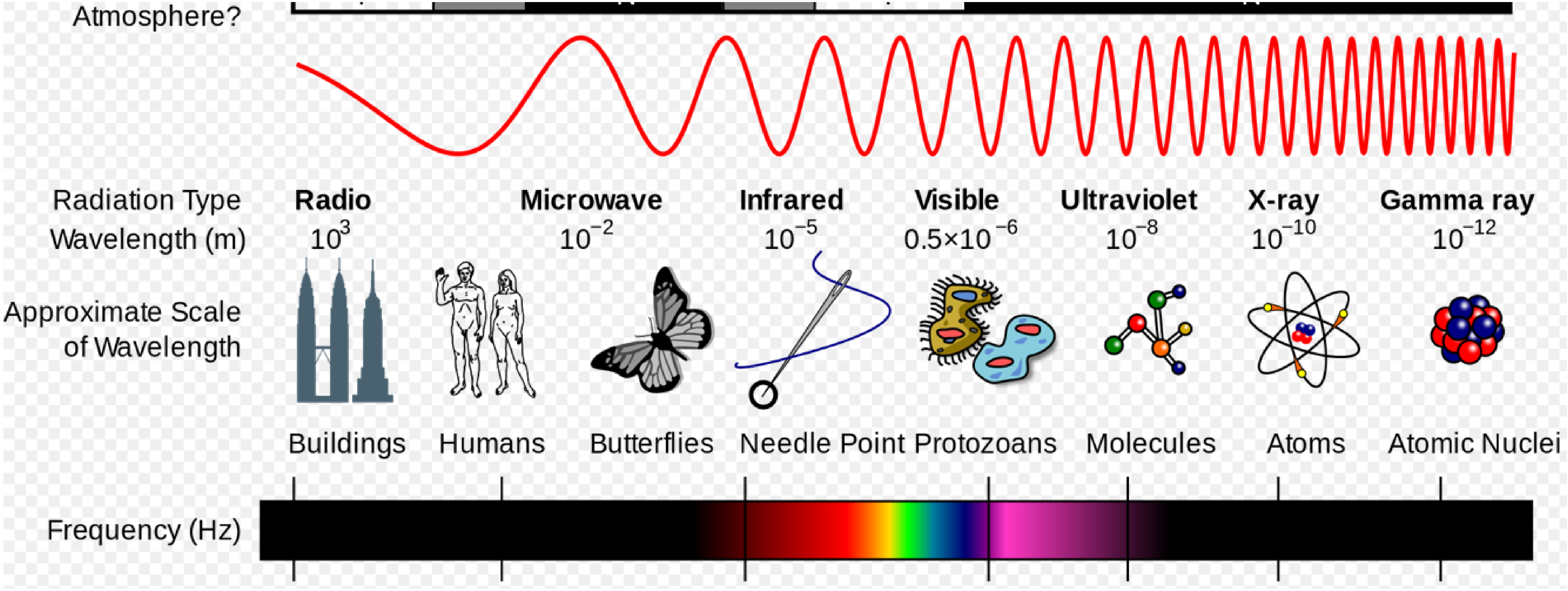
- Radio signals bounce off walls/objects (multipath)
- Multiple copies of the same signal cancel each other



The Radio Spectrum

Electromagnetic ("radio") waves can have very different frequencies

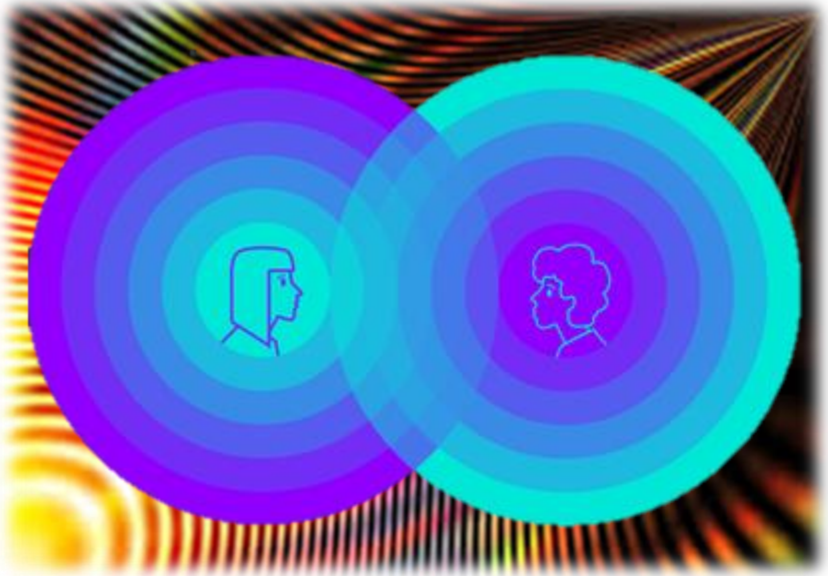
- Only a very **small part of the spectrum** is **used for communication**



10 kHz 100 MHz 1 THz

Spectrum Sharing (1)

Since radio waves propagate in all directions, the wireless medium is shared between all its users

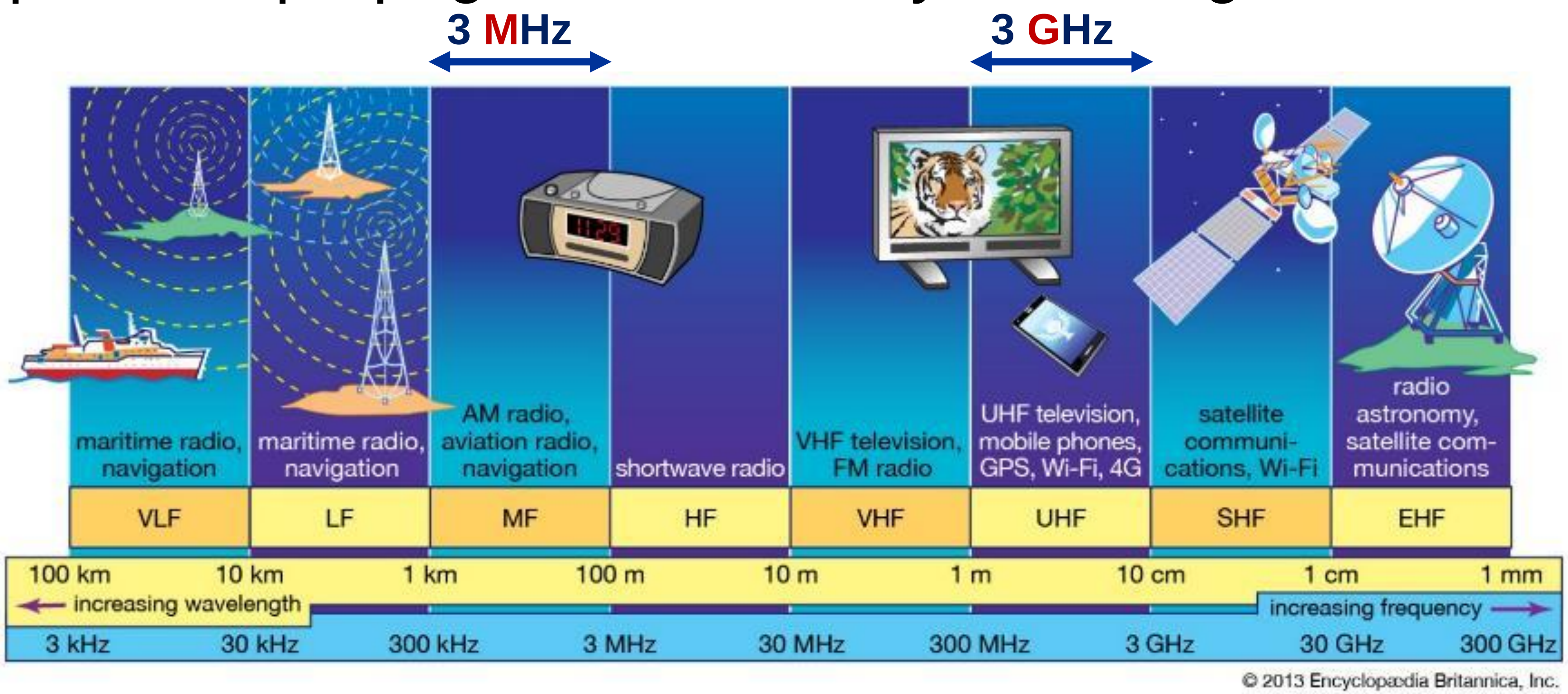


- **Multiple users of the spectrum interfere with each other !!**

Spectrum Sharing (2)

Different applications are assigned to different parts of the spectrum (communication bands)

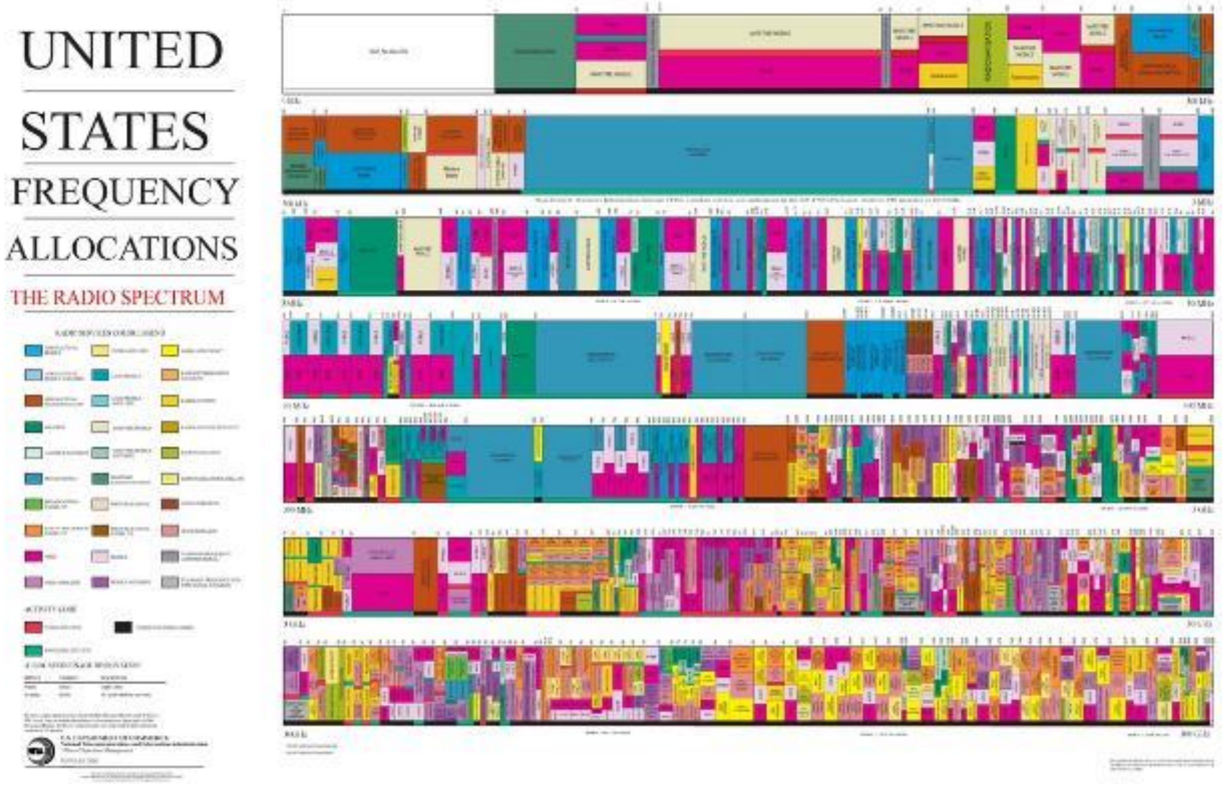
- At high frequencies much more space is available than at low ones
- Low frequencies propagate more easily over longer distances



Regulated vs ISM Bands

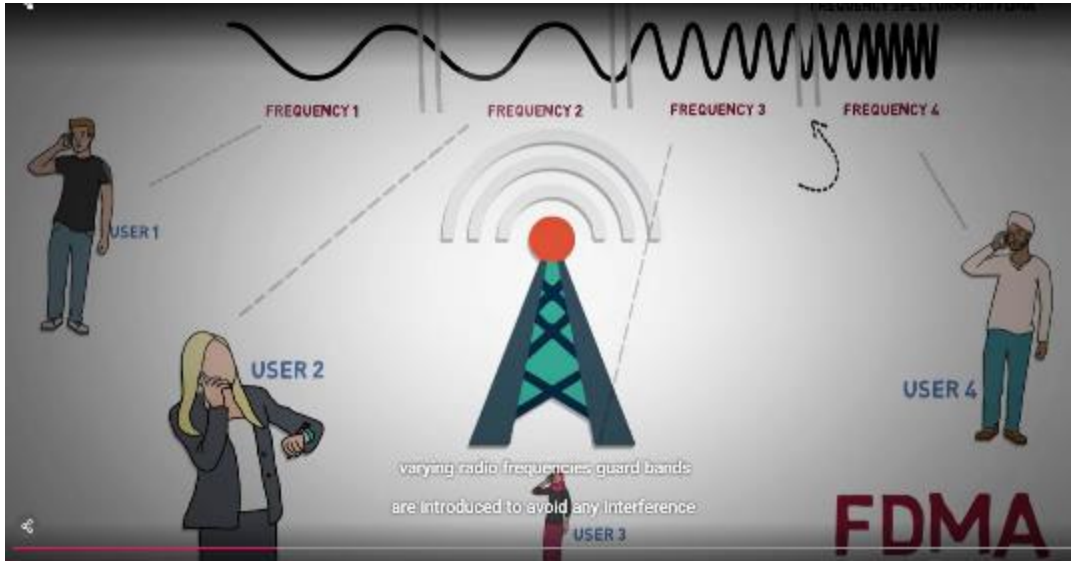
The use of most frequencies is dedicated to specific purposes and strictly regulated: use requires an official license (sometimes costly)

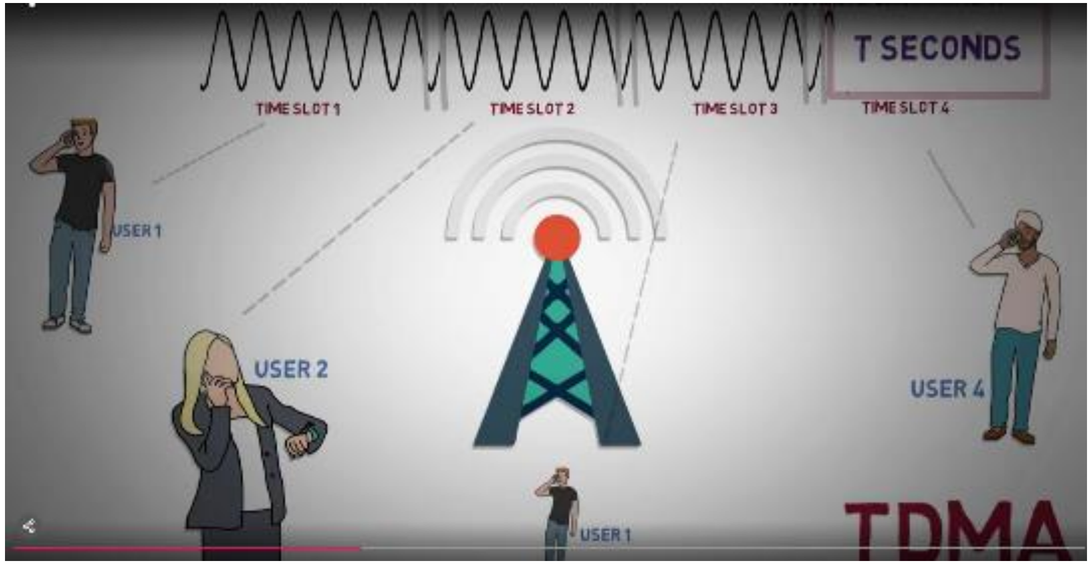
ISM bands: available to use by anyone without the need for a license



Spectrum Sharing: Multiple Access

We also share spectrum between many different users (with the same or similar applications) across either frequency or time





FDMA

Assign to different frequencies

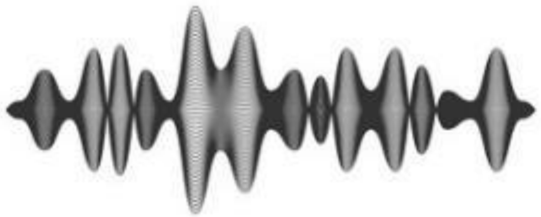
TDMA

Assign to different time slots

Analog vs Digital Communication

- **Computers naturally think/communicate in bits: ‘0’s and ‘1’s**
- **Images, video, voice are naturally analog (need conversion)**

Mostly used today for communication



0100100100100010 10
1010010100101011 10
0101001010010010 10

Everything represented as “bits”

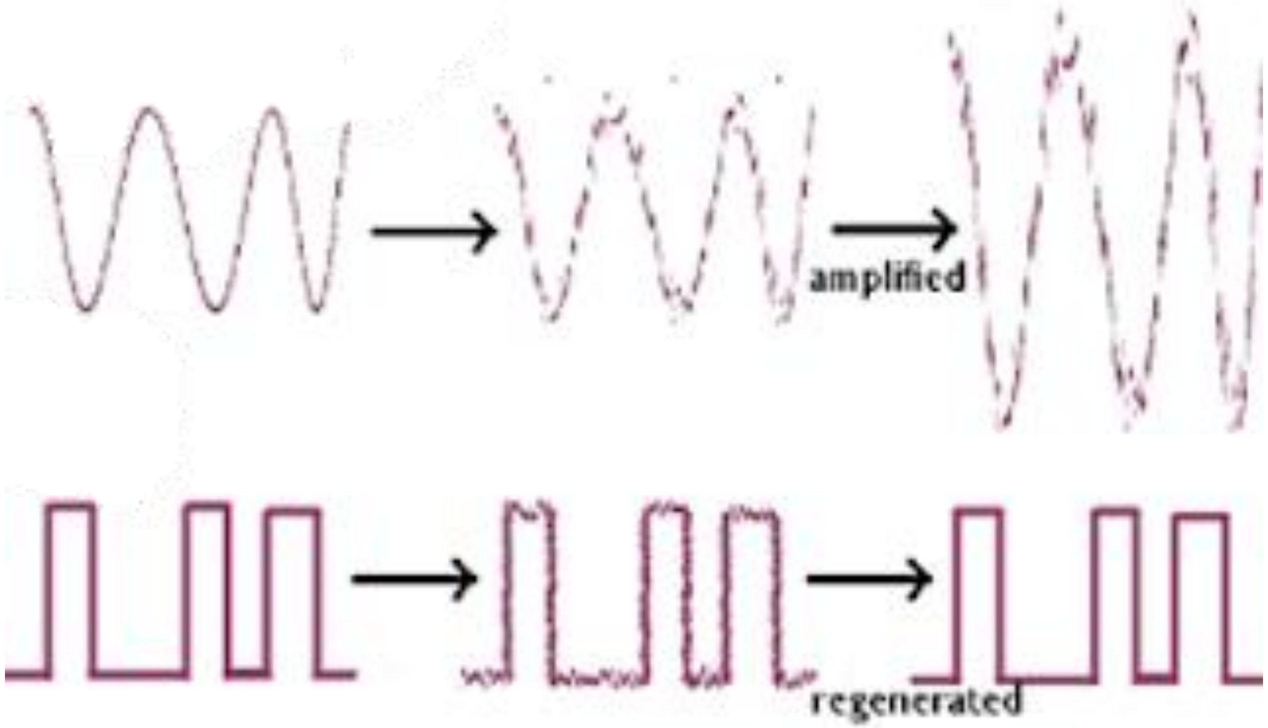
Analog vs Digital Communiction

Transmitted signals are always received with distortions (noise)

- **Analog communication: distortions can not be fully removed**
- **Digital communication: distortions can either be fully removed or communication fails**

Analog

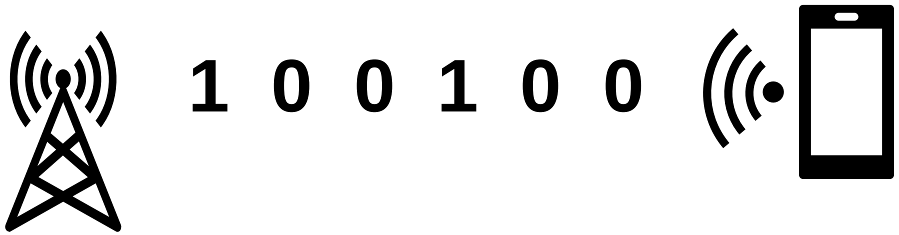
Digital

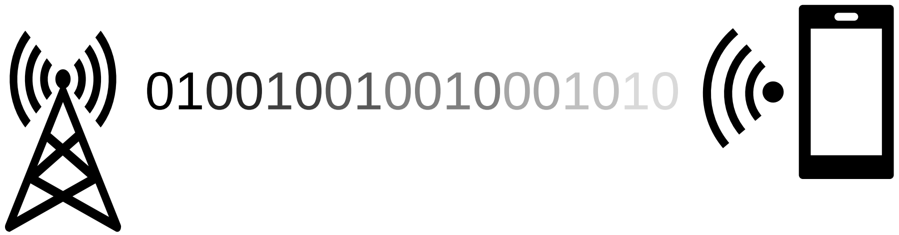


Link Between Data Rate and Spectrum Usage

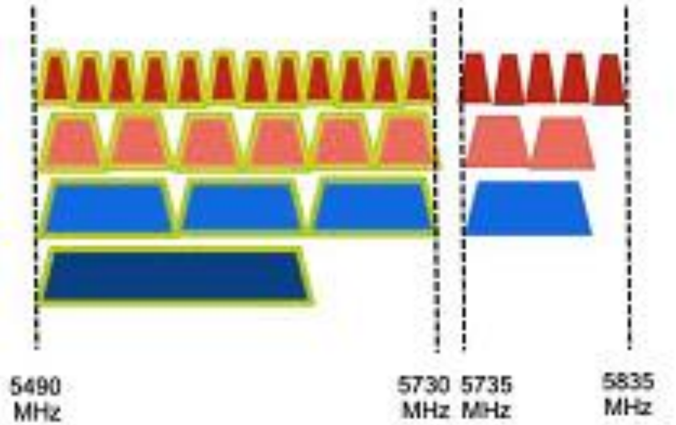
Data bits are sent one-by-one: sending more bits takes more time

Sending bits faster (higher data rates) comes at a price:



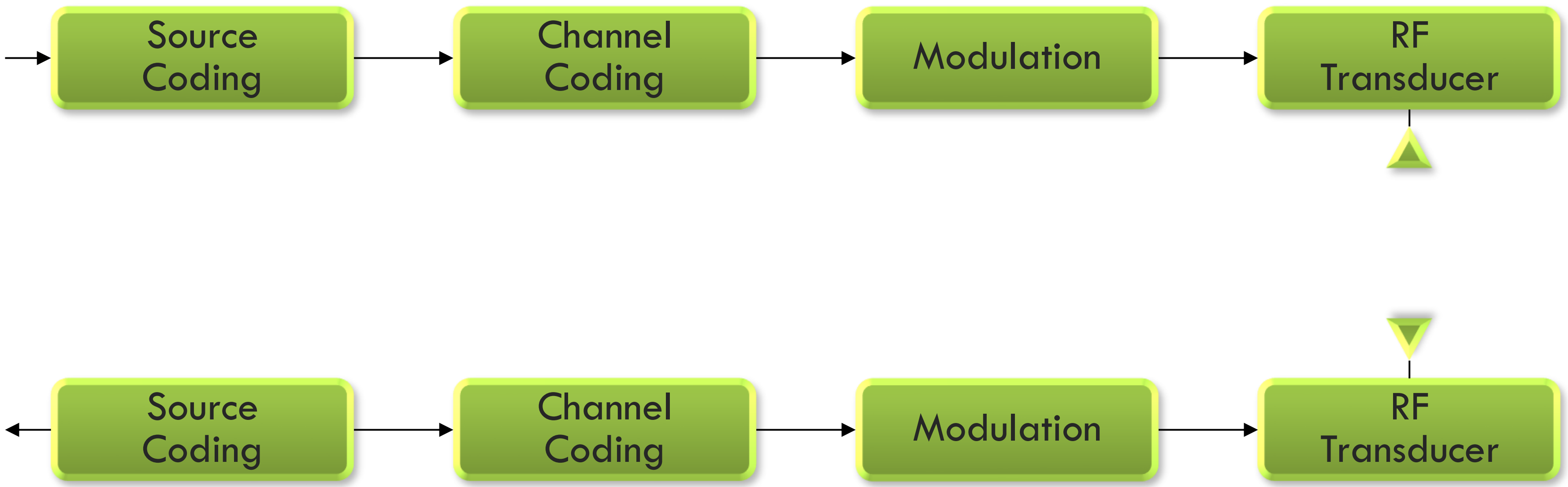


- **Bits are weaker: more vulnerable (more likely to get lost)**
- **Consume more of the precious spectrum**



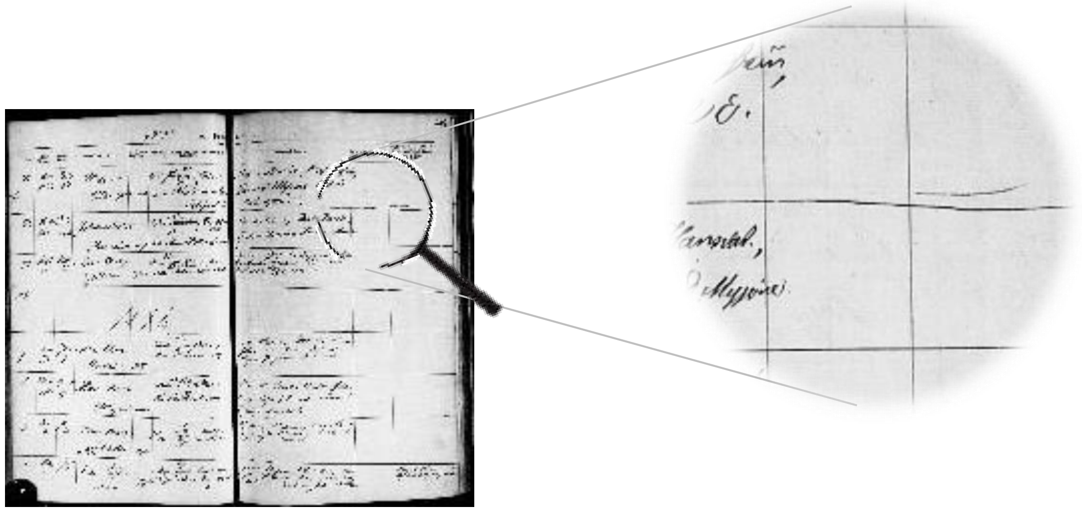
BASIC (digital) Communication System

- **Source coding: reduce amount of data to be transmitted**
- **Channel coding: Add extra bits to protect data during transmission**
- **Modulation: encode bits into robust (analog) waveforms**
- **Transducer: Transfer EM signals/waves to/from the medium**



Data Compression (Source coding)

Data (audio/images/video,…) is often highly redundant (contains very little actual information)



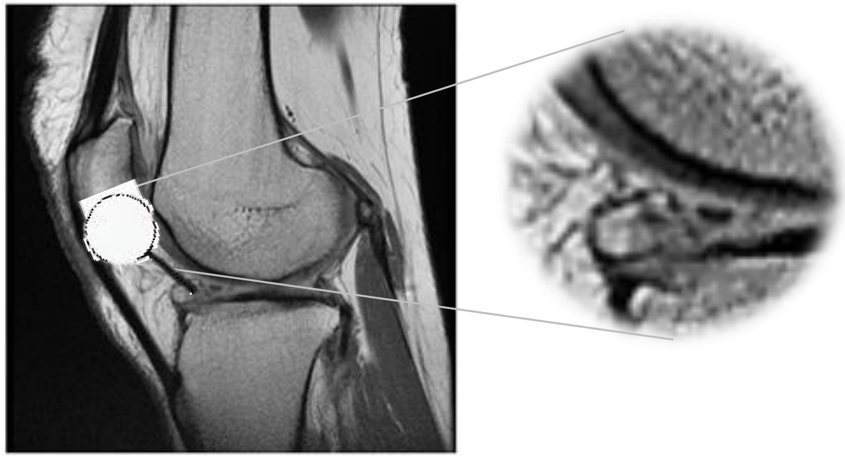
0100100100010
1100000000111
0101000000010
111111111111111
0100000000010
0100000000010

$01\bar{0}1\bar{0}1\bar{0}1011$
$\bar{0}\bar{1}0101\bar{0}10\bar{1}0$
$1\bar{0}1001\bar{0}1010$

- **Compression removes redundancy to represent the information with fewer bits in a more compact form**
- **Relaxes communication requirements (fewer bits to transmit)**
- **Individual *compressed bits* are also *more precious* (more sensitive)**

Lossless vs Lossy Compression

Often not all data is actually relevant/**interesting**

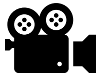


Lossless compression

removes only data that can 100% be re-constructed

Lossy compression

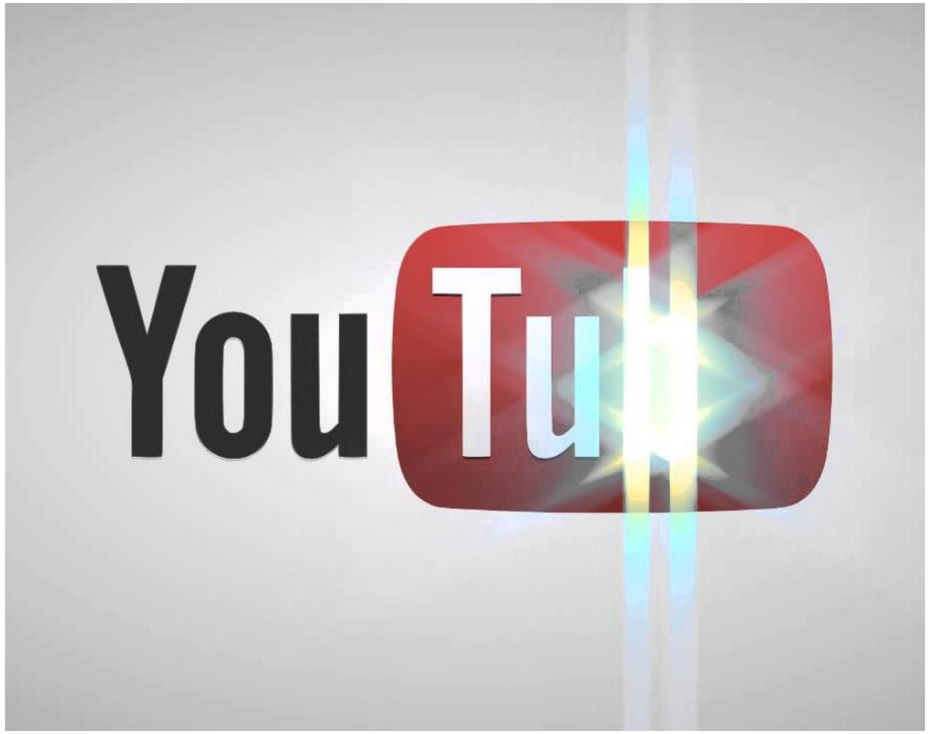
also removes information that is not very interesting

Lossless		Lossy
2x – 3x		4x – 20x
2x – 3x		4x – 100x
5x – 12x		20x – 200x

Staggering Quality Demands Datarates

Even with heavy compression **growing quality demands still lead to staggering data rates**

4k UHD
(4096x2160 @ 60Hz = 23.8 Gbit/s)
> 70 Mbps Compressed

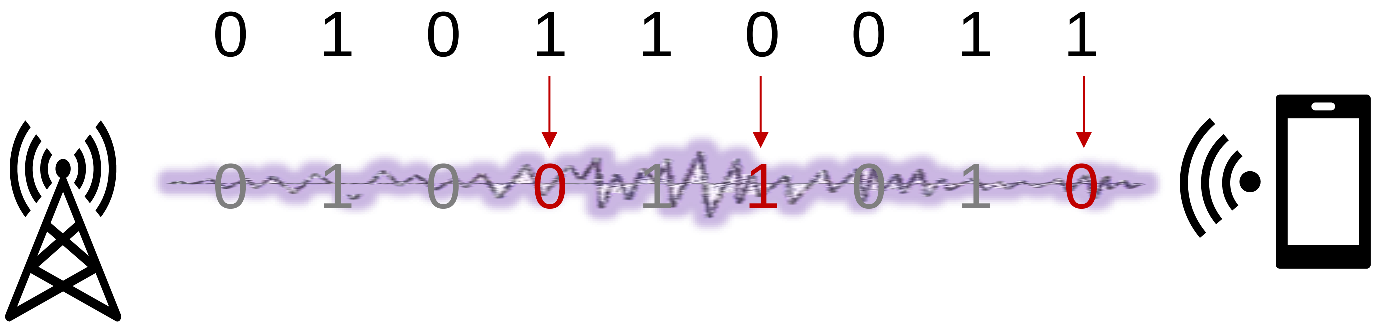


Full HD
(1980x1080 @ 30 fps = 1.49 Gbit/s)
5 Mbps Compressed

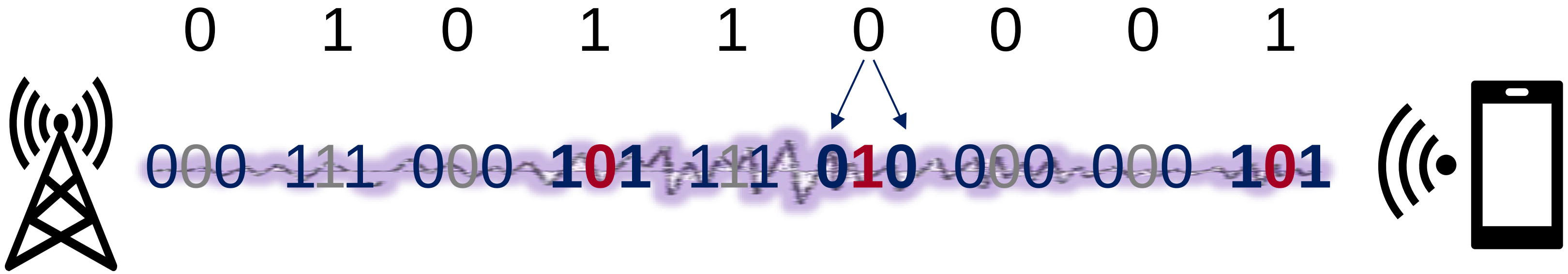
1 Gbit = 1’000’000’000 bit

Error Correction (Channel Coding)

During transmission some bits are inevitably altered by noise.

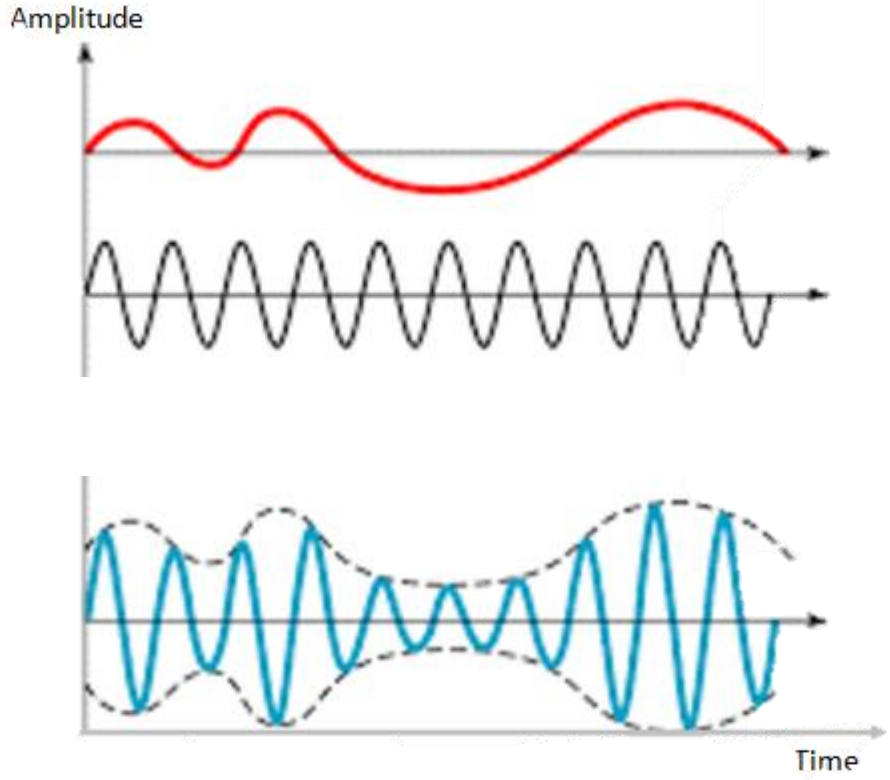


Add redundancy to correct errors from the transmission at the receiver.



Modulation

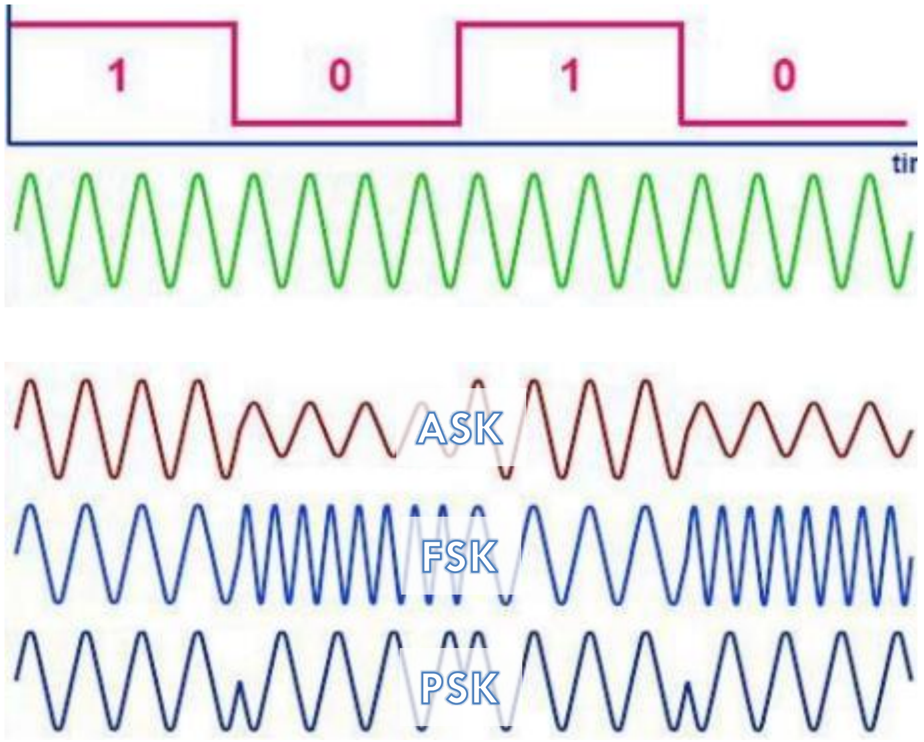
Convert data (analog or binary ‘0’/’1’) into different (modulated) waveforms that can be distinguished by the receiver



Data Signal

“Carrier”

Modulated Signal



Analog Modulation

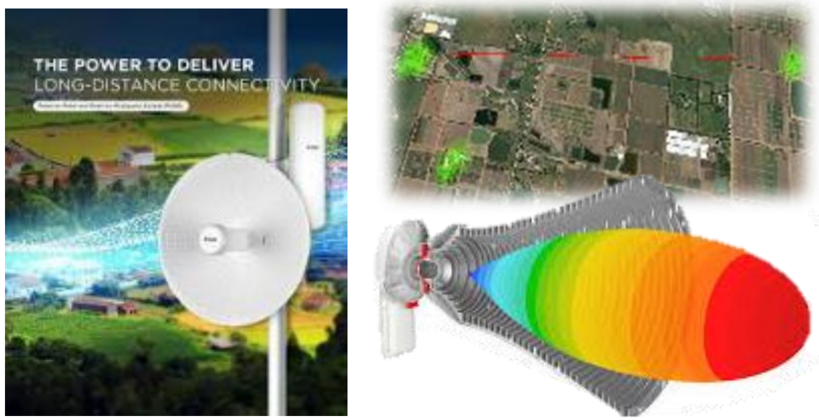
Digital Modulation

RF and Antennas

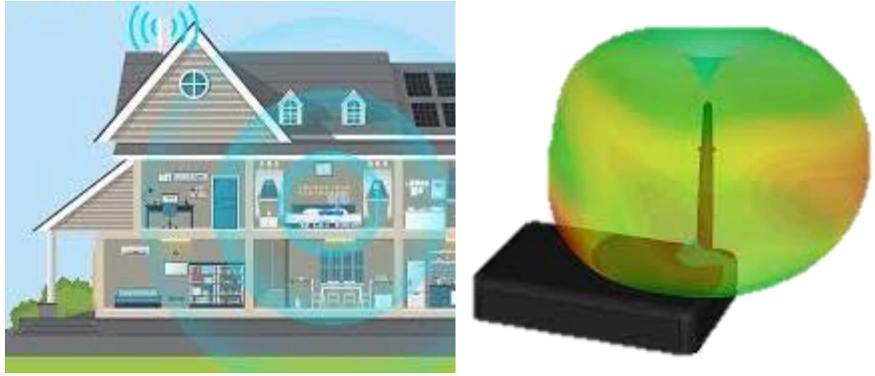
Radio Frequency (RF) components amplify the modulated signal and antennas couple the signal to the air/ether.

Choice of the antenna has an important impact on quality of the link

- Tradeoff: “directivity” (focus) vs “signal strength” (distance/data rate)



Highly Focused
long range, in one direction only

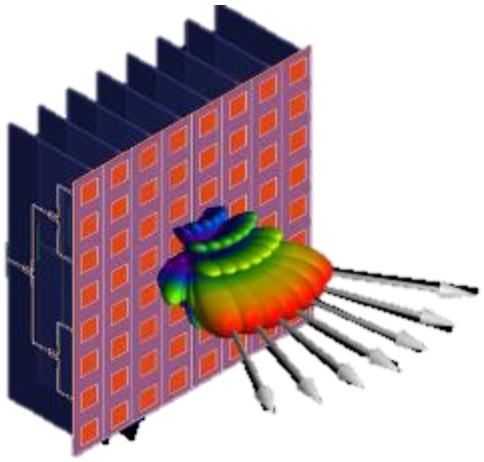


Omni Directional
shorter range, but everywhere

Massive MIMO

With many users or in changing environments (mobility) fixed focused beams are often not useful.

Adaptive antennas focus parallel beams on individual users and follow them as they move to send energy only where needed

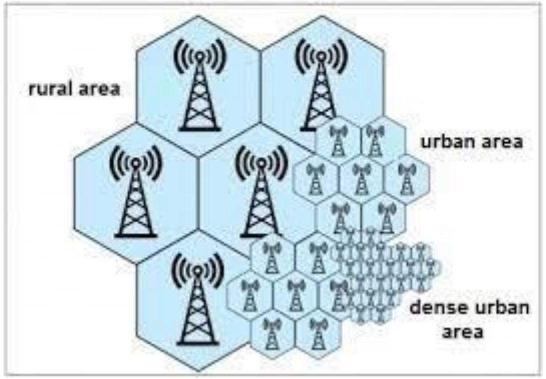


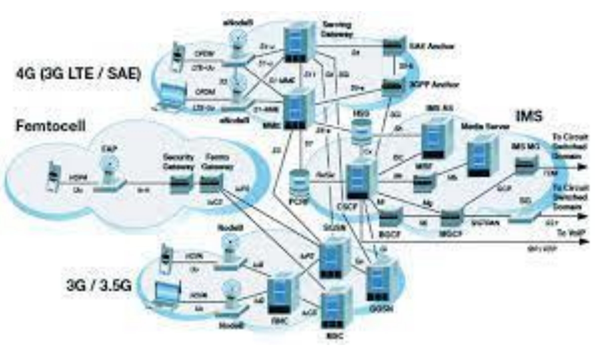
MASSIVE MIMO Antenna

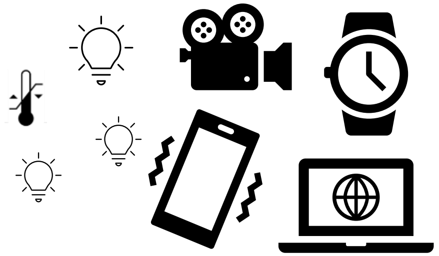
Multiple Beams follow users

Wireless Networks

Most modern wireless systems are more than a point-to-point link

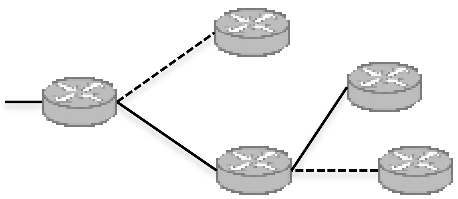




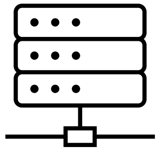


End Nodes/Devices
Sensors, actors phones, computers, …

Gateways
provide connectivity between different types of networks



Routers
connect multiple networks of the same type



Servers & data centers
Complex applications and services

Communication System Metrics (1)

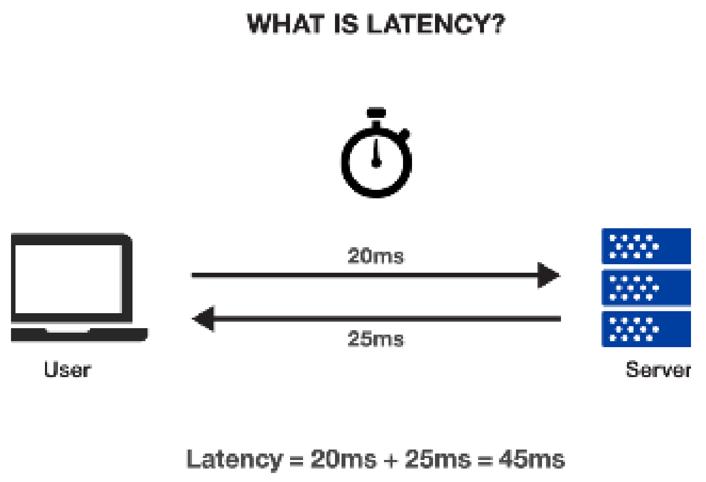
Communication Systems must meet many **conflicting requirements** at the same time:

High data rate
in Mbps or Gbps

System capacity
number of concurrent users

Communication System Metrics (2)

Communication Systems must meet many **conflicting requirements** at the same time:



Low latency (Ping): measured in milli seconds (ms)

Long range: max. distance for stable operation (m)

Energy efficiency: battery lifetime of mobile devices (pJ/bit)

Communication Standards and Proprietary Systems

For systems to communicate, both (all) sides need to talk "the same language": same compression, coding, modulation, frequency, BW, …

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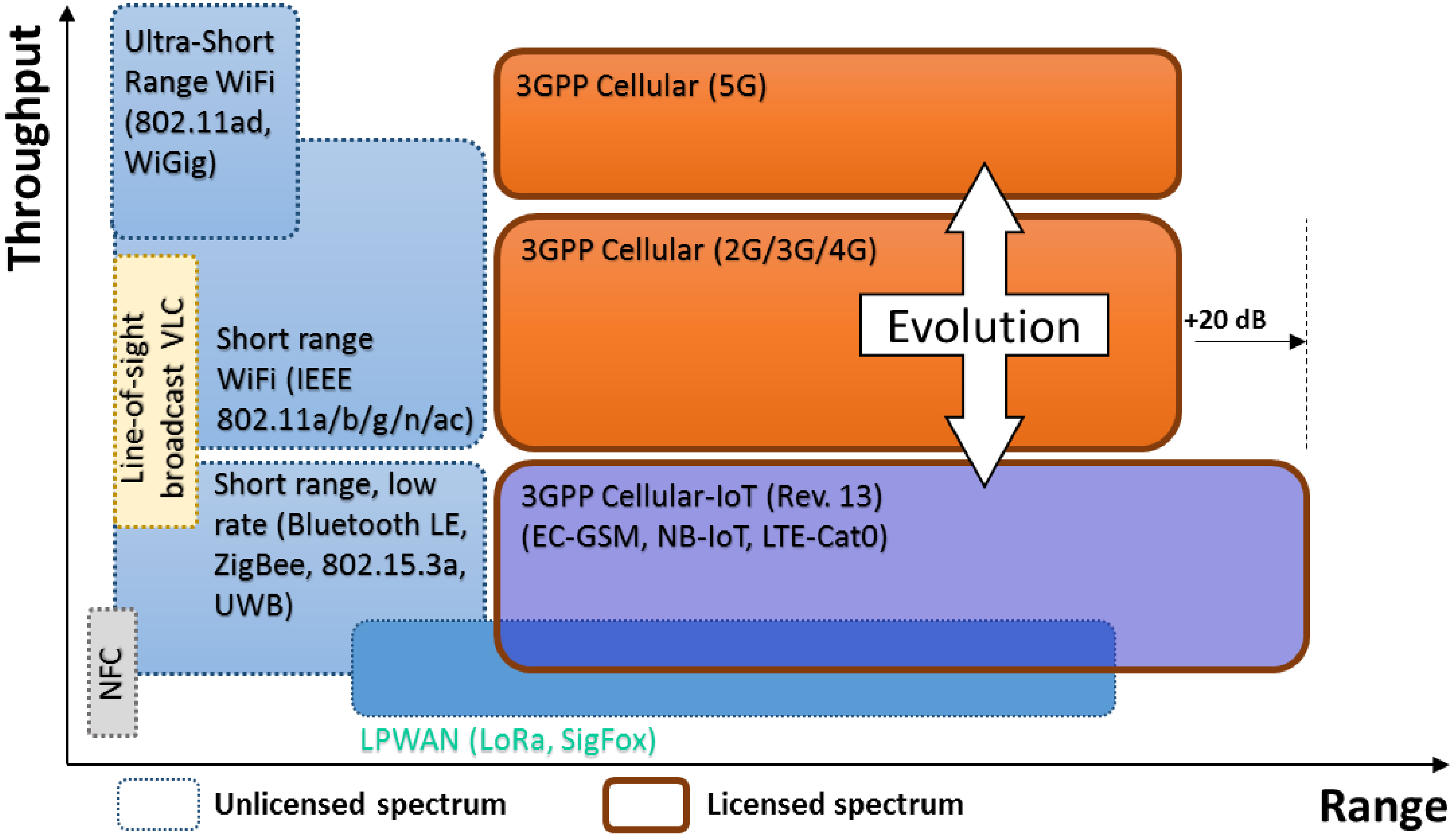
- Success of the mobile phone: **strong trend toward standardization**

Proprietary systems
Highly optimized for a very specific application, sold by a single vendor

Standards
Compromise between requirements and vendors, but interoperable

Communication standards landscape

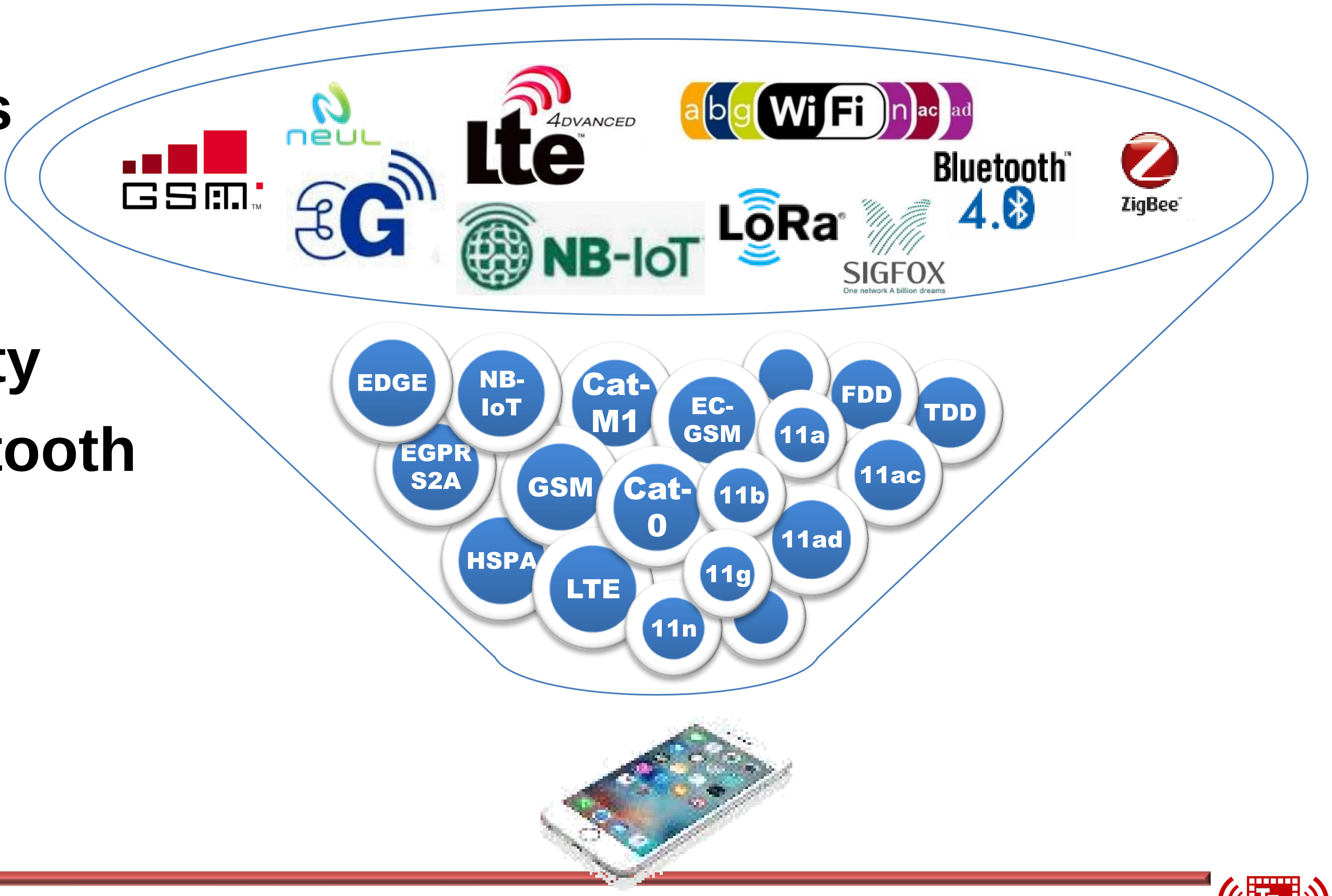
Different requirements lead to dozens of different standards



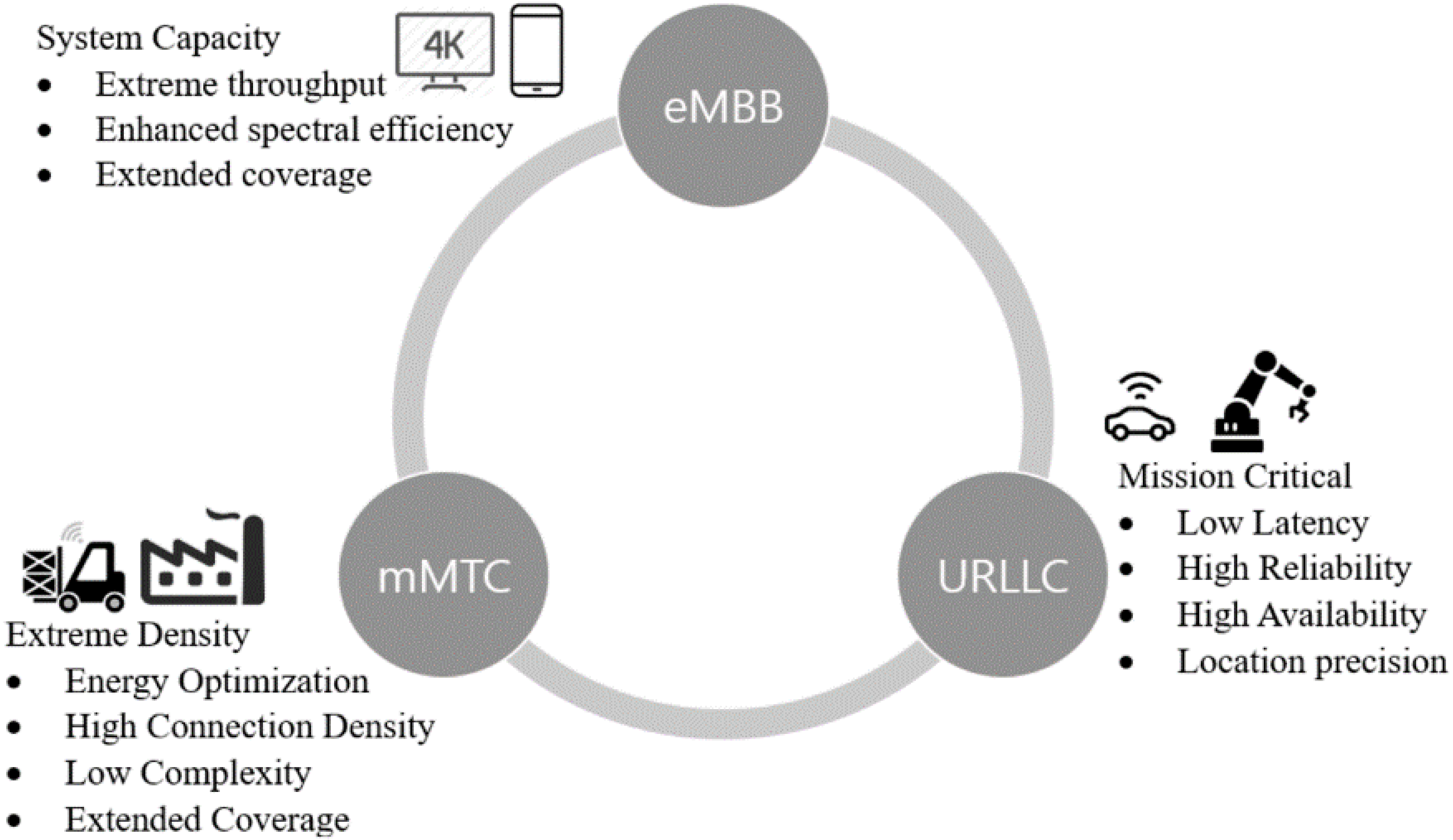
Multi-Standard-Support

Support of many standards is not only driven by technical arguments

- **Competing standards**
- **Need for backward compatibility**
- **Device interoperability**
- **Marketing: e.g., Bluetooth is a MUST**



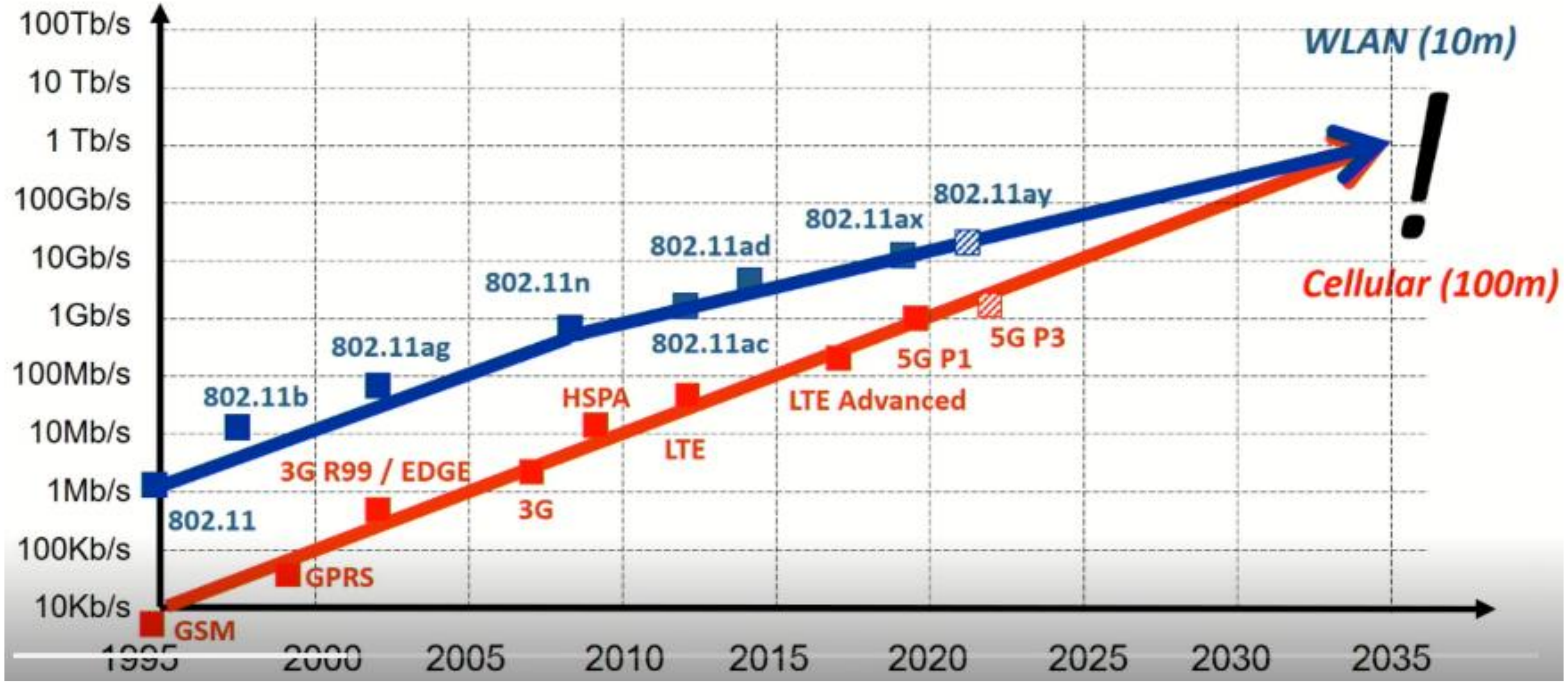
TODAY: Four Main Focus Areas



Data/Connectivity (eMBB/WiFi)

Achieve the highest data rates for a reasonable number of users

- Driven by two standard families: WiFi (WLAN) and Cellular (3GPP)
- Every generation provides a 10x increase in data rate over 10 years

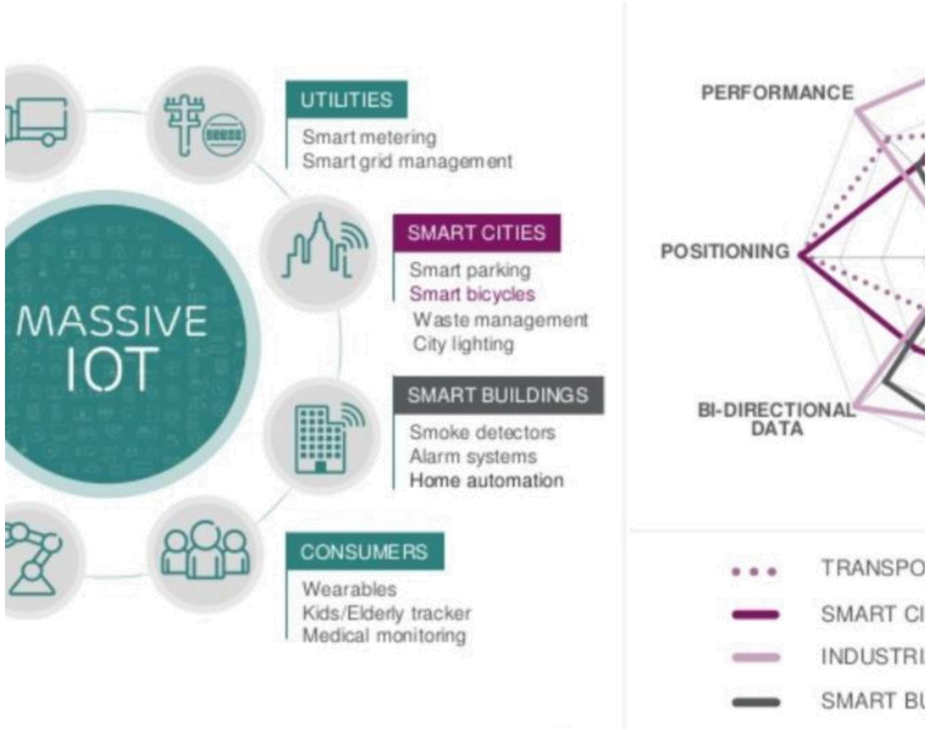


Keynote: Gerhard Fettweis - Terahertz Communication - B5GS 2019

The Internet of Things (IoT)

The **IoT is a concept that envisions the connection of almost anything** to the global internet (Cloud)

Everything connects to the cloud



Some of the countless IoT application areas

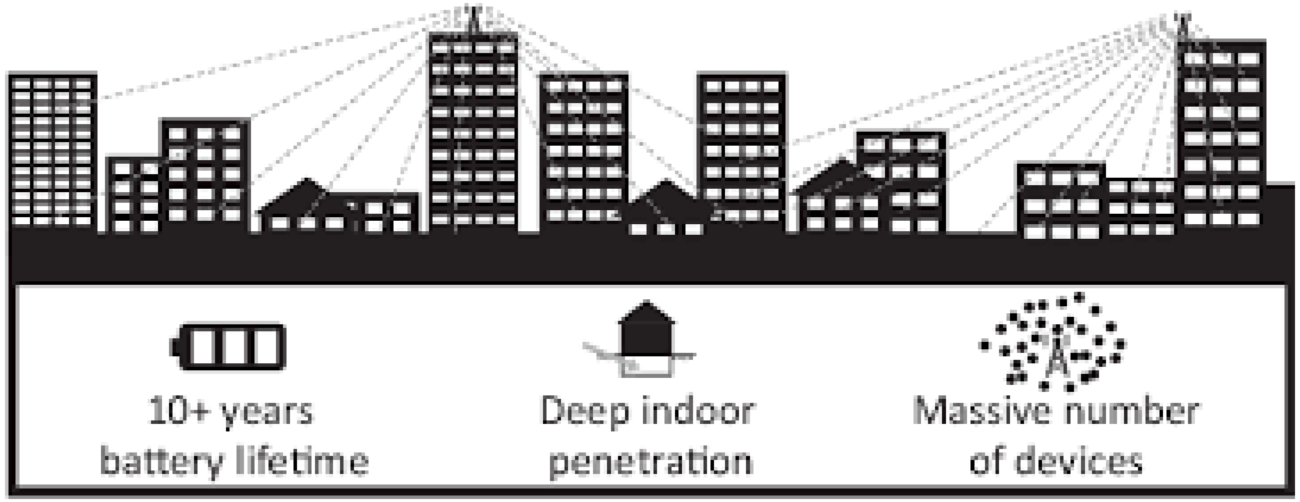
Source: Orange and Ericsson, 3GPP GERAN meeting #69

Machine Type Communication (MTC)

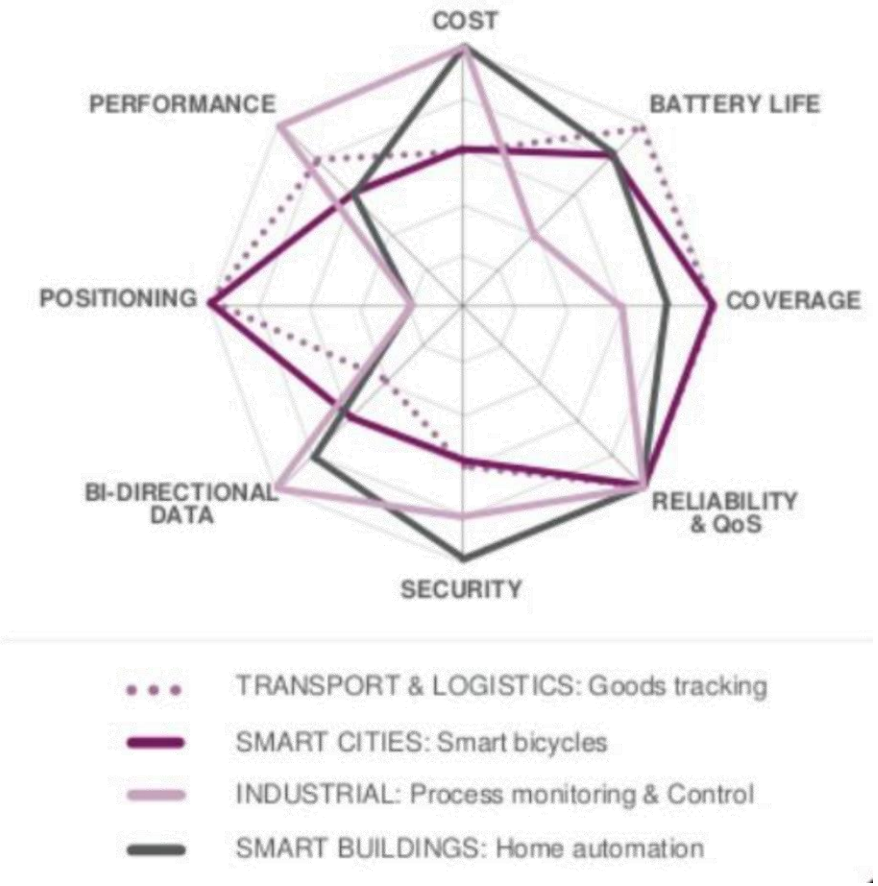
MTC provides connectivity for the Internet of Things (IoT)

Requirements are tailored for a huge number of low-cost devices

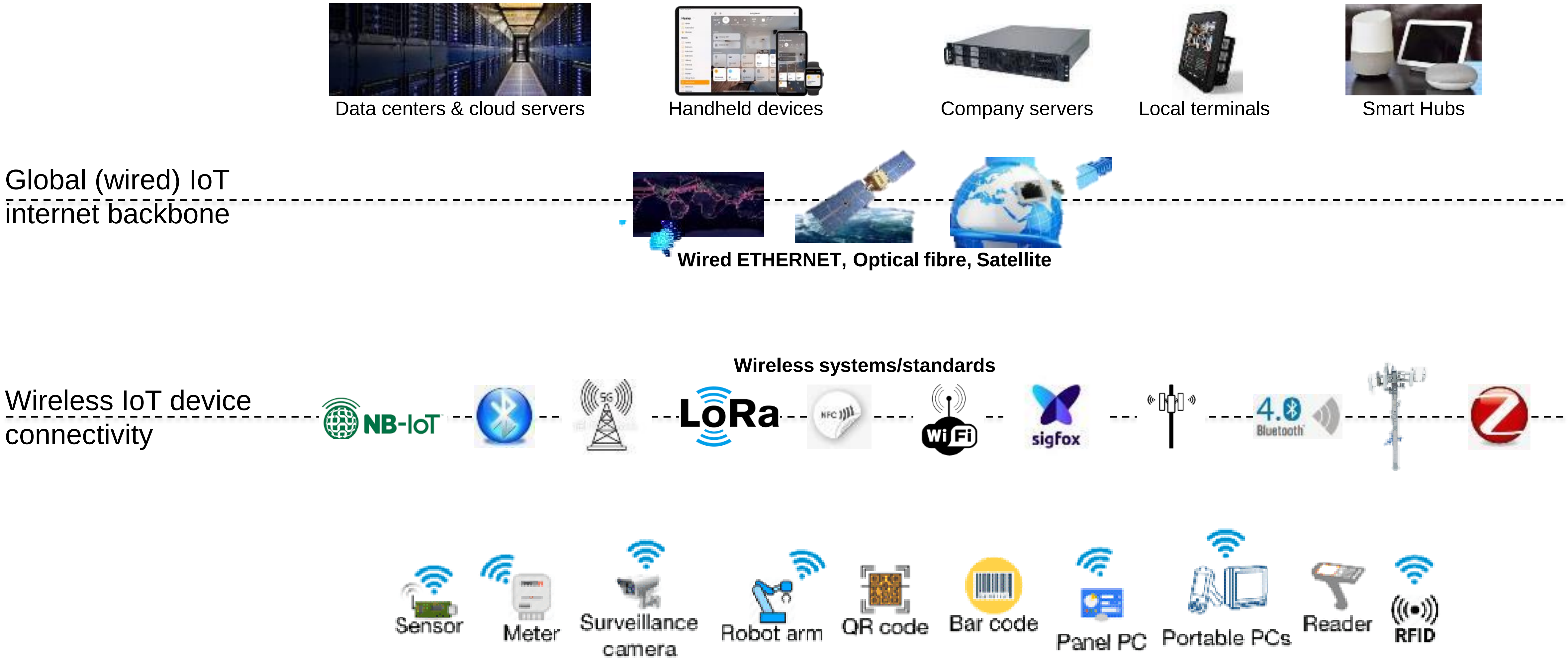
- Low cost and long battery life with low data rates



MTC for IoT objectives



Cloud Provides Services for the IoT



Ultra Reliable Low Latency Communication (URLLC)

Provides the ability to control critical systems

Conflicting requirements of low latency and high reliability

- Latencies below 1milli second (1ms) is 10 – 20x lower than mobile
- Reliability of data delivery allowing less than 1 of 1’000’000 messages to be lost (10^{-6}): 100’000x better than mobile (looses 10% of the data)