Algorithms for Wireless Communications

Andreas Burg

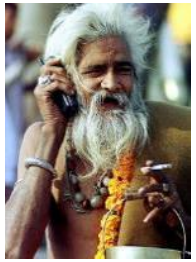
Telecommunications Circuits Laboratory, EPFL

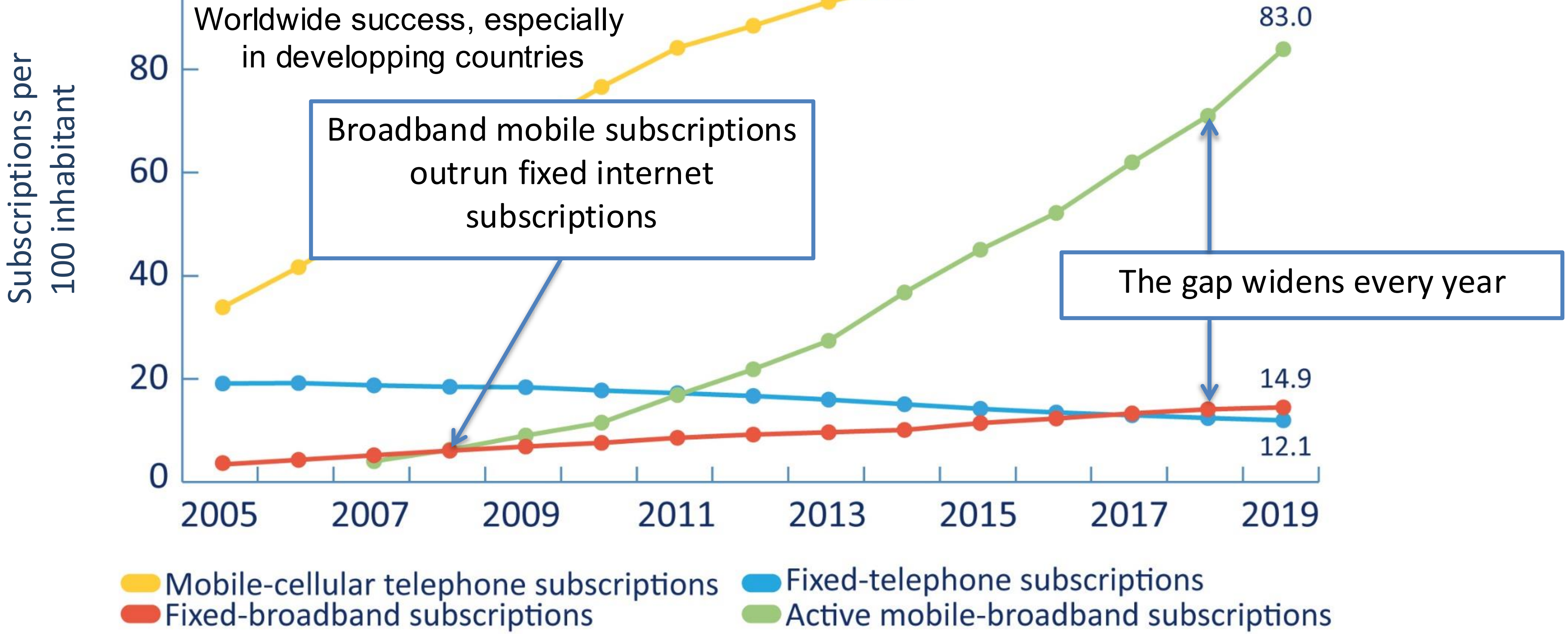
Lecture 1: Intro/Background
09/09/2025

EPFL

Evolution Toward Wireless Only

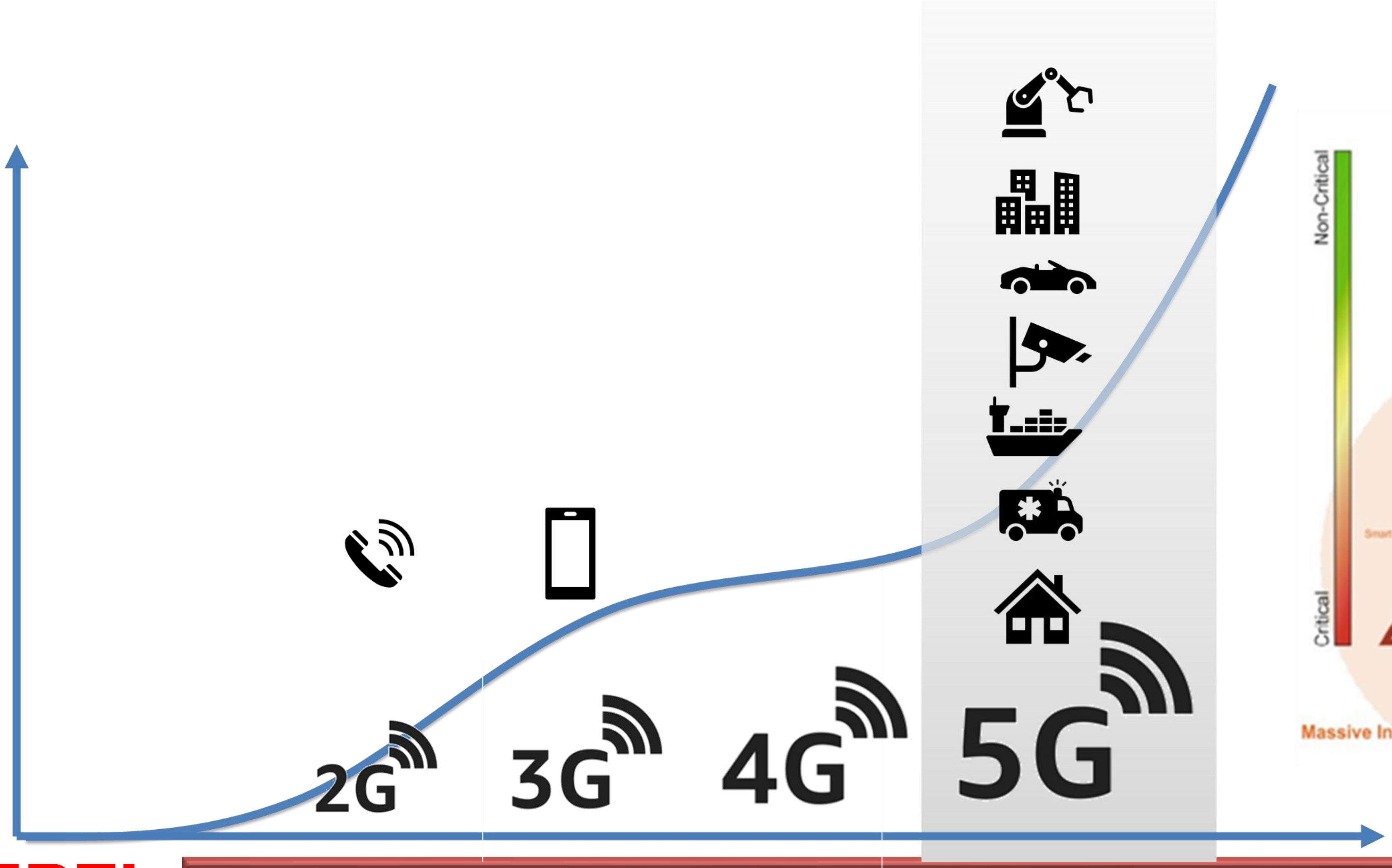
ITU, 2019

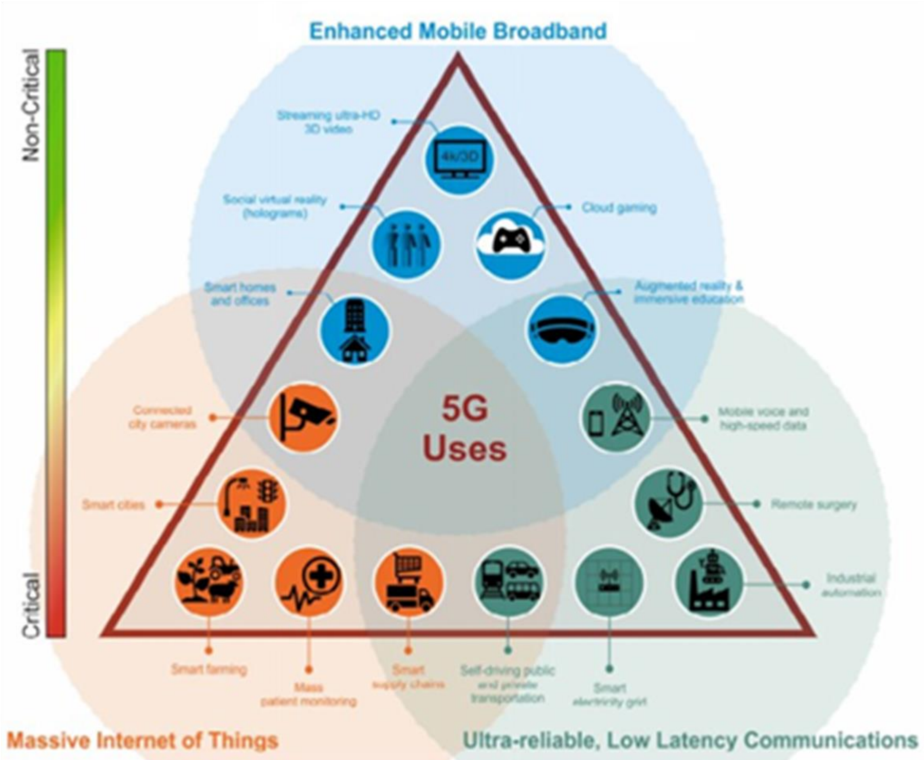




Evolution of Mobile Communication

- The third-generation partnership project (3GPP) resulted so far in 5 generations of mobile communication standards driven by more and more demanding applications





6G is on the Horizon and THE Topic of Adademic and Industrial Research

What to expect:

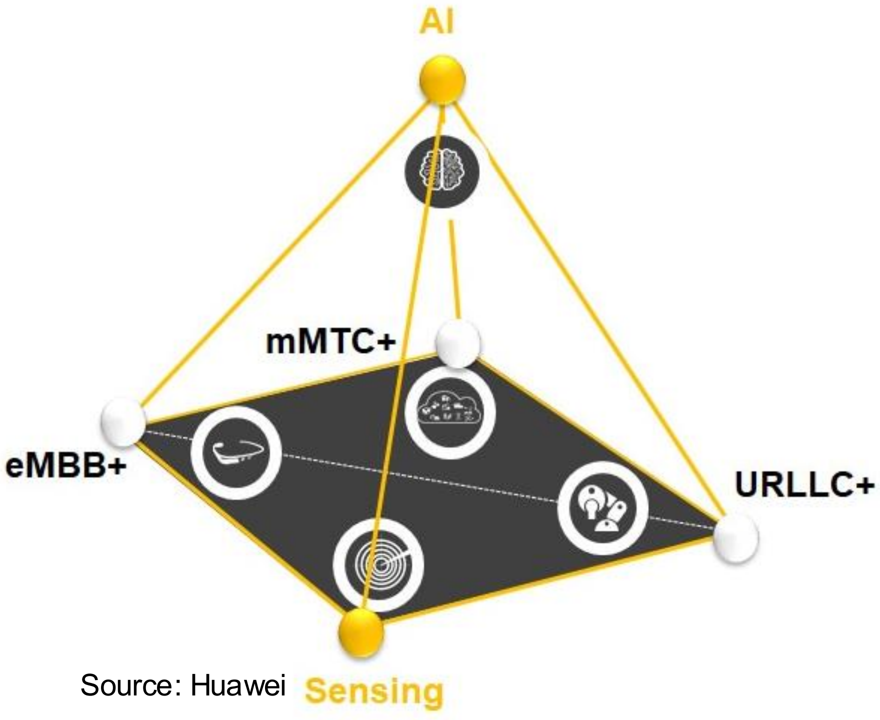
- **Evolution**

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

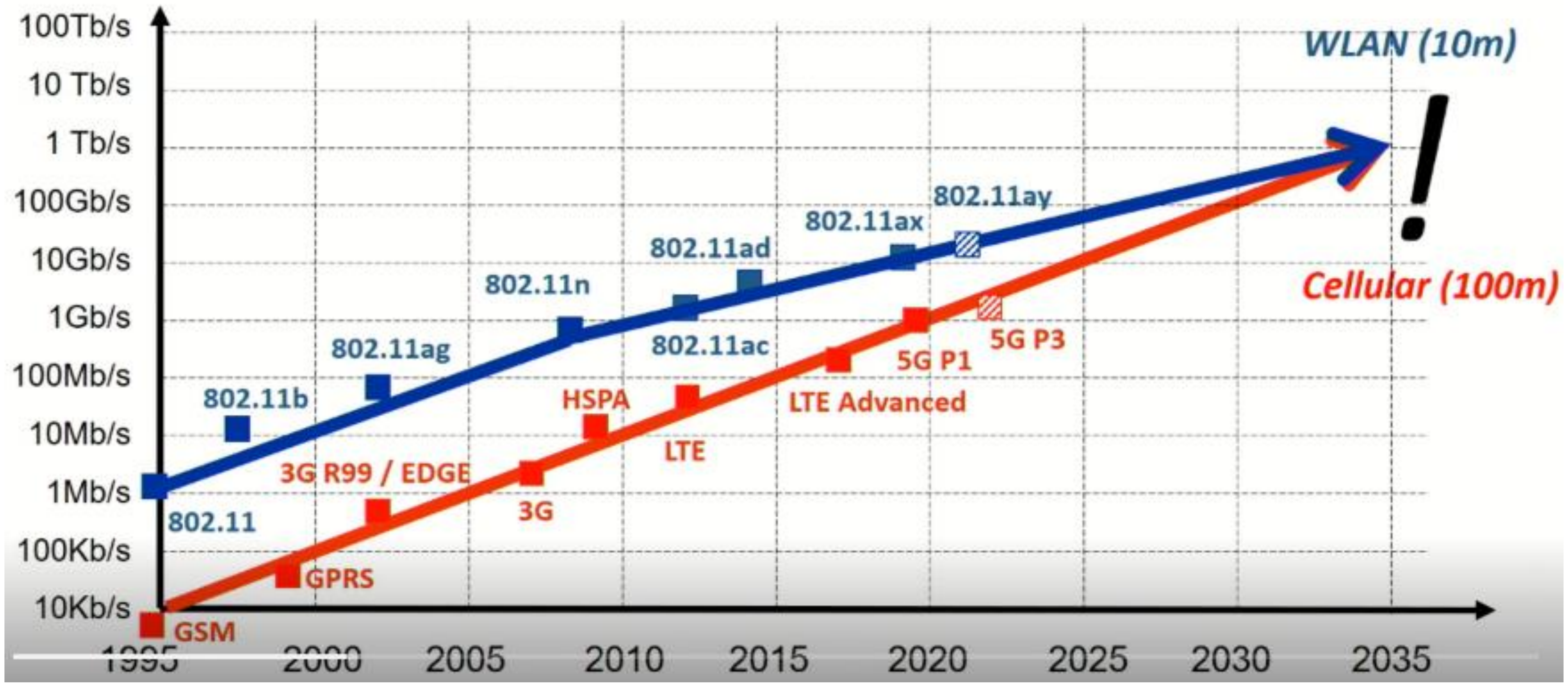


Source: Huawei

Data/Connectivity Evolution (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

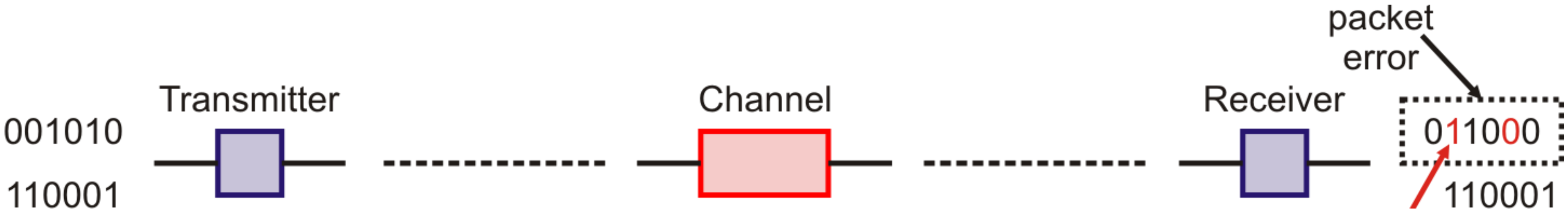


Wi Fi™

3GPP™ A GLOBAL INITIATIVE

EPFL

Communication system model



Transmitter: encode data into signals that can be sent over the channel

- Often defined in detail by more and more complex standards
- Encoding should enable reliably communication, adjusted to the channel

Channel: alters and distorts the signal on its way

- Typically unknown or only within the range of statistical variations

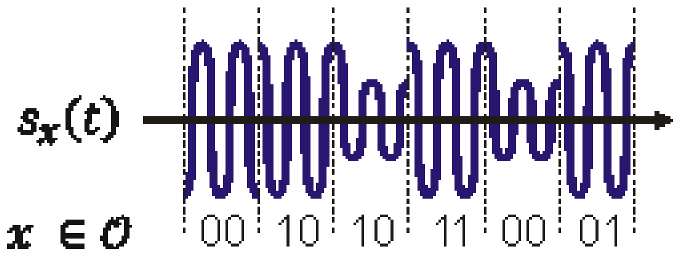
Receiver: recover the transmitted data reliably

- Optimum receiver algorithms that mitigate impact of the channel
- Energy efficient implementation

Physical Layer for Wireless Communication

Real-world channels typically convey only continuous time analog waveforms rather than abstract symbols

- Symbols need to be mapped to more physical quantities
- These quantities must be represented by continuous-time waveforms



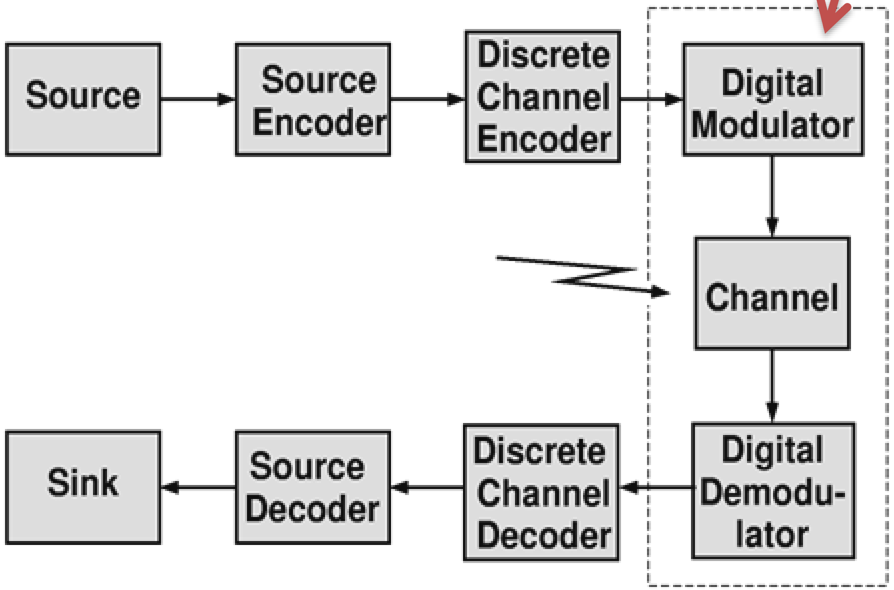
$$x \in \mathcal{O} \rightarrow s_x(t)$$

Modulation

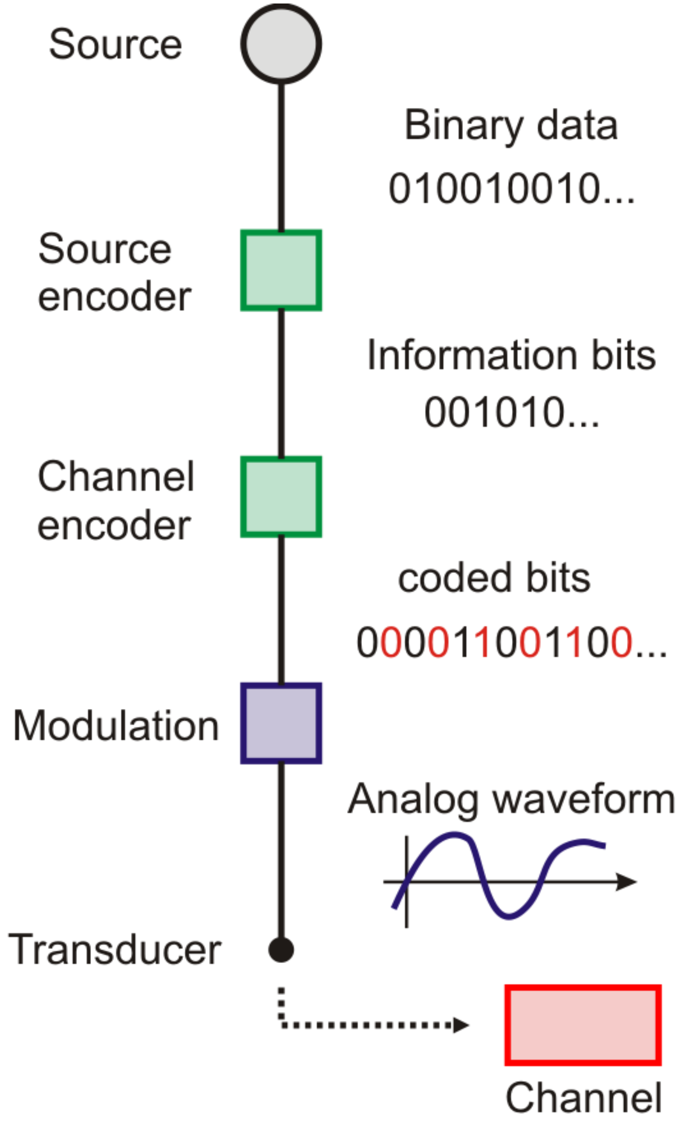
- Express data bits as a signal waveform that can be transmitted over a channel

Demodulation

- Recover an appropriate set of channel output symbols from a received waveform



Encoding and transmission of digital signals

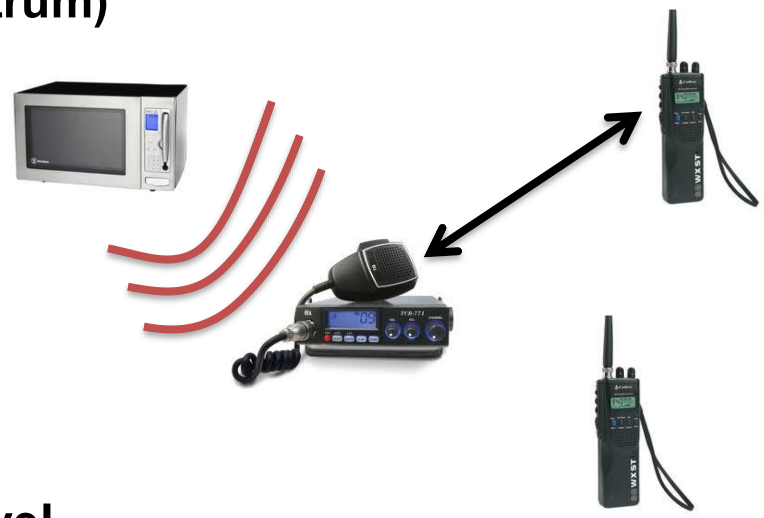


- **Source coding** (compression): removes redundancy from the signal to find the "most compact" representation of the information
- **Channel coding** (forward error correction): adds redundancy to protect fragile information bits against errors
- **Modulation**: Convert coded bits into an analog (electrical) signal (waveform)
- **Transducer:** adapt signal to the medium (e.g., antenna, speaker, …)
- **Channel**: noise and signal distortions

Radio Spectrum is Limited -> Need High Spectral Efficiency

Radio communication uses a shared medium (electromagnetic spectrum)

- Concurrent emissions at the same frequency interfere with each other
- Electronic devices cause emissions into the radio frequency bands
- Transmitted power determines the range of interference

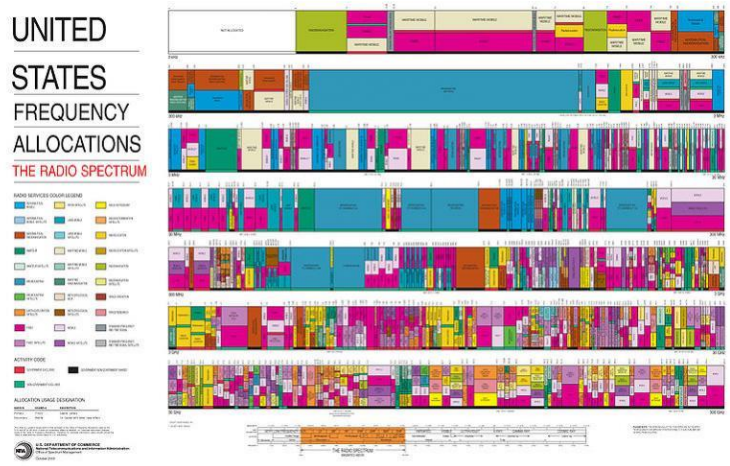


Use of the EM spectrum is regulated on national and international level

- International regulating body: **ITU-R**
- Division into frequency bands assigned to services
- Bands can be **licensed** or **unlicensed**
- Licensed bands:
  - Services with a large coverage and signal power
  - TV, GSM, Satellite, …

Auction results table

Frequency band	Dense Air Ltd.	Salt	Sunrise	Swisscom
700 MHz FDD	0	20 MHz	10 MHz	30 MHz
700 MHz SDL	0	0	10 MHz	0
1400 MHz SDL	0	10 MHz	15 MHz	50 MHz
2600 MHz TDD	0	0	0	0
3.5 – 3.8 GHz TDD	0	80 MHz	100 MHz	120 MHz
Auction price	0	94'500'625	89'238'101	195'554'002



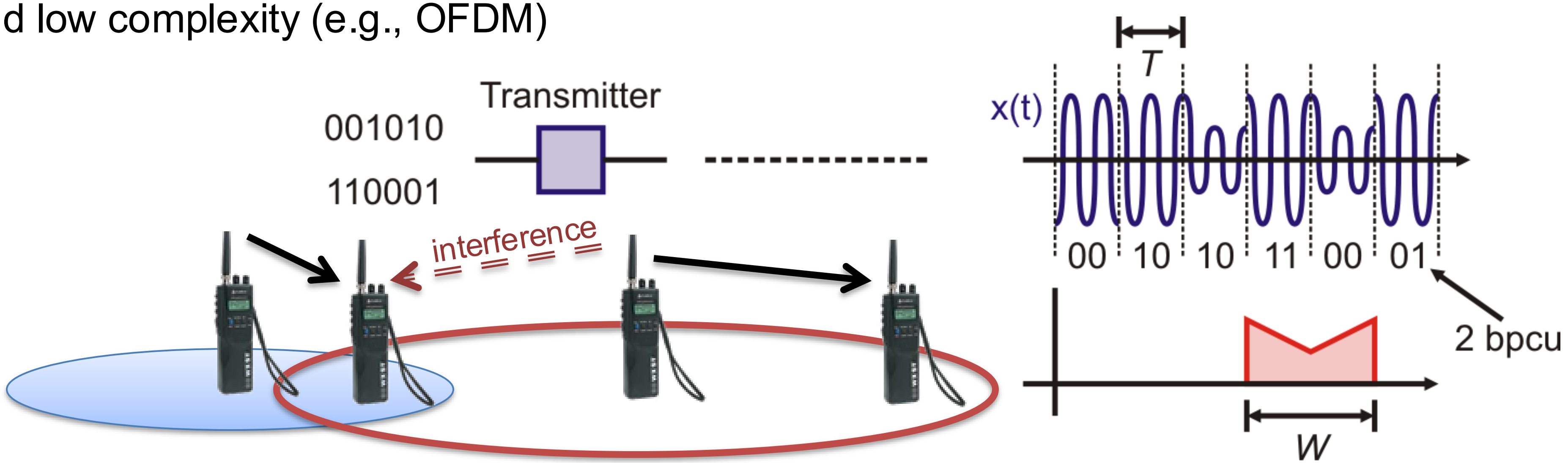
Modulation

Examples

- Analog modulation: band limited signal -> radio frequency signal
- Digital modulation: bits or symbols -> radio frequency signal

Objectives

- High data rate with minimum bandwidth (spectral efficiency)
- Robustness against signal distortions
- Minimize interference to others (e.g., UWB)
- Multiplexing (e.g., CDMA: use orthogonal waveforms for different users)
- Simplicity and low complexity (e.g., OFDM)



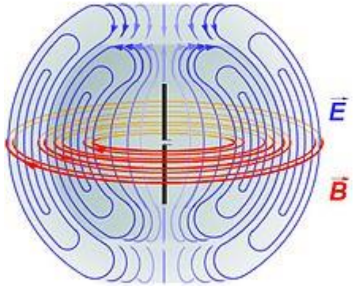
The wireless channel

- Electromagnetic waves propagates through the environment
- Received signal: electromagnetic field captured by the receive antenna

- Attenuation and alternation of the transmitted signal on its way to the receiver
- Comprises antenna characteristics and the propagation environment

Rules of propagation are well known

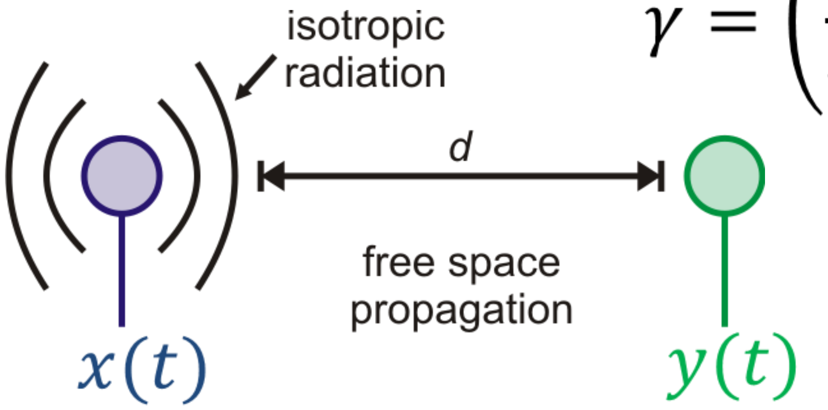
Maxwell equations

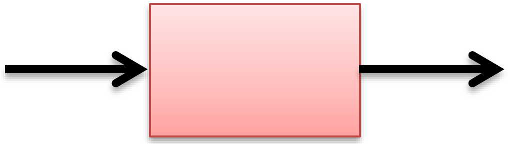


Dipole antenna
Source: Wikipedia

Example: free space path loss

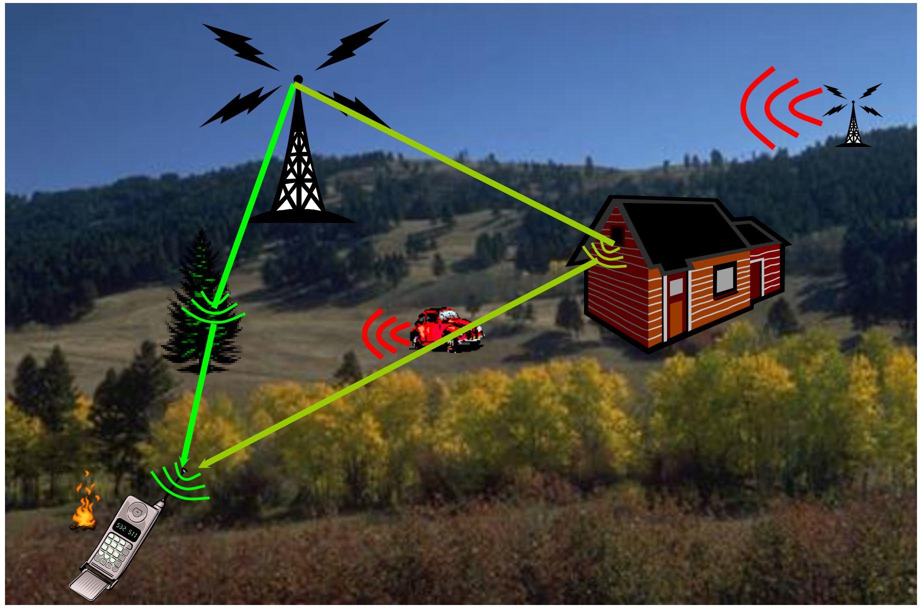
$$\gamma = \left(\frac{c}{4\pi f d}\right)^2$$





$$y(t) = x(t)\gamma$$

The wireless channel



- Path loss
- Shadowing
- Scattering and fast fading
- Multipath propagation
- Thermal noise
- Interference

The propagation environment alters the signal before it arrives at the receiver

- Many other parameters are inherently unknown: e.g., time delay between transmitter and receiver, or uncertainties in the carrier frequency

In addition to the unknown transmitted signal, the receiver does not know the parameters of the channel

Uncertainties

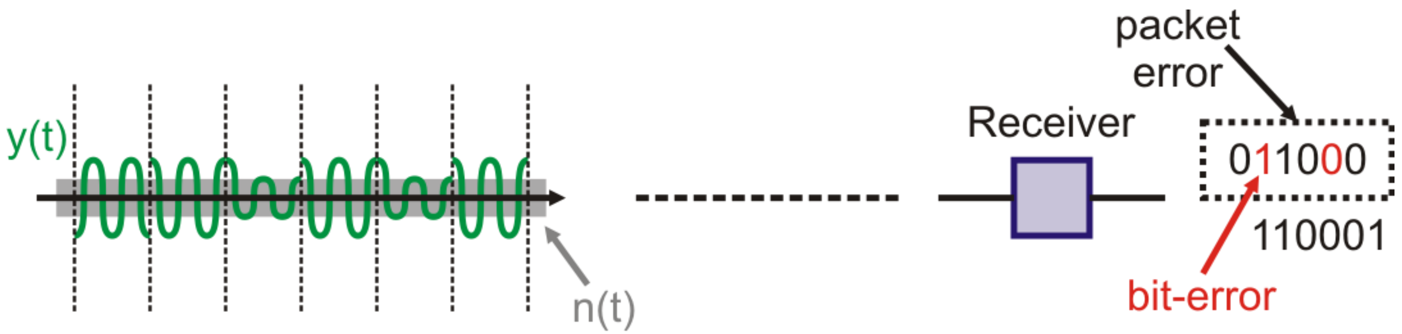
In reality, transmitter and receiver are far apart and not automatically synchronized

Besides the actual data, many other parameters are unknown to the receiver

- Frame timing: when is a block of information starting?
- Channel parameters: how was the signal altered in the channel?
- Sampling frequency: what is the right moment to sample a symbol?
- Carrier frequency: what is the precise RF frequency at which the data is transmitted?

Unknown parameters must be known in order to recover the data correctly

Receiver tasks and the principle of synchronized detection



Recover the transmitted symbols from the received signal

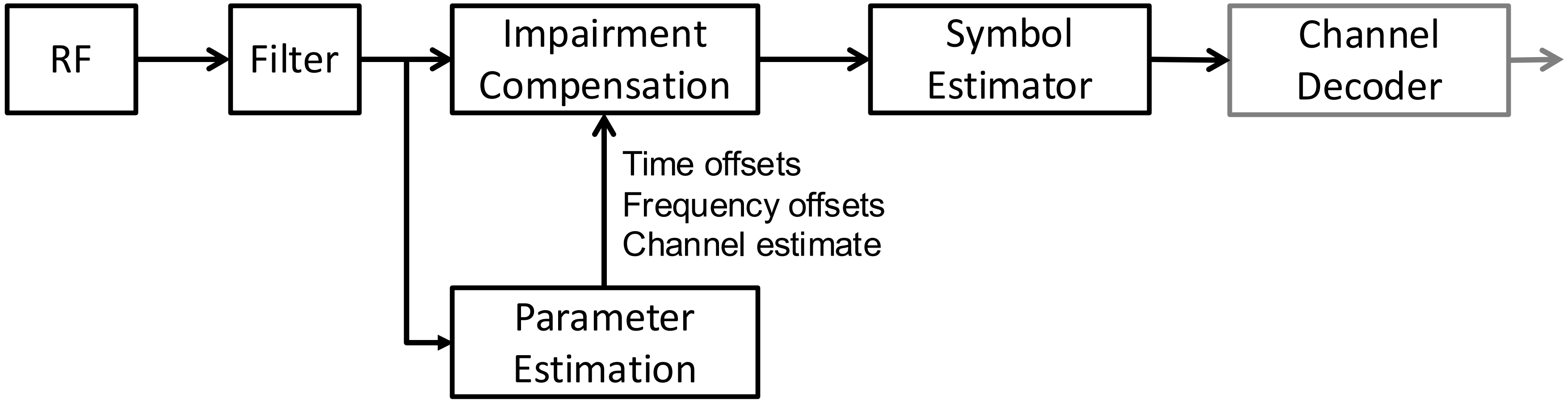
- Estimate unknown system (timing and frequency offset) and channel parameters
- Correct non-idealities such as timing or frequency offset
- Undo the mapping (modulation) done in the transmitter
- Remove interfering signals as much as possible
- Remove distortions on the signal caused during transmissions
- Perform the best possible estimate of the transmitted signal in the presence of residual noise, distortions, and interference

Synchronized detection: estimate unknown parameters before or while receiving data and use estimates as if they were the real values

Receiver Architecture

Receiver composed of various estimation blocks

- Estimation of unknown transmission parameters
- Recovery of the transmitted symbols

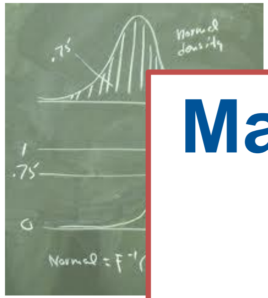


We systematically construct these algorithms from scratch by

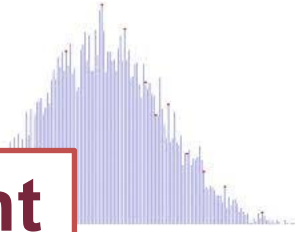
- Setting up a mathematical model of the transmission
- Formulating the objective for the receiver: e.g., minimizing the risk of errors
- Solving for what we are looking for

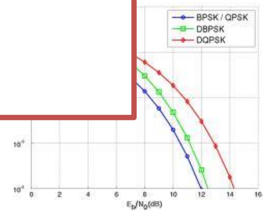
Methodology and tools

Analytical math



Monte carlo computer simulation





Mathematical Theory and Experiment are complementary

1. **System description: signals, algorithms and channel model**
2. Analytical performance analysis based on simplified models provides intuition
3. Synthesis: Estimation and detection theory used to systematically derive (optimum) receiver structures
4. Mathematical analysis used to compute performance bounds

1. Verify theoretical calculations
2. Evaluate performance for complex models channel models
3. Include effects that can not be evaluated analytically (e.g., implementation loss)

EPFL

Lab sessions

How the lab session works:

- Exercises instruction on Moodle released each week
- Write and test your solution on MATLAB
- Submit your code on MATLAB Grader (No need to submit anything on Moodle)
- During the week after the submission deadline, the solutions will be available on Moodle as well as a feedback for every question asked