CS356R: Introduction to Wireless Networking

Lili Qiu
UT Austin

Spring 2026

Course Information

- Instructor: Lili Qiu, lili@cs.utexas.edu
- Office: GDC 6.806
- Lecture: M/W 3:30 – 5pm @ ECJ 1.204
- Office hour: M 10-11am
- Course homepage: http://www.cs.utexas.edu/~lili/classes/S26-CS356R
- http://piazza.com

Course Material

- Required textbook
  - Mobile Communications by Jochen Schiller

- Recommended references
  - Computer Networking: A top down approach featuring the Internet by James Kurose and Keith Ross
  - 802.11 Wireless Networks: The Definitive Guide by Matthew S. Gast
  - Fundamentals of Wireless Communications by David Tse
  - Ad Hoc Networking by Charles E. Perkins

Course Workload

- Grading
  - Quizzes: 20%
  - Homework: 30%
  - Exam I: 22% (2/25)
  - Exam II: 28% (4/27)
- We will strictly enforce UTCS code of conduct
  - You need to write the solution.
  - No sharing of course materials with current or future students
  - https://wikis.utexas.edu/display/coursematerials/Sample+Use+Statements+for+Syllabus

Course Overview

- Part I: Introduction to wireless networks
  - Physical layer
  - MAC
    - Introduction to MAC and IEEE 802.11
    - Rate adaptation
    - Packet recovery
  - Routing
    - Mobile IP
    - DSR, AODV, DSDV
  - Transport protocols in wireless networks
    - Problems with TCP over wireless
    - Other proposals

Course Overview (Cont.)

- Part II: Different types of wireless networks
  - Wireless Sensing
  - Cellular networks
  - Wireless Security
  - AI + Wireless
  - Smart Surfaces

History of Wireless Communication

History

- Tesla credited with first radio communication in 1893
- Wireless telegraph invented by Guglielmo Marconi in 1896
- First telegraphic signal traveled across the Atlantic ocean in 1901
- Used analog signals to transmit alphanumeric characters

Satellites

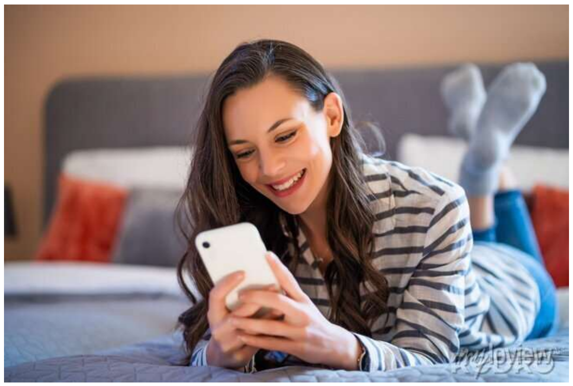
- Launched in 1960
- First satellites could carry 240 voice circuits
- In 1998 satellites carried:
  - 1/3 of all voice traffic
  - All television signals between countries!
- Modern satellites induce 250 ms propagation delay
- New ones in lower orbits can allow for data services such as Internet access

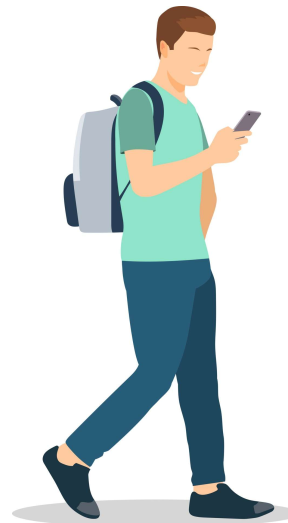
Mobile Phones

- 2-way 2-party communication using digital transmission technology
- In 2002 the number of mobile phones exceeded that of land lines
- More than 1 billion mobile phones!
- The only telecommunications solution in developing regions
- How did it all start?

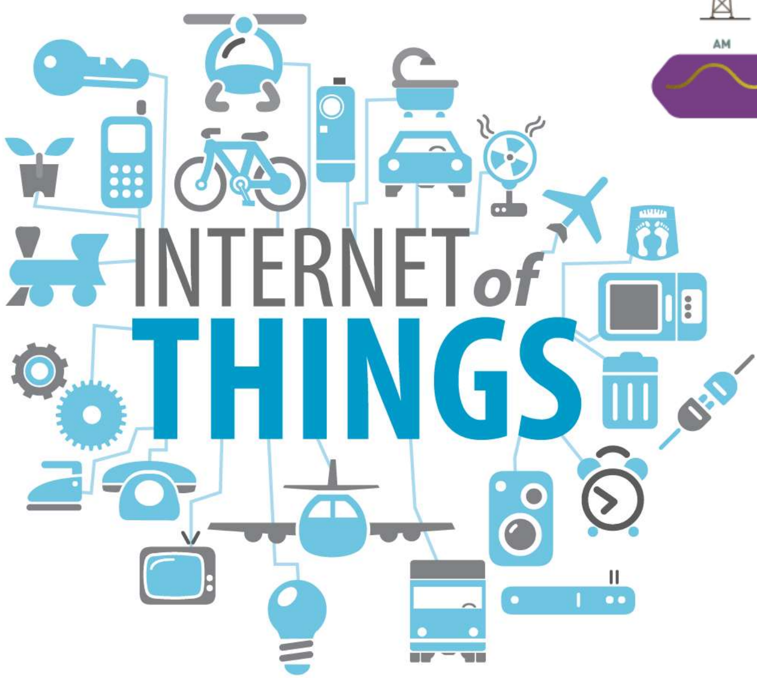
Introduction to Wireless Networks

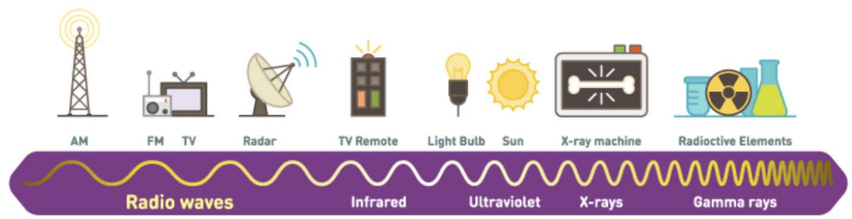
Impacts of Wireless Technology





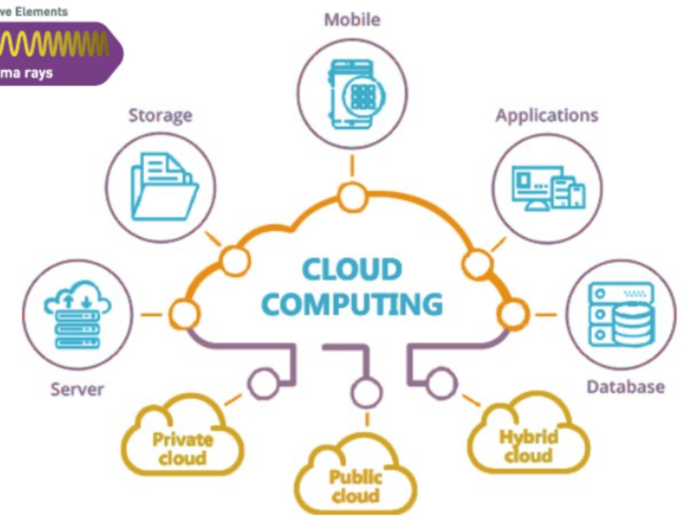
Motivation for Wireless Communication

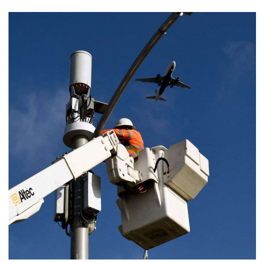




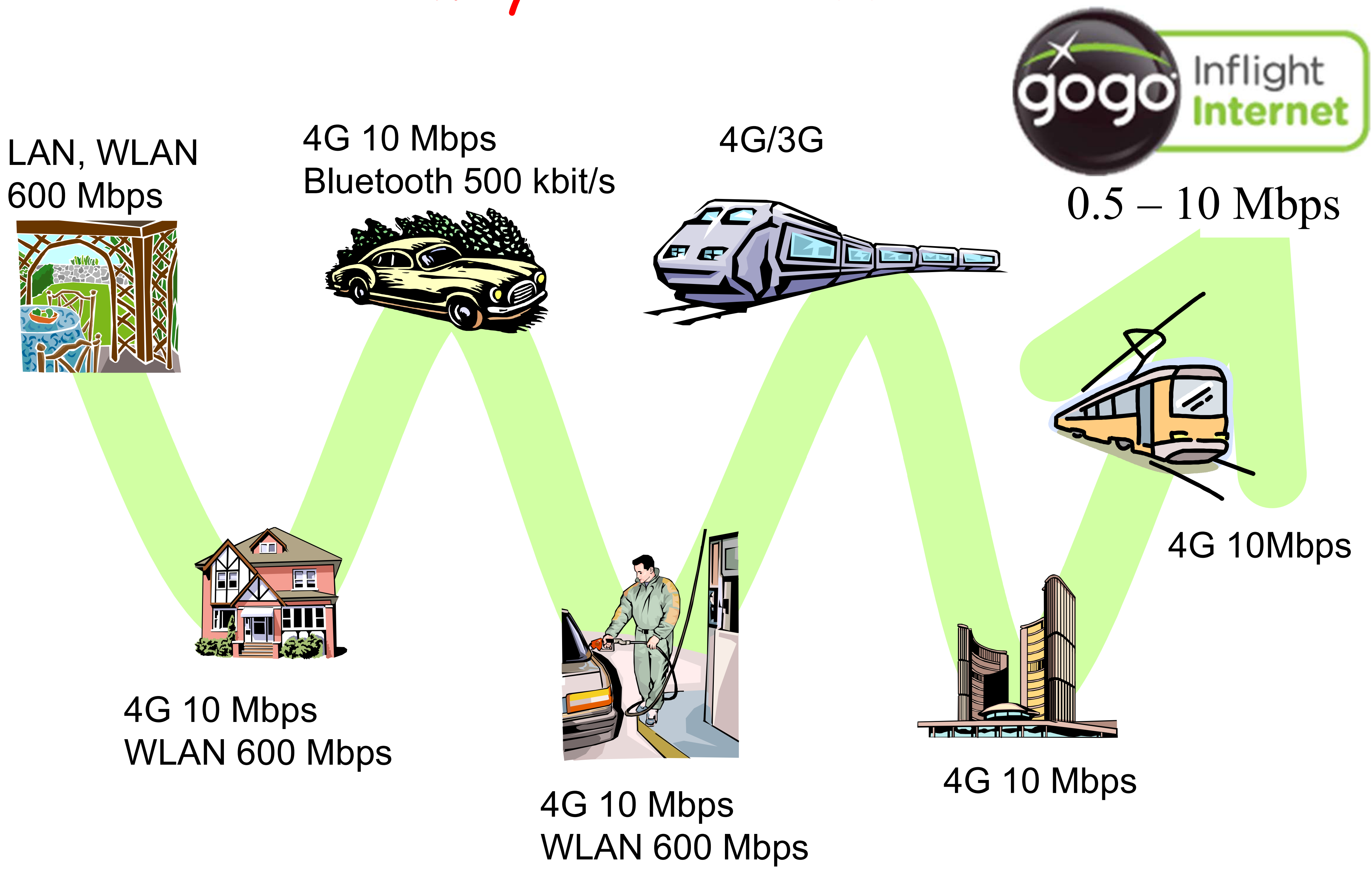
Wireless networks

(Wi-Fi, 5G, satellites, …)

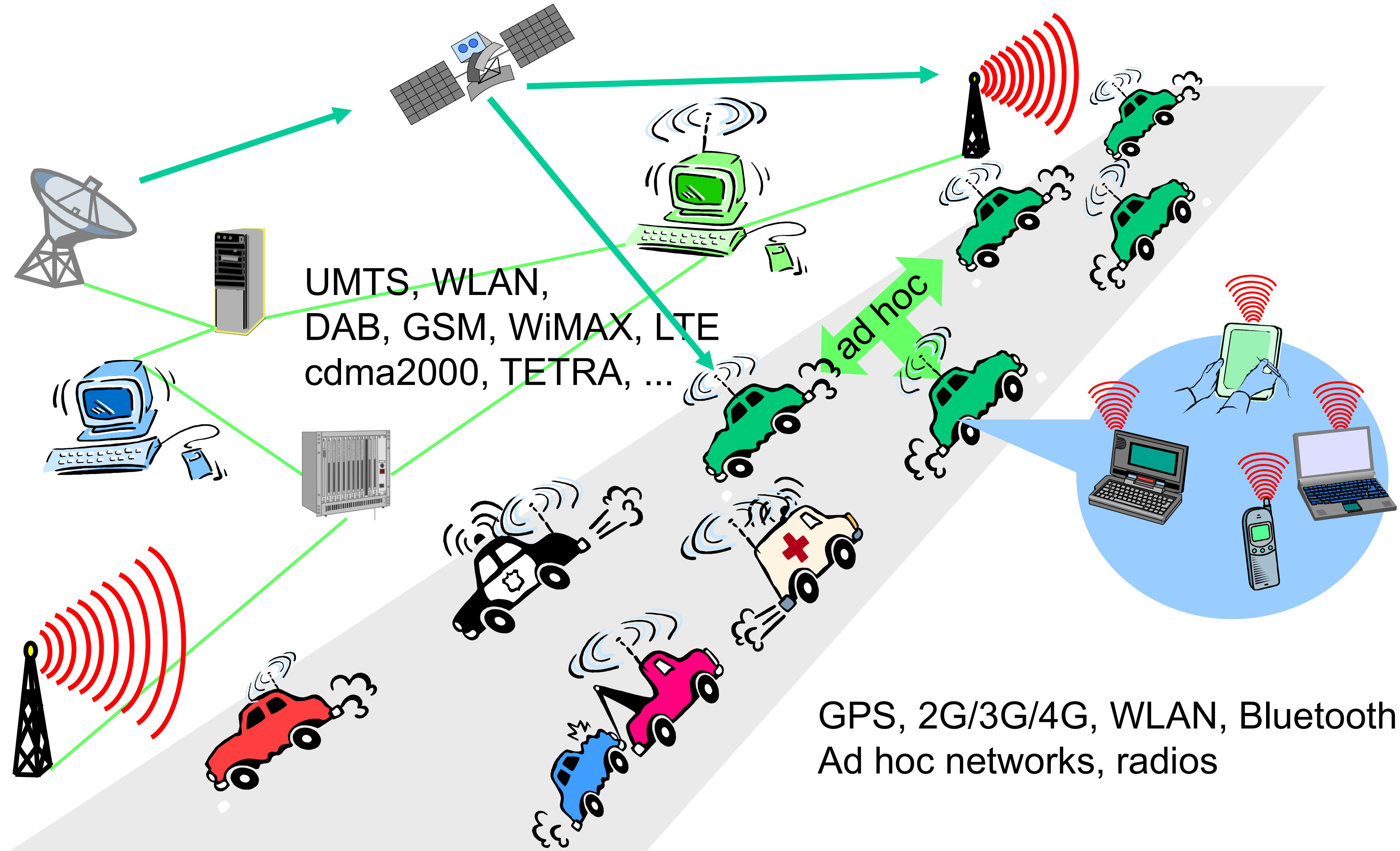




Mobile and Wireless Services – Always Best Connected



On the Road



UMTS, WLAN,
DAB, GSM, WiMAX, LTE
cdma2000, TETRA, ...
ad hoc
GPS, 2G/3G/4G, WLAN, Bluetooth,
Ad hoc networks, radios

WI-FI TECHNOLOGY

WiFi Evolution: From WiFi 5 to WiFi 7

WiFi 5

Standard: 802.11ac (2013)

Max Speed: 3.5 Gbps

Channel Width: 160 MHz

Modulation: 256-QAM

MIMO: 4x4 DL MU-MIMO

Latency: 30-50 ms

WiFi 6/6E

Standard: 802.11ax (2019-20)

Max Speed: 9.6 Gbps

Channel Width: 160 MHz

Modulation: 1024-QAM

MIMO: 8x8 DL+UL MU-MIMO

Latency: 10-30 ms

WiFi 7

Standard: 802.11be (2024)

Max Speed: 46 Gbps

Channel Width: 320 MHz

Modulation: 4096-QAM

MIMO: 16x16 DL+UL

Latency: <5 ms

Key WiFi 7 Innovations

1. **Multi-Link Operation (MLO)**
   Simultaneous operation across 2.4, 5, and 6 GHz bands for higher speeds and seamless roaming
2. **Multi-Resource Units (MRU)**
   Enhanced OFDMA with flexible resource allocation, 4× more subcarriers than WiFi 6
3. **Advanced Preamble Puncturing**
   Avoids interfered sub-channels, maximizing spectrum utilization

WiFi 7 Use Cases

AR/VR Applications
Sub-5ms latency for immersive experiences

8K Streaming
46 Gbps supports uncompressed video

Dense IoT Deployments
Support for 26,000+ devices per AP

LIGHT-BASED COMMUNICATION

LiFi Technology: Illuminating Connectivity

How LiFi Works

LiFi uses **Light Fidelity** to transmit data through LED light modulation. It works by varying light intensity at high speeds (imperceptible to the human eye) to send data to receivers, which convert light signals back to electronic data.

Key Mechanism:

- LED bulbs modulate at nanosecond speeds
- Photodiodes receive and decode signals
- Standard LED infrastructure can be retrofitted

10,000×
Broader spectrum than radio

100×
Faster than WiFi

LiFi vs WiFi Comparison

Security

LiFi: Military-grade
Light doesn't penetrate walls

WiFi: Vulnerable
RF signals leak through walls

Speed

LiFi: Ultra-high
No spectrum congestion

WiFi: High
Shared RF spectrum

Interference

LiFi: None
Immune to RF interference

WiFi: Moderate
Affected by congestion

Advantages

Enhanced Security
Confined to illuminated areas, no wall penetration

High Speed
Access to 1000× more spectrum than RF

Energy Efficient
Piggybacks on existing LED infrastructure

Applications

- Healthcare: Secure hospital networks, medical device connectivity
- Education: High-speed classroom internet without RF interference
- Defense: Secure military communications, EM-silent environments
- Smart Homes: IoT device integration, lighting-based connectivity

SATELLITE BROADBAND

LEO Constellations: Bridging the Digital Divide

LEO vs GEO Satellite Comparison

Latency

20-40ms
LEO (500-1,200 km)

600-700ms
GEO (36,000 km)

6,000+
Starlink satellites

650
OneWeb satellites

Major LEO Constellations

Starlink (SpaceX)
6,000+ launched, targeting 12,000. Direct-to-consumer model.

OneWeb (Eutelsat)
650 satellites. B2B and government clients.

Amazon Kuiper
3,236 satellites approved. AWS ecosystem integration.

Rural Broadband

Bridging the digital divide in remote areas lacking terrestrial infrastructure

Maritime & Aviation

Continuous connectivity for ships, offshore platforms, and aircraft

Disaster Resilience

Rapid deployment when terrestrial networks fail

Strategic Integration with 5G/6G

LEO satellites are becoming integral to **non-terrestrial networks (NTN)**, providing global coverage and seamless handoffs between terrestrial and satellite networks. This convergence enables true ubiquitous connectivity, supporting IoT devices, autonomous vehicles, and critical communications anywhere on Earth. The strategic race for space-based internet reflects national priorities for digital sovereignty, economic competitiveness, and technological leadership in the emerging space economy.

INTELLIGENT TRANSPORTATION

Vehicular Networks: V2X Communication

V2V

Vehicle-to-Vehicle

Direct communication for collision avoidance, platooning, and traffic coordination.

V2I

Vehicle-to-Infrastructure

Communication with traffic lights, road sensors, and smart city infrastructure.

V2P

Vehicle-to-Pedestrian

Alerts and safety warnings for pedestrians and cyclists.

5G NR-V2X & 6G Evolution

5G NR-V2X (New Radio Vehicle-to-Everything) provides ultra-reliable low-latency communication (URLLC) for advanced automotive applications. Toward **6G**, vehicular networks will achieve sub-1ms latency, enabling truly autonomous transportation.

Ultra-Low Latency
Sub-1ms for real-time decision making

High Reliability
99.999% for safety-critical applications

Massive Connectivity
Support for millions of connected vehicles

Safety Applications

Collision Avoidance
Real-time threat detection and emergency braking

Emergency Vehicle Warning
Automatic alerts for approaching ambulances and fire trucks

Traffic Signal Priority
Green light optimization for emergency and public transport

Platooning
Coordinated vehicle following with minimal spacing

Sensor Sharing
Collective perception beyond line-of-sight

MASSIVE IOT CONNECTIVITY

LPWAN: Enabling Massive IoT

LoRaWAN

Spectrum: Unlicensed ISM

Range: 2-15 km

Data Rate: 0.3-50 kbps

Battery: 5-10 years

NB-IoT

Spectrum: Licensed cellular

Range: 10-50 km

Data Rate: 20-250 kbps

Battery: 10+ years

LTE-M

Spectrum: Licensed cellular

Range: 10-50 km

Data Rate: 200 kbps-1 Mbps

Battery: 5-10 years

Key Characteristics

5-10 Year Battery
Deep sleep modes

Long Range
10-50 km coverage

Low Cost
$5-20 per module

Massive Scale
Millions of devices

Sector Applications

Smart Agriculture
Soil monitoring, livestock tracking

Utilities
Smart metering, leak detection

Smart Cities
Parking, waste management

Logistics
Asset tracking, cold chain monitoring

Technology Comparison & Selection

LoRaWAN

Private networks, long battery life, unlicensed spectrum flexibility

NB-IoT

Carrier-grade reliability, indoor penetration, smart metering

LTE-M

Higher data rates, mobility, real-time tracking applications

6G ENABLER

Terahertz Communication: The 6G Frontier

The Terahertz Spectrum

Terahertz frequencies (100 GHz to 10 THz) offer massive bandwidth for **terabit-per-second (Tbps)** speeds, addressing 5G spectrum scarcity.

D Band (110-170 GHz)
Primary research focus for 6G

H Band (220-330 GHz)
Future expansion potential

1000×
More bandwidth

<1ms
Ultra-low latency

6G Applications

Holographic Communication
Real-time, high-definition holograms for remote collaboration

Wireless Data Centers
Ultra-high-capacity wireless backhaul, flexible data center design

Wireless Networks on Chips
Sub-millimeter terahertz transceivers for chip-to-chip communication

Ultra-Capacity Backhaul
Rural connectivity, digital divide bridging

Industrial Holography
Remote operation, immersive design

Nano-Things Internet
Biomedical sensors, smart dust networks

Challenges & Research Directions

Key Challenges:

- **Device Technology:** Limited commercial THz components
- **Transmission Range:** High path loss, short distance
- **System Integration:** Antenna design, signal processing

6G Vision:

- THz complements mmWave and sub-6 GHz for a multi-layer architecture
- Integrated sensing and AI-driven network optimization
- Seamless connectivity from terrestrial to satellite networks

Motivation for Wireless Sensing

- AI advances depend on the availability of data
- Conventional AI rely on visual and auditory data
- Wireless sensing expands the horizon

Capabilities:

- ✓ Perceive beyond line of sight and in the dark
- ✓ Detect subtle movement (e.g., breathing)
- ✓ Sense various physical properties & chemical composition (e.g., salt, glucose, fat, pollutant)

Advantages:

- ➢ Privacy preserving
- ➢ Energy efficient
- ➢ Non-invasive
- ➢ Device-free support

BEYOND COMMUNICATION

Wireless Sensing: Beyond Traditional Communication

WiFi Channel State Information (CSI)

Wireless sensing exploits WiFi signals to detect environmental changes. **CSI** captures how signals travel from transmitter to receiver, revealing disturbances caused by movement, presence, or activities.

Key Principle:

Human movement alters multipath propagation. By analyzing these changes, systems infer presence, motion, and activities **without cameras**.

Sub-mm
Detection accuracy

Through-wall
Sensing capability

Sensing Applications

Elderly Care
Fall detection, daily activity monitoring, emergency alerts

Smart Homes
Occupancy sensing, HVAC automation, intrusion detection

Healthcare
Vital sign monitoring, breathing pattern analysis

Privacy-Preserving
No cameras or visual recording

Infrastructure-Free
Leverages existing WiFi networks

Through-Wall
Senses through obstacles

Emerging Technologies: mmWave & Terahertz Sensing

Higher frequencies offer **sub-millimeter resolution**, enabling:

- **Gesture recognition:** Touchless device control
- **Vital sign monitoring:** Heart rate, respiration
- **Object identification:** Material characterization

Integrated Sensing and Communication (ISAC) is a key 6G pillar:

- Dual-use signals for communication and sensing
- Enhanced environmental awareness
- Smart city and autonomous driving applications

PERSONAL HEALTH ECOSYSTEM

Wearable Sensing: Personal Health Monitoring

Common Sensors

- **ECG**
  Heart electrical activity
- **SpO_2**
  Blood oxygen saturation
- **Temperature**
  Body and skin temperature
- **Accelerometer**
  Movement and orientation

Communication Protocols

- **BLE**
  Low-power, short-range
- **Wi-Fi**
  High-speed data sync
- **3G/4G/5G**
  Remote monitoring

Data Flow:

Sensors → Microcontroller → Communication Module → **Cloud Platform** → AI Analytics → **EHR Integration**

Healthcare Applications

Cardiac Monitoring
Continuous ECG for arrhythmia detection

Blood Glucose
Non-invasive glucose monitoring

Blood Pressure
Cuffless BP monitoring

Sleep Monitoring
Sleep stages, apnea detection

Key Challenges

Battery Life
5-10 day operation, solar charging

Sensor Accuracy
Medical-grade validation required

Data Security
HIPAA compliance, end-to-end encryption

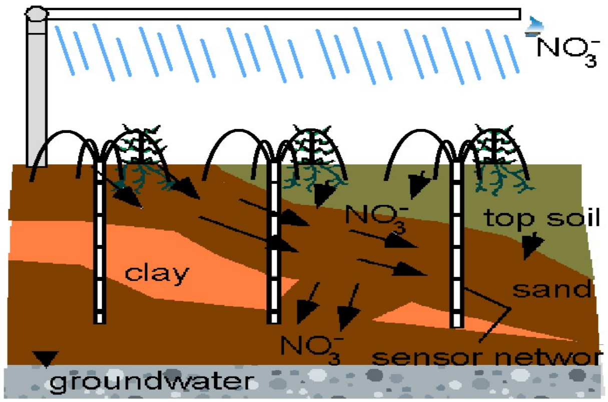
The Internet of Medical Things (IoMT) is revolutionizing healthcare through continuous, real-time monitoring and AI-powered early intervention.

Environmental Monitoring

Ecosystems, Biocomplexity

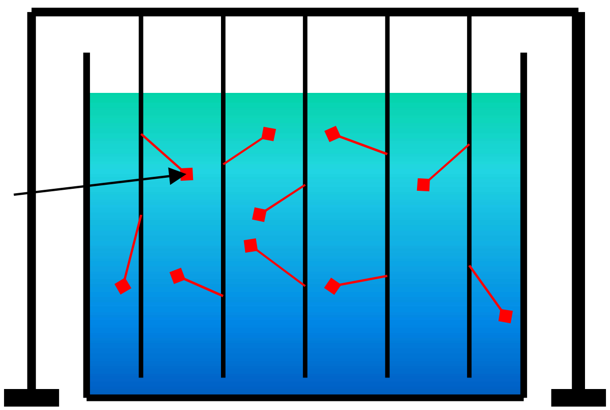
- Micro-sensors, on-board processing, wireless interfaces feasible at very small scale--can monitor phenomena "up close"
- Enables spatially and temporally dense environmental monitoring

Embedded Networked Sensing will reveal previously unobservable phenomena

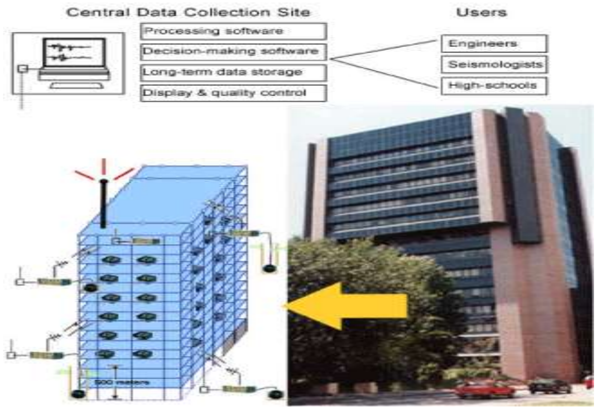


Contaminant Transport

Marine Microorganisms

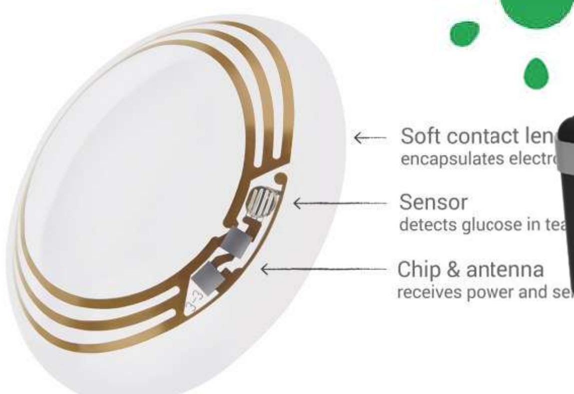


Seismic Structure Response



Wearable Technology

kiwi
wearable tech



CUTTING THE CORD

Wireless Power Transfer: Cutting the Cord

Near-Field WPT

WPT

Uses **inductive coupling** for power transfer over short distances (mm to cm).

Applications:
Smartphone charging, EV charging, biomedical implants

Efficiency:
60-95% for well-aligned coils

Far-Field WPT

Uses **RF/microwave radiation** for long-distance power transfer (m to km).

Applications:
IoT sensors, RFID, UAV powering

Efficiency:
Up to 66% with beamforming

Smartphone Charging
Qi standard, 5-15W

Medical Implants
Non-invasive charging

Smart Textiles
Wearable sensors

Simultaneous Wireless Information and Power Transfer (SWIPT)

SWIPT uses the same RF signal to carry both information and power, ideal for low-power IoT devices.

Key Challenges:

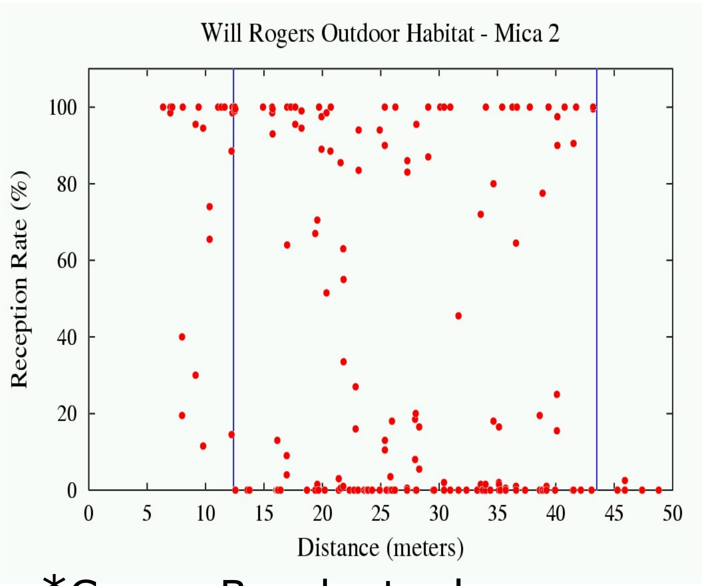
- Efficiency vs. distance trade-offs
- Safety concerns and regulatory limits
- Standardization needs for interoperability

Challenges in Wireless Networking Research

Challenge 1: Unreliable and Unpredictable Wireless Links

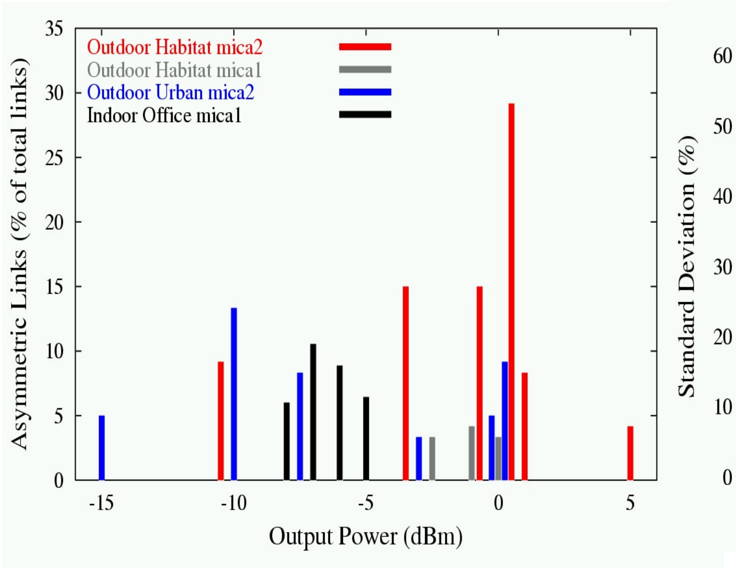
- Wireless links are less reliable
- They may vary over time and space

Reception v. Distance

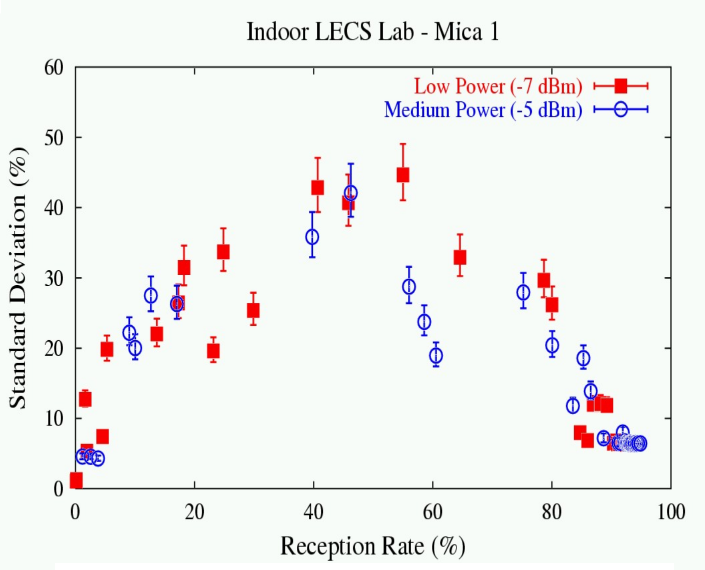


*Cerpa, Busek et. al

Asymmetry vs. Power



Standard Deviation v. Reception rate



What Robert Poor (Ember) calls "The good, the bad and the ugly"

Challenge 2: Open Wireless Medium

- Wireless interference

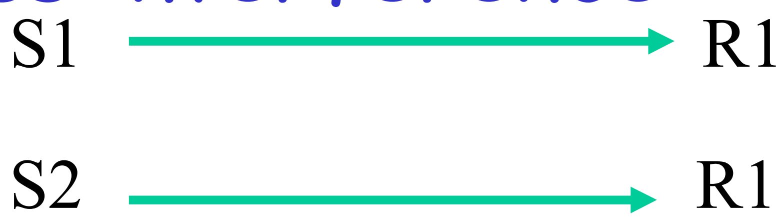
Challenge 2: Open Wireless Medium

- Wireless interference

- Hidden terminals

Challenge 2: Open Wireless Medium

- Wireless interference

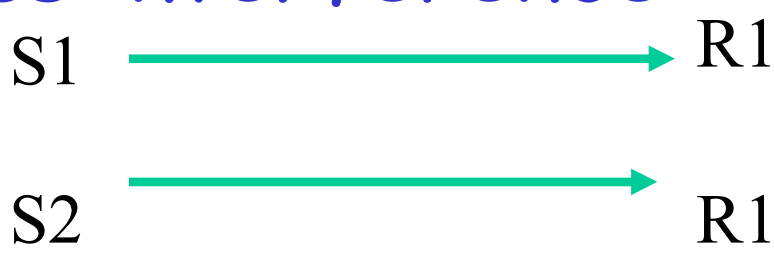


- Hidden terminals

- Exposed terminal

Challenge 2: Open Wireless Medium

- Wireless interference



- Hidden terminals

- Exposed terminals

- Wireless security
  - Eavesdropping, Denial of service, …

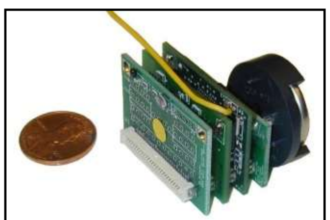
Challenge 3: Intermittent Connectivity

- Reasons for intermittent connectivity
  - Mobility
  - Environmental changes
- Existing networking protocols assume always-on networks
- Under intermittent connected networks
  - Routing, TCP, and applications all break
- Need a new paradigm to support communication under such environments

Challenge 4: Limited Resources

- Limited battery power
- Limited bandwidth
- Limited processing and storage power

Sensors, embedded controllers



Mobile phones
• voice, data
• simple graphical displa
• GSM

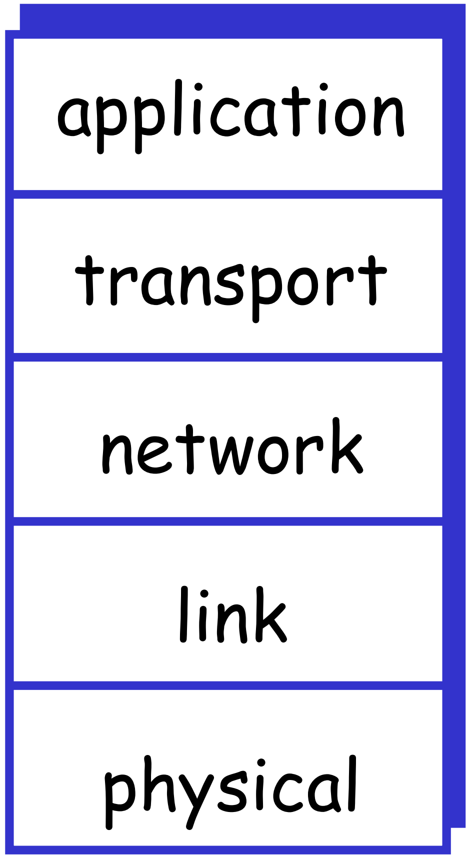
PDA
• data
• simpler graphical displays
• 802.11

Laptop
• fully functional
• standard applications
battery; 802.11

Introduction to Wireless Networking

Internet Protocol Stack

- Application: supporting network applications
  - FTP, SMTP, HTTP
- Transport: data transfer between processes
  - TCP, UDP
- Network: routing of datagrams from source to destination
  - IP, routing protocols
- Link: data transfer between neighboring network elements
  - Ethernet, WiFi
- Physical: bits “on the wire”
  - Coaxial cable, optical fibers, radios

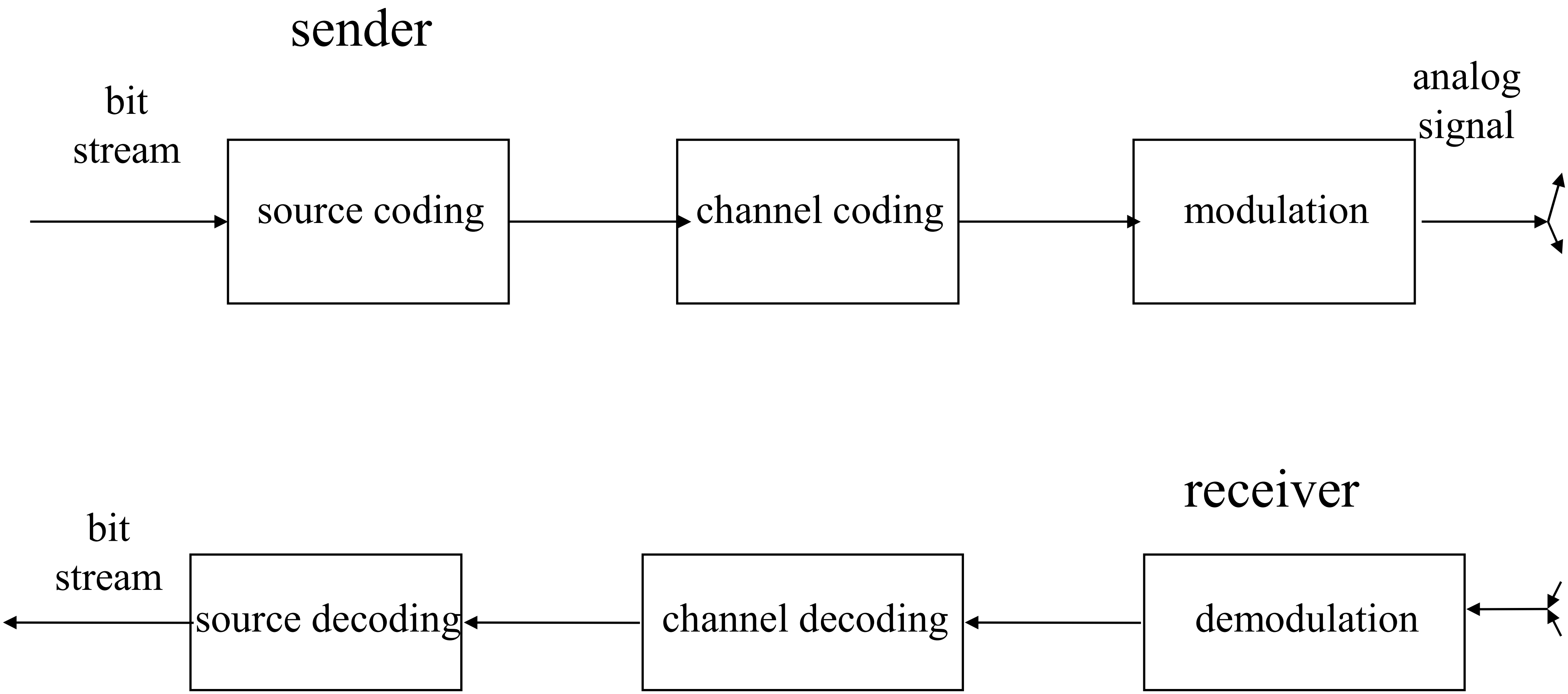


Physical Layer

Outline

- Signal
- Frequency allocation
- Signal propagation
- Multiplexing
- Modulation
- Spread Spectrum

Overview of Wireless Transmissions



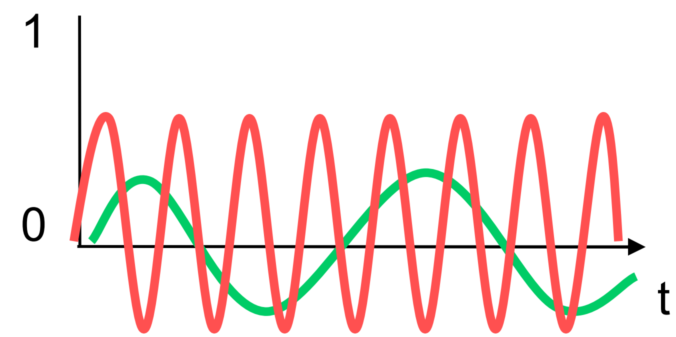
Signals

- Physical representation of data
- Function of time and location
- Classification
  - continuous time/discrete time
  - continuous values/discrete values
  - analog signal = continuous time and continuous values
  - digital signal = discrete time and discrete values

Signals (Cont.)

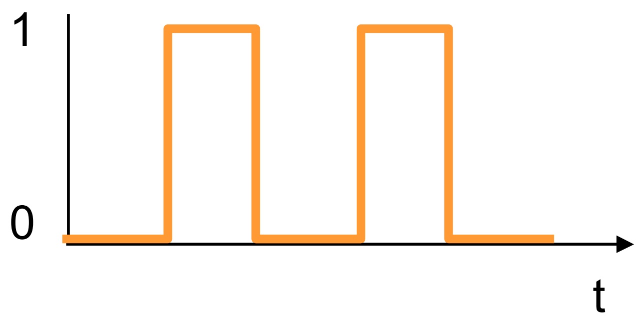
- Signal parameters of periodic signals:
  - period T, frequency f=1/T
  - amplitude A
  - phase shift φ
  - sine wave as special periodic signal for a carrier:

$$s(t) = A_t \sin(2 \pi f_t t + \varphi_t)$$

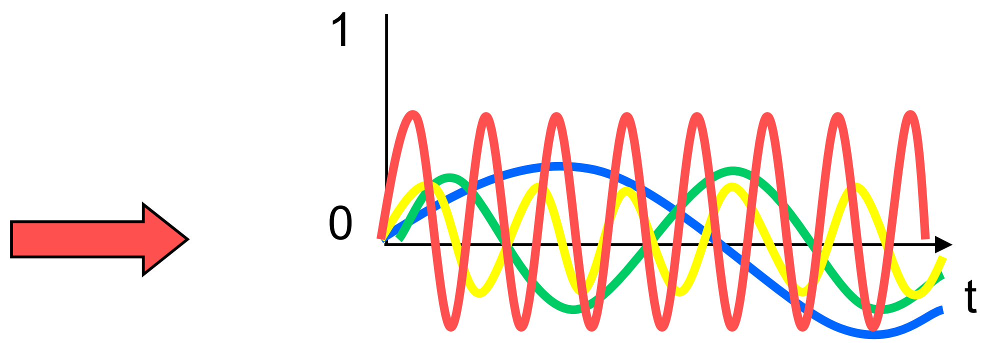


Fourier Transform: Every Signal Can be Decomposed as a Collection of Harmonics

$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi nft) + \sum_{n=1}^{\infty} b_n \cos(2\pi nft)$$

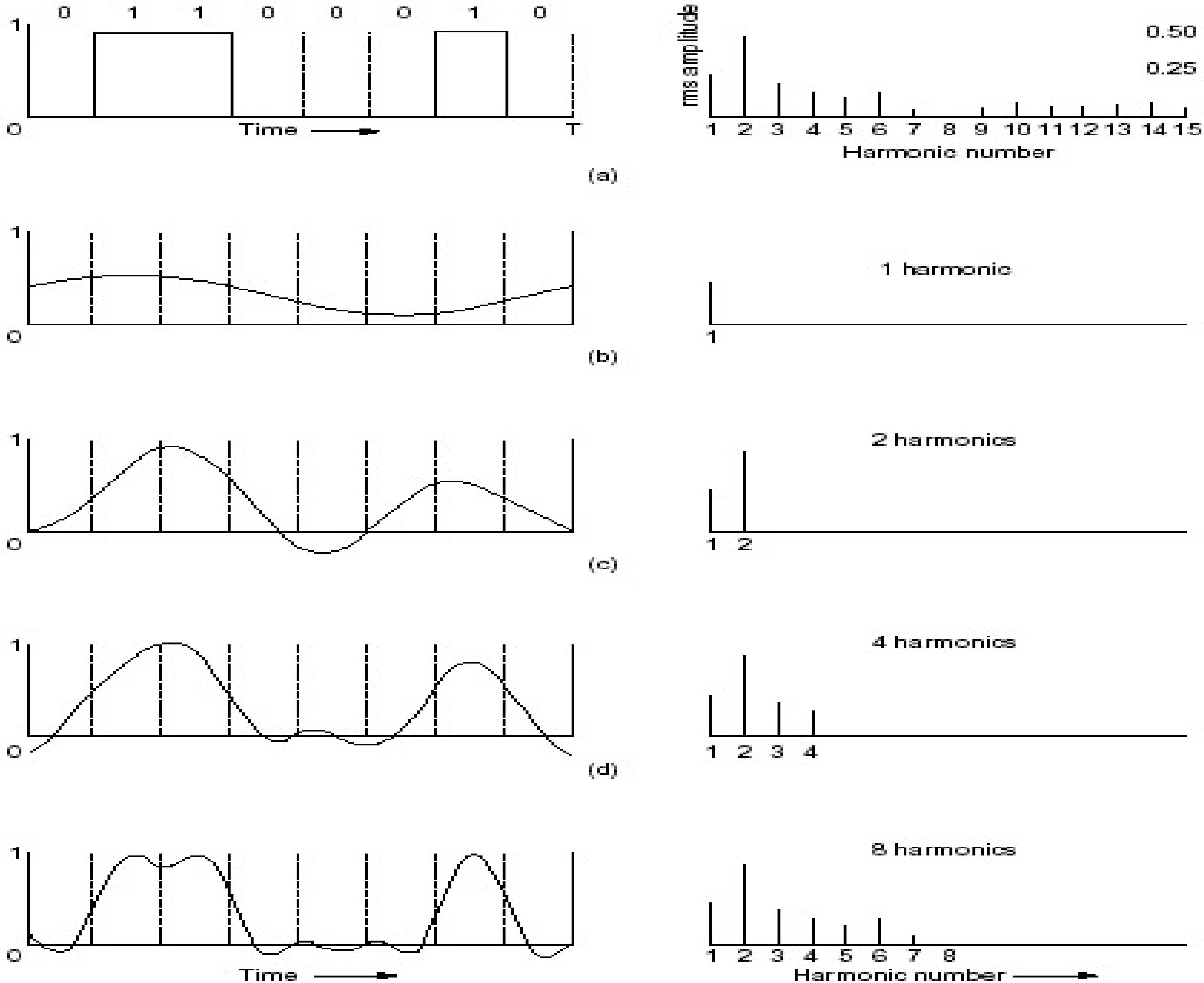


ideal periodical digital signal

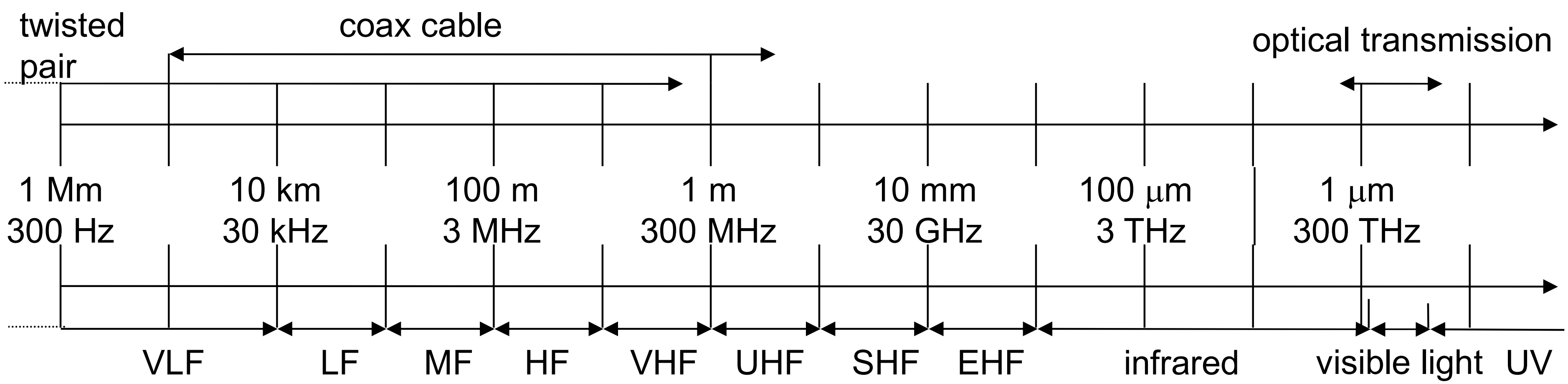


decomposition

The more harmonics used, the smaller the approximation error.


0 1 1 0 0 0 1 0
1
0
Time
T
(a)
rms amplitude
0.50
0.25
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Harmonic number
(b)
1 harmonic
(c)
2 harmonics
(d)
4 harmonics
8 harmonics
Time
Harmonic number

Frequencies for Communication



VLF = Very Low Frequency

LF = Low Frequency, submarine

MF = Medium Frequency, radio

HF = High Frequency, radio

VHF = Very High Frequency, TV

UHF = Ultra High Freq. phone

SHF = Super High Freq. WiFi

EHF = Extra High Frequency

UV = Ultraviolet Light

Frequency and wave length: $\lambda = c/f$, wave length λ, speed of light $c \cong 3 \times 10^8 m/s$, frequency f

Frequencies and Regulations

- ITU-R holds auctions for new frequencies, manages frequency bands worldwide (WRC, World Radio Conferences)

	Europe	USA	Japan
Cellular Phones	**GSM** 450-457, 479-486/460-467,489-496, 890-915/935-960, 1710-1785/1805-1880 **UMTS** (FDD) 1920-1980, 2110-2190 **UMTS** (TDD) 1900-1920, 2020-2025	**AMPS**, **TDMA**, **CDMA** 824-849, 869-894 **TDMA**, **CDMA**, **GSM** 1850-1910, 1930-1990	**PDC** 810-826, 940-956, 1429-1465, 1477-1513
Cordless Phones	**CT1+** 885-887, 930-932 **CT2** 864-868 **DECT** 1880-1900	**PACS** 1850-1910, 1930-1990 **PACS-UB** 1910-1930	**PHS** 1895-1918 **JCT** 254-380
Wireless LANs	**IEEE 802.11** 2400-2483 **HIPERLAN 2** 5150-5350, 5470-5725	902-928 **IEEE 802.11** 2400-2483 5150-5350, 5725-5825	**IEEE 802.11** 2471-2497 5150-5250
Others	**RF-Control** 27, 128, 418, 433, 868	**RF-Control** 315, 915	**RF-Control** 426, 868

Why Need A Wide Spectrum

Why Need A Wide Spectrum: Shannon Channel Capacity

- The maximum number of bits that can be transmitted per second by a physical channel is:

$$W \log_2 (1 + \frac{S}{I+N})$$

where W is the frequency range that the media allows to pass through, SINR is the signal noise ratio

Signal, Noise, and Interference

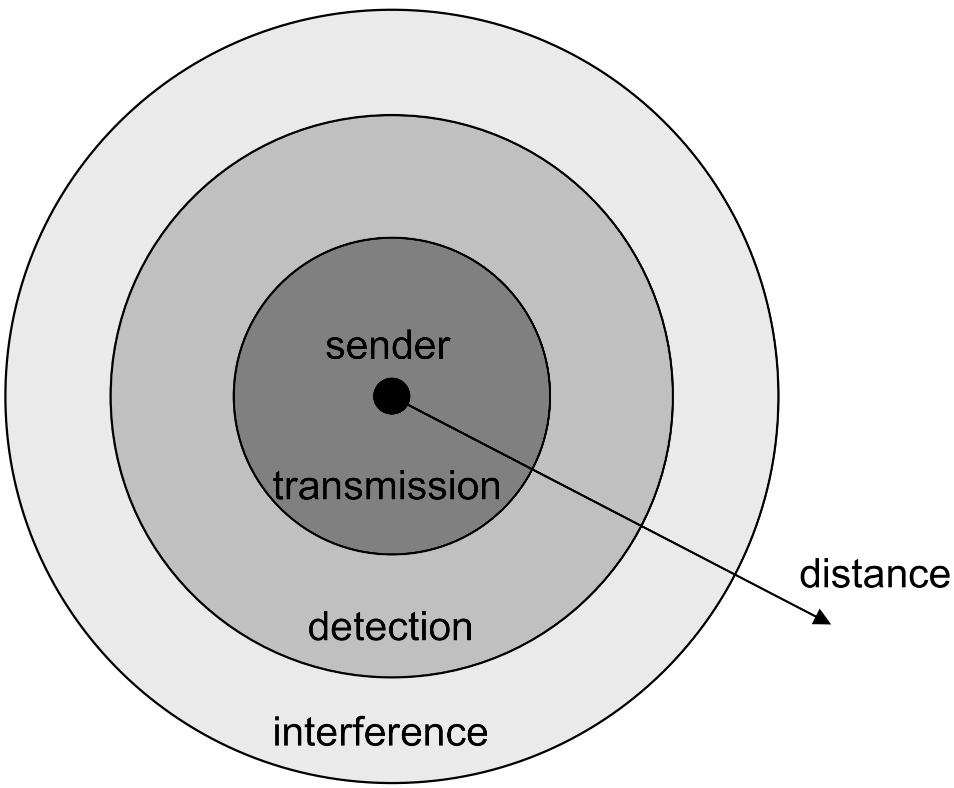
- Signal (S)
- Noise (N)
  - Includes thermal noise and background radiation
  - Often modeled as additive white Gaussian noise
- Interference (I)
  - Signals from other transmitting sources
- SINR = S/(N+I) (sometimes also denoted as SNR)

dB and Power conversion

- dB
  - Denote the difference between two power levels
  - (P2/P1)[dB] = 10 * log10 (P2/P1)
  - P2/P1 = 10^(A/10)
  - Example: P2 = 100 P1, P2/P1=10 dB
- dBm and dBW
  - Denote the power level relative to 1 mW or 1 W
  - P[dBm] = 10*log10(P/1mW)
  - P[dBW] = 10*log10(P/1W)
  - Example: P = 0.001 mW, P = 100 W

Signal Propagation Ranges

- Transmission range
  - communication possible
  - low error rate
- Detection range
  - detection of the signal possible
  - no communication possible
- Interference range
  - signal may not be detected
  - signal adds to the background noise



Outline

- Signal
- Frequency allocation
- Signal propagation
- Multiplexing
- Modulation
- Spread Spectrum

Signal Propagation

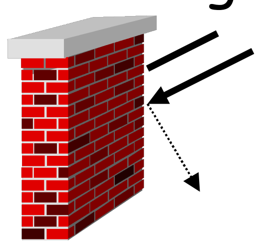
- Does signal propagation via a straight line?

Recap

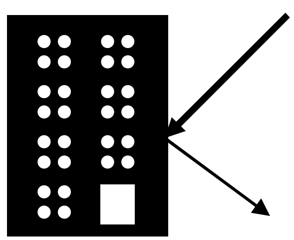
- Name 5 layers in the Internet protocol stack.
- Pros and cons of layering.
- What is a signal?
- Difference between analog vs. digital signal?
- How do we represent different signals?
- Does a signal always follow a straight line?
- Path loss models

Signal Propagation

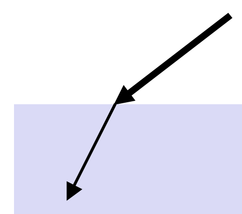
- Propagation in free space always like light (straight line)
- Receiving power proportional to $1/d^2$
  (d = distance between sender and receiver)
- Receiving power additionally influenced by
  - shadowing
  - reflection at large obstacles
  - refraction depending on the density of a medium
  - scattering at small obstacles
  - diffraction at edges
  - fading (frequency dependent)



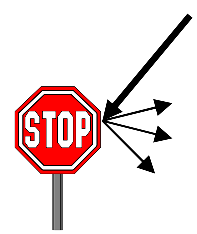
shadowing



reflection



refraction



scattering

diffraction

Path Loss

- Free space model

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

Path Loss

- Free space model

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

- Two-ray ground reflection model

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L} \qquad d_c = (4\pi h_t h_r) / \lambda$$

Path Loss

- Free space model

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

- Two-ray ground reflection model

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L}$$

$$d_c = (4\pi h_t h_r) / \lambda$$

- Log-normal shadowing

$$P(d)[dB] = \overline{P}(d)[dB] + X_\sigma$$

Path Loss

- Free space model

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

- Two-ray ground reflection model

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L} \qquad d_c = (4\pi h_t h_r)/\lambda$$

- Log-normal shadowing

$$P(d)[dB] = \overline{P}(d)[dB] + X_\sigma$$

- Indoor model

$$P_r(d)[dBm] = P_t(d)[dBm] - 10n\log\left(\frac{d}{d_0}\right) - \begin{cases} nW * WAF & nW < C \\ C * WAF & nW \geq C \end{cases}$$

Path Loss

- Free space model

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

- Two-ray ground reflection model

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L} \qquad d_c = (4\pi h_t h_r)/\lambda$$

- Log-normal shadowing

$$P(d)[dB] = \overline{P}(d)[dB] + X_\sigma$$

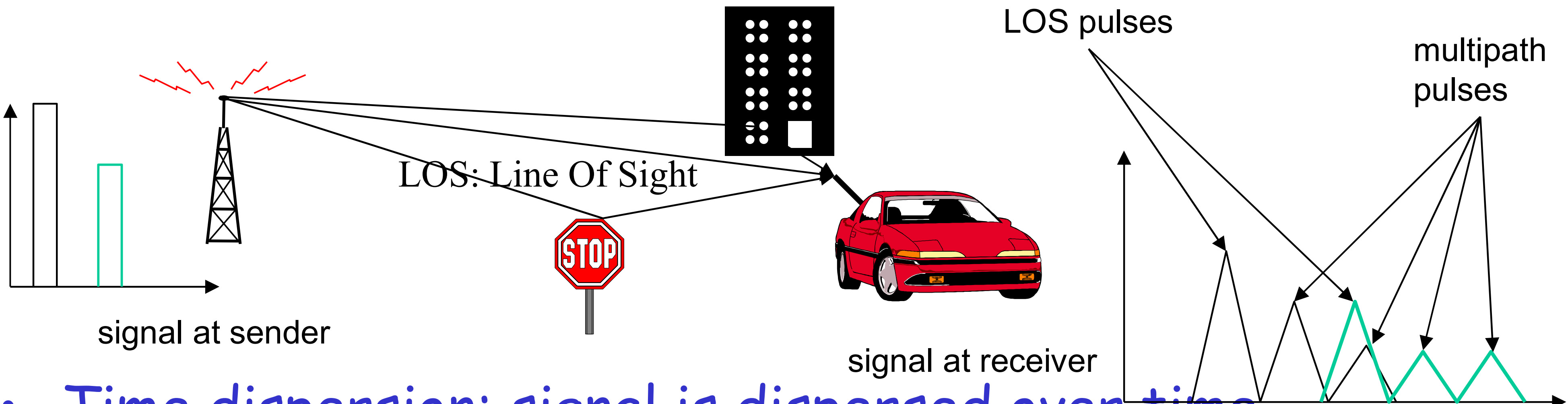
- Indoor model

$$P_r(d)[dBm] = P_t(d)[dBm] - 10n\log\left(\frac{d}{d_0}\right) - \begin{cases} nW * WAF & nW < C \\ C * WAF & nW \ge C \end{cases}$$

- P = 1 mW at d0=1m, what's Pr at d=2m?

Multipath Propagation

- Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction



- Time dispersion: signal is dispersed over time

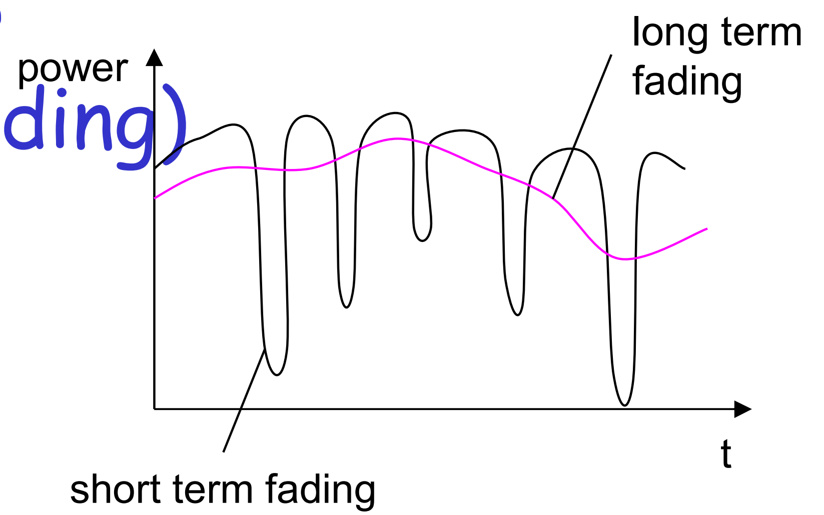
  ➔ interference with "neighbor" symbols, Inter Symbol Interference (ISI)

- The signal reaches a receiver directly and phase shifted

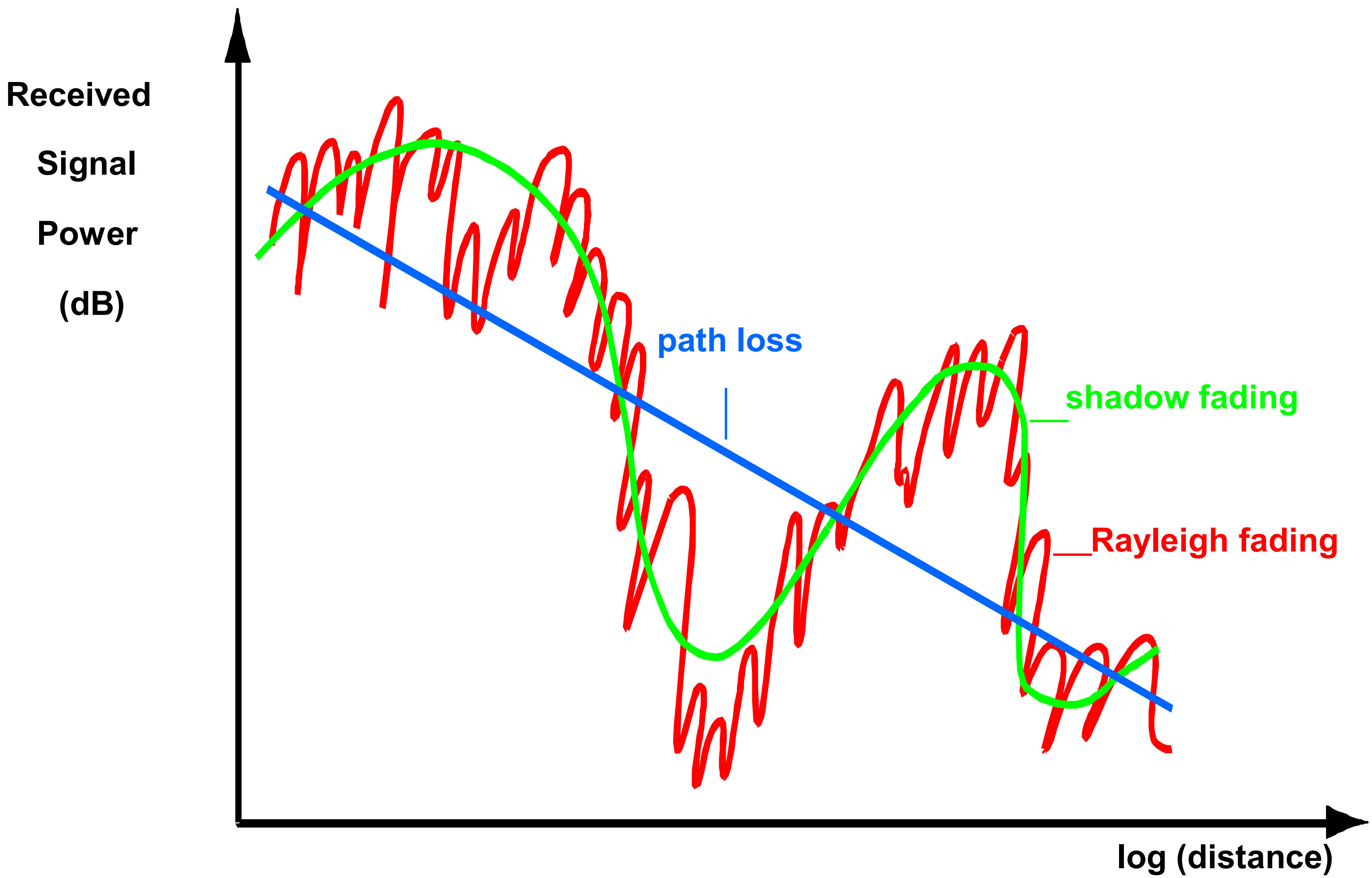
  ➔ distorted signal based on the phases of different parts

Fading

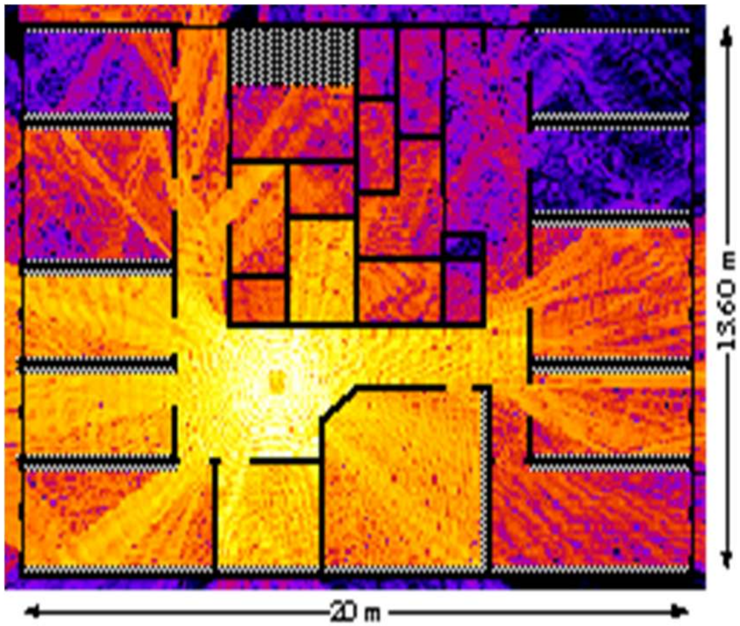
- Channel characteristics change over time and location
  - e.g., movement of sender, receiver and/or scatters
- ➔ quick changes in the power received (short term/fast fading)
- Additional changes in
  - distance to sender
  - obstacles further away
- ➔ slow changes in the average power received (long term/slow fading)

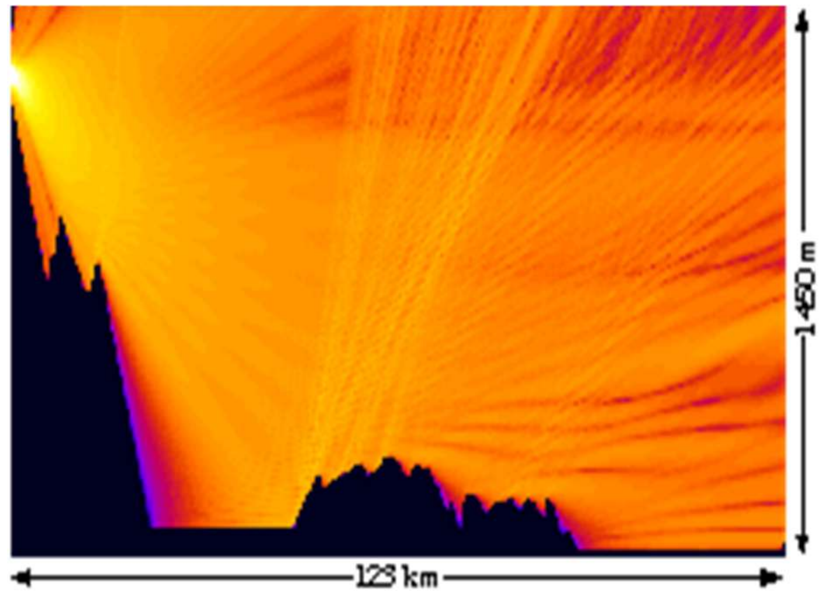


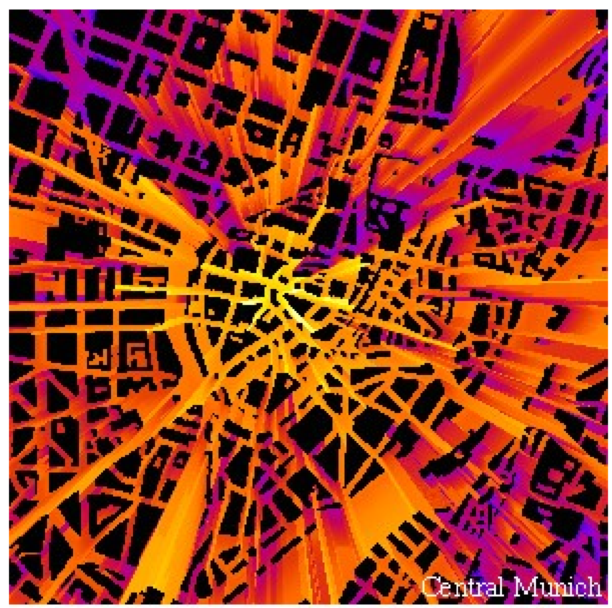
Typical Picture



Real world example







Outline

- Signal
- Frequency allocation
- Signal propagation
- Multiplexing
- Modulation
- Spread Spectrum

Multiplexing

- Goal: multiple use of a shared medium
- Multiplexing in different dimensions

Multiplexing

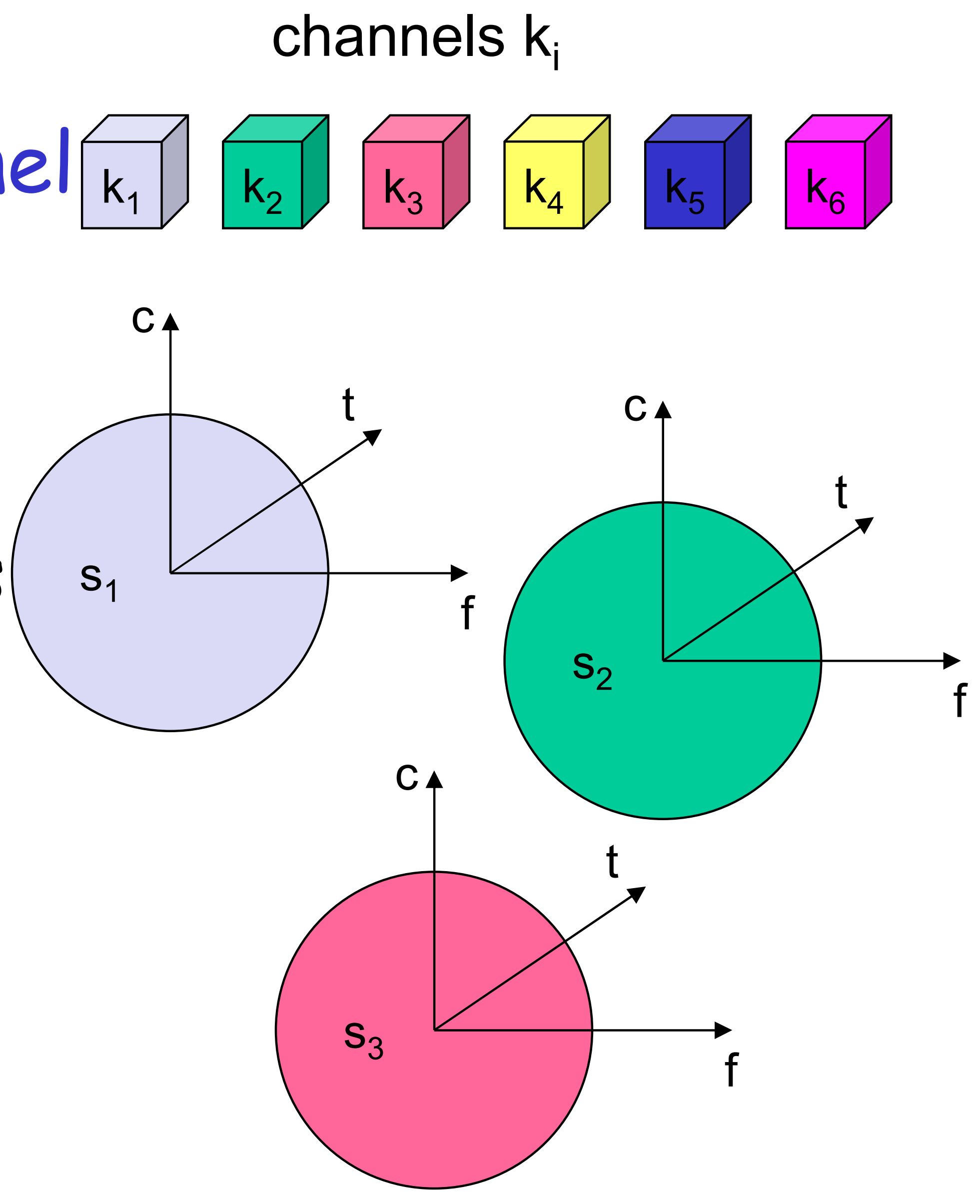
- Goal: multiple use of a shared medium

- Multiplexing in 4 dimensions
  - space (s)
  - time (t)
  - frequency (f)
  - code (c)

- Important: guard spaces needed!

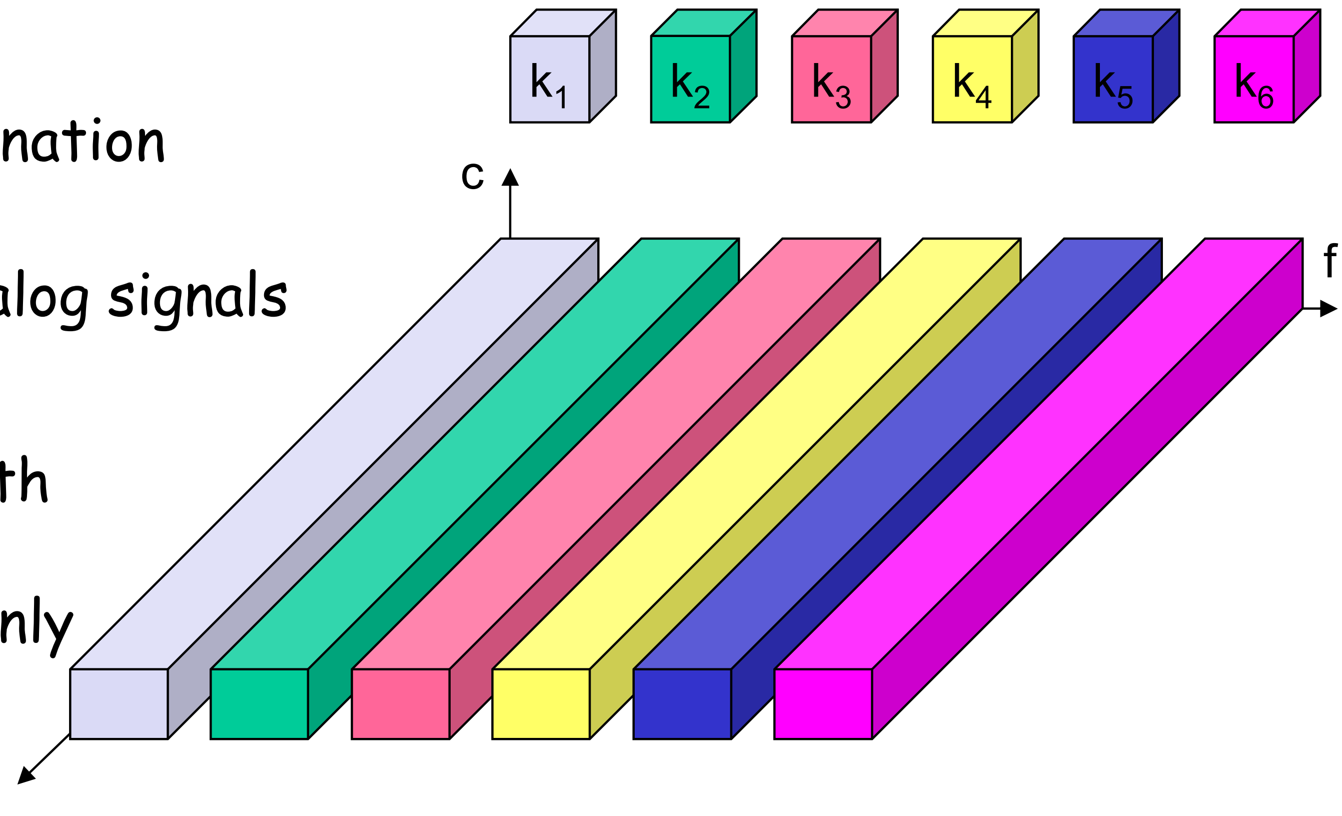
Space Multiplexing

- Assign each region a channel
- Pros
  - no dynamic coordination necessary
  - works also for analog signals
- Cons
  - Inefficient resource utilization



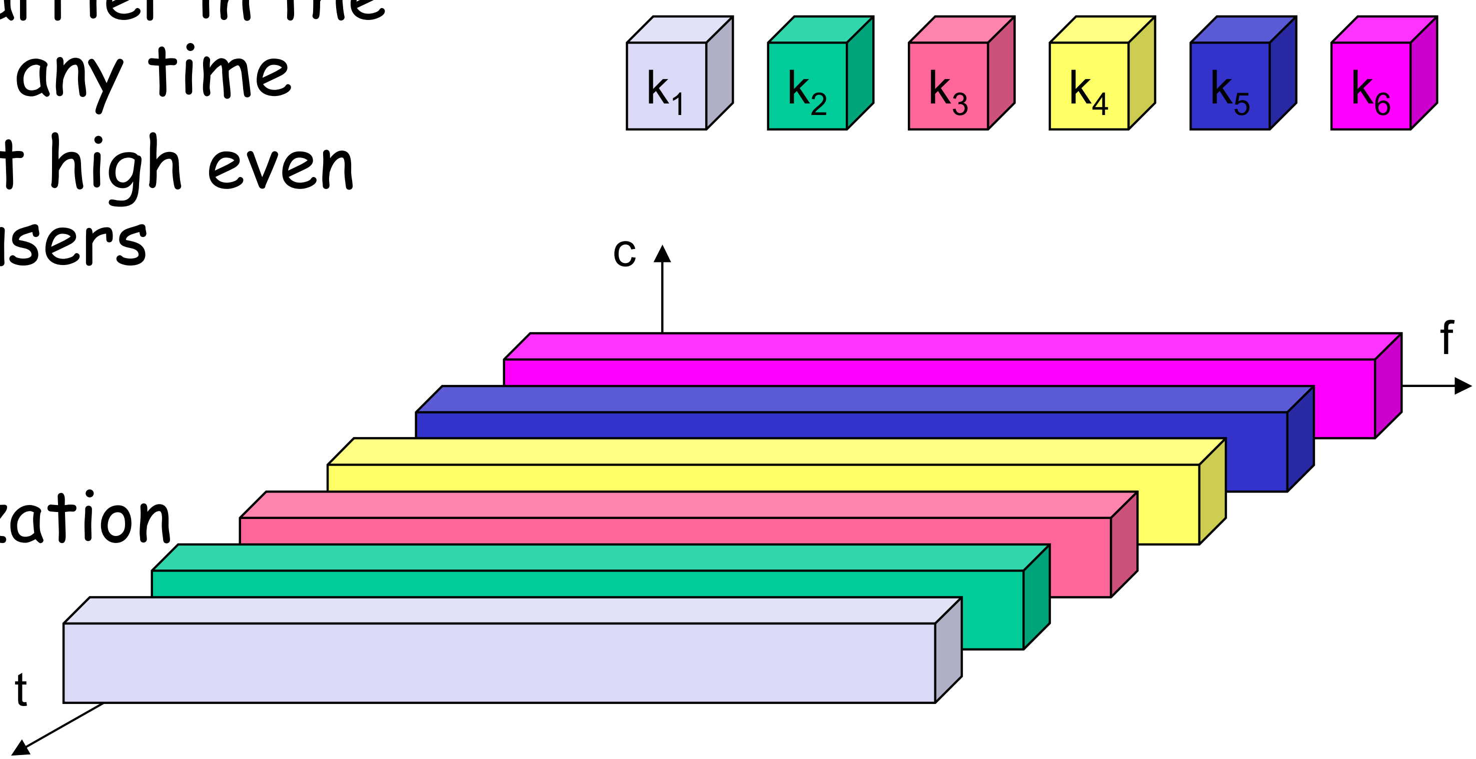
Frequency Multiplexing

- Separation of the whole spectrum into smaller frequency bands
- A channel gets a certain band of the spectrum for the whole time
- Pros:
  - no dynamic coordination necessary
  - works also for analog signals
- Cons:
  - waste of bandwidth if the traffic is distributed unevenly
  - Inflexible
  - guard spaces



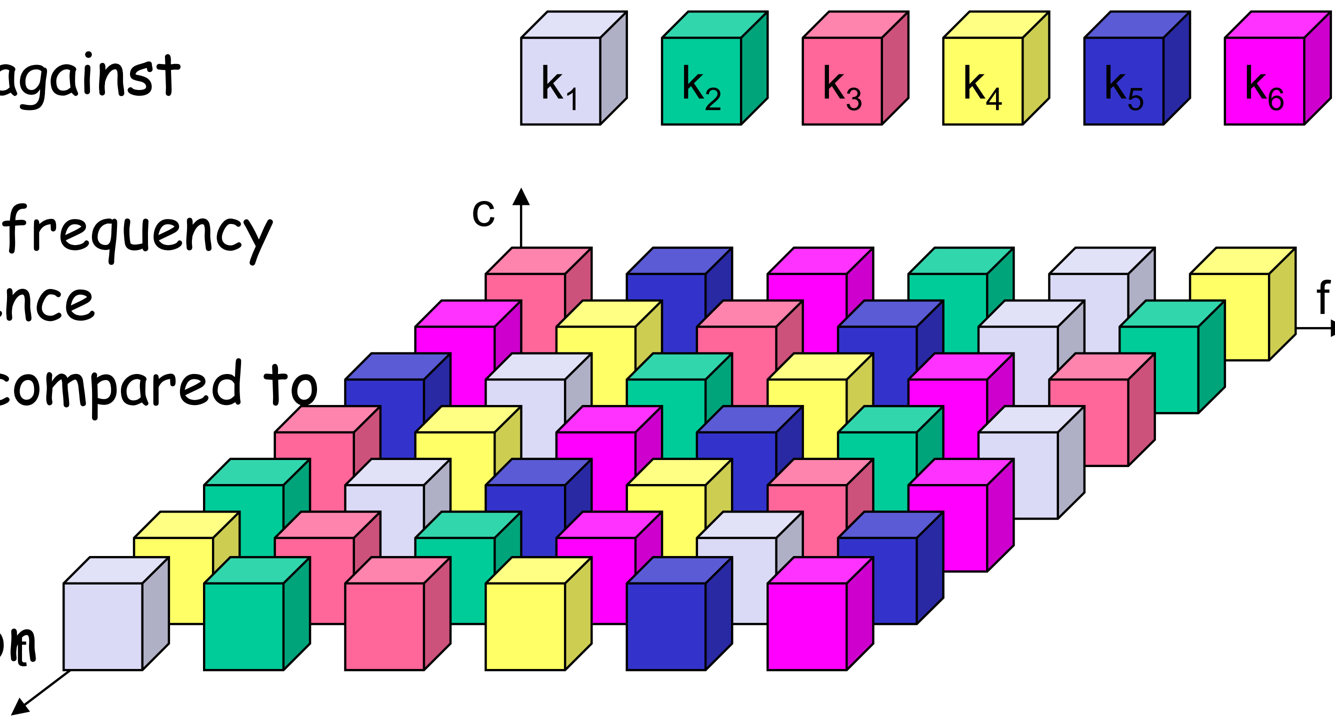
Time Multiplex

- A channel gets the whole spectrum for a certain amount of time
- Pros:
  - only one carrier in the medium at any time
  - throughput high even for many users
- Cons:
  - precise synchronization necessary



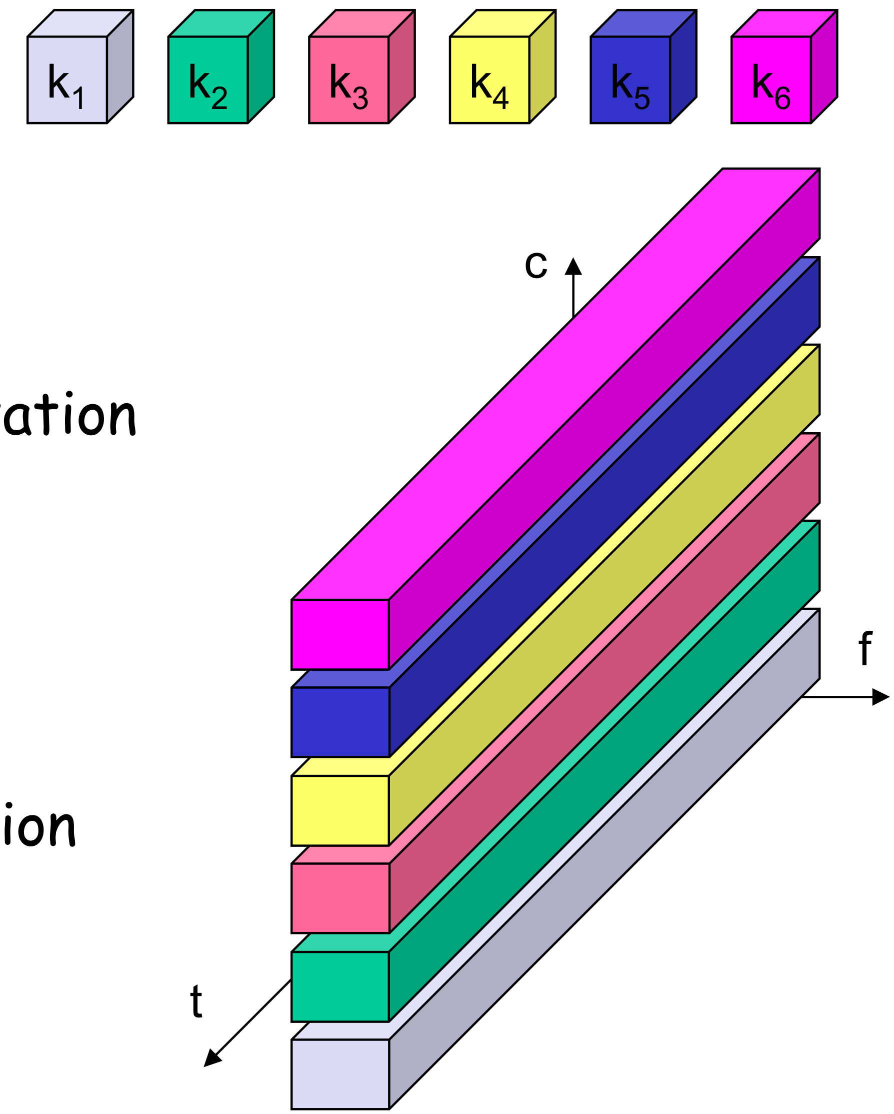
Time and Frequency Multiplexing

- Combination of both methods
- A channel gets a certain frequency band for a certain amount of time (e.g., GSM)
- Pros:
  - better protection against tapping
  - protection against frequency selective interference
  - higher data rates compared to code multiplex
- Cons:
  - precise coordination required



Code Multiplexing

- Each channel has a unique code
- All channels use the same spectrum simultaneously
- Pros:
  - bandwidth efficient
  - no coordination and synchronization necessary
  - good protection against interference and tapping
- Cons:
  - more complex signal regeneration
  - need precise power control
- Implemented using spread spectrum technology



Outline

- Signal
- Frequency allocation
- Signal propagation
- Multiplexing
- Modulation
- Spread Spectrum

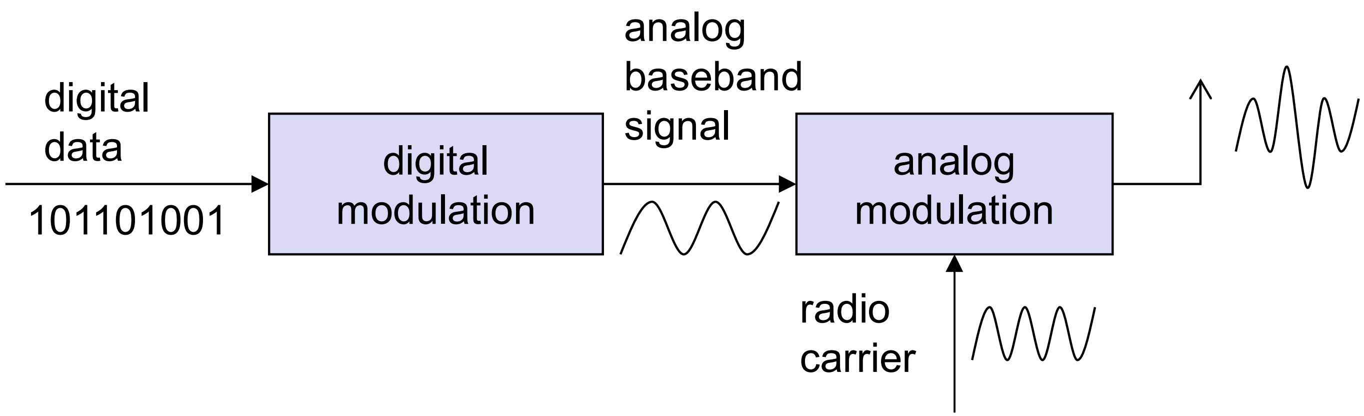
Modulation I

- Digital modulation
  - Digital data is translated into an analog signal (baseband)
  - Difference in spectral efficiency, power efficiency, robustness
- Analog modulation
  - Shifts center frequency of baseband signal up to the radio carrier
  - Reasons?

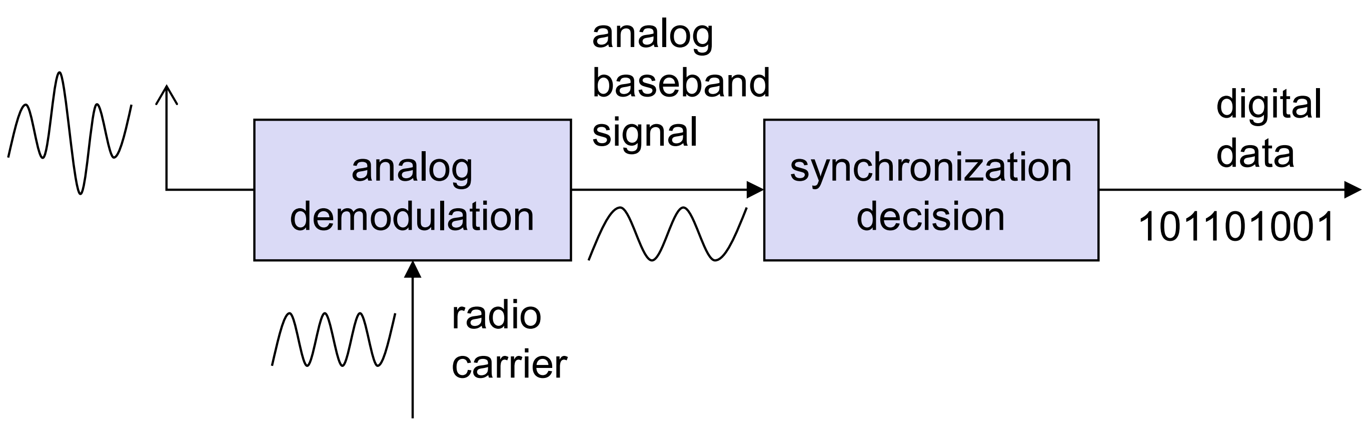
Modulation I

- Digital modulation
  - Digital data is translated into an analog signal (baseband)
  - Difference in spectral efficiency, power efficiency, robustness
- Analog modulation
  - Shifts center frequency of baseband signal up to the radio carrier
  - Reasons
    - Antenna size is on the order of signal's wavelength
    - More bandwidth available at higher carrier frequency
    - Medium characteristics: path loss, shadowing, reflection, scattering, diffraction depend on the signal's wavelength

Modulation and Demodulation



radio transmitter



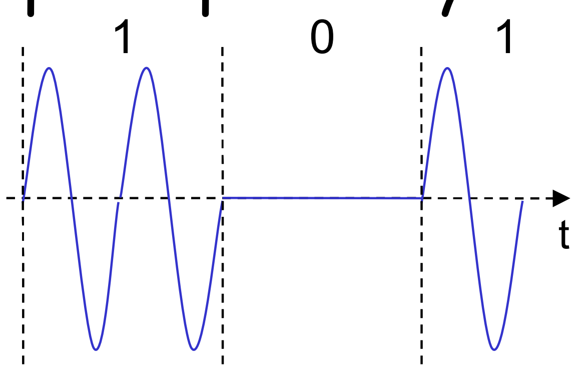
radio receiver

Modulation Schemes

- Amplitude Modulation (AM)
- Frequency Modulation (FM)
- Phase Modulation (PM)

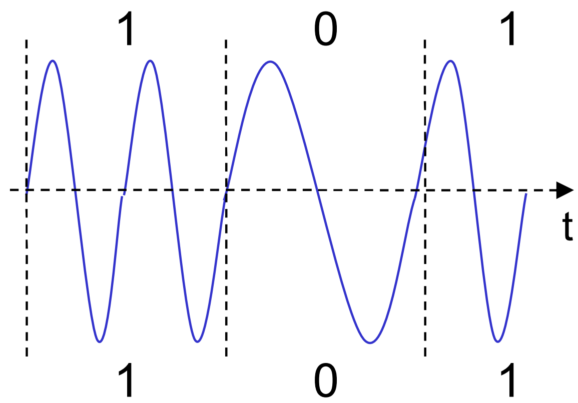
Digital Modulation

- Modulation of digital signals known as Shift Keying
- Amplitude Shift Keying (ASK):
  - Pros: simple
  - Cons: susceptible to noise
  - Example: optical system, IFR



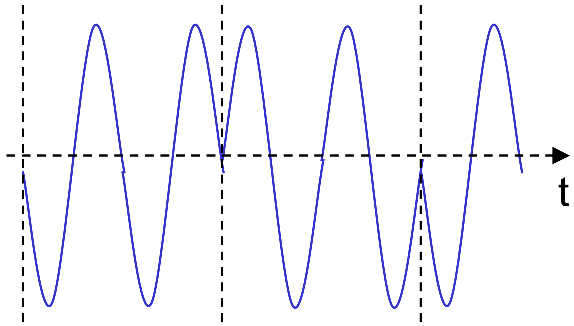
Digital Modulation II

- Frequency Shift Keying (FSK):
  - Pros: less susceptible to noise
  - Cons: requires larger bandwidth



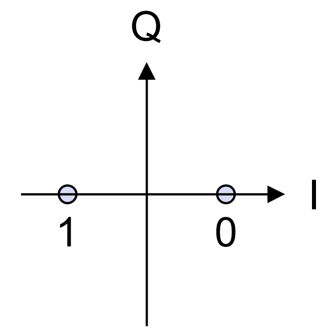
Digital Modulation III

- Phase Shift Keying (PSK):
  - Pros:
    - Less susceptible to noise
    - Bandwidth efficient
  - Cons:
    - Require synchronization in frequency and phase → complicates receivers and transmitter



Phase Shift Keying

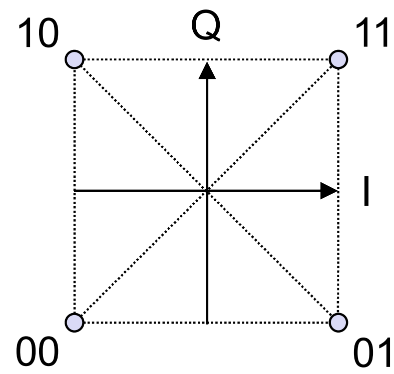
- BPSK (Binary Phase Shift Keying):
  - bit value 0: sine wave
  - bit value 1: inverted sine wave
  - very simple PSK
  - low spectral efficiency
  - robust, used in satellite systems

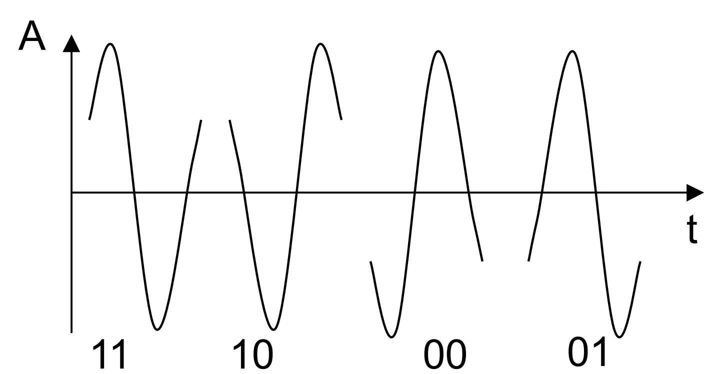


How to send more bits?

Phase Shift Keying (Cont.)

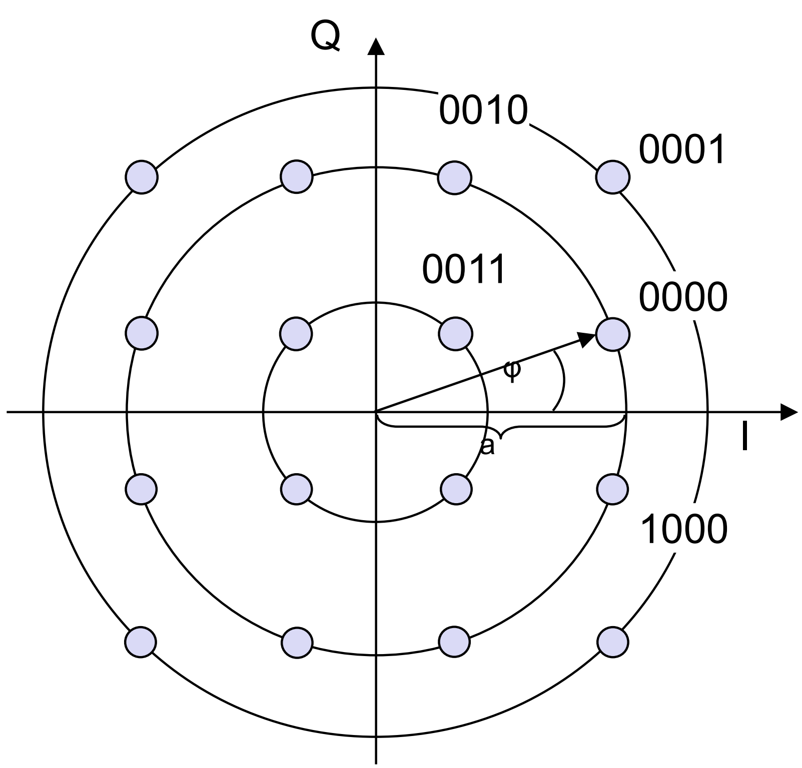
- QPSK (Quadrature Phase Shift Keying):
  - 2 bits coded as one symbol
  - needs less bandwidth compared to BPSK
  - symbol determines shift of sine wave
  - Often also transmission of relative, not absolute phase shift: DQPSK - Differential QPSK





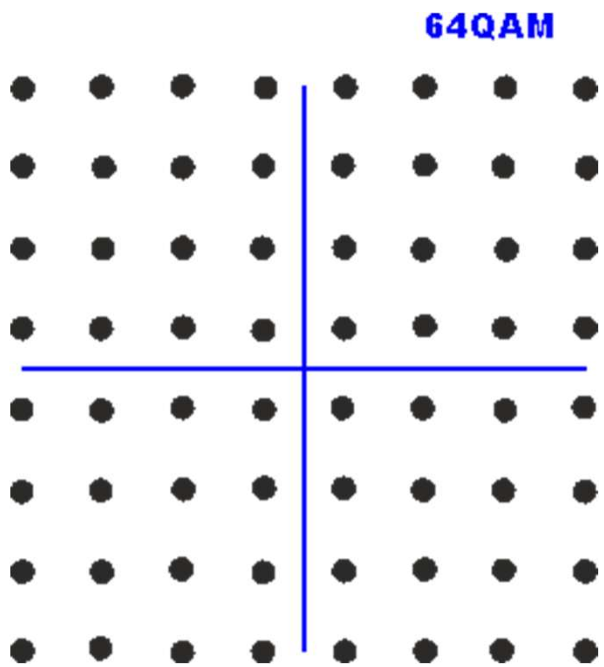
Quadrature Amplitude Modulation

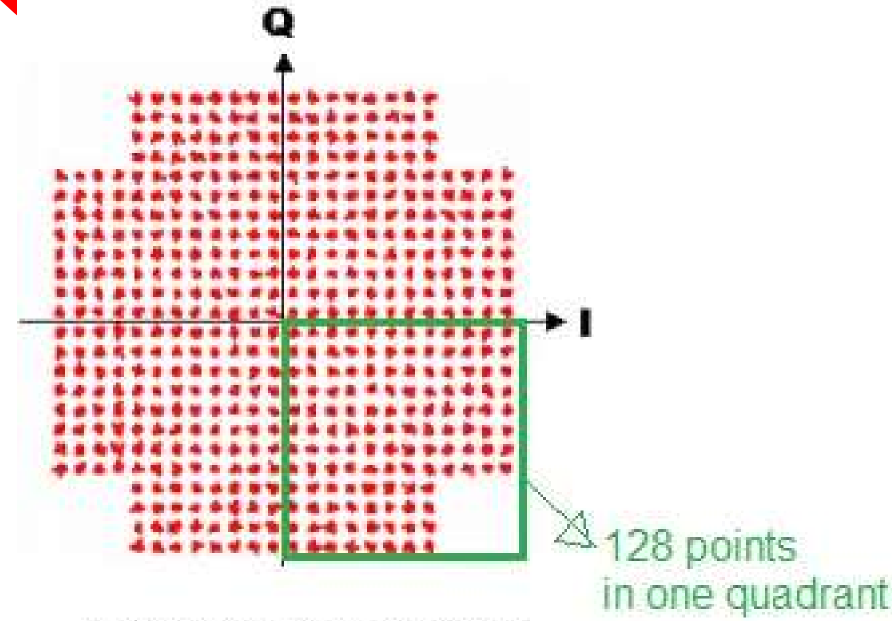
- Quadrature Amplitude Modulation (QAM): combines amplitude and phase modulation
- It is possible to code n bits using one symbol
  - 2^n discrete levels
- bit error rate increases with n



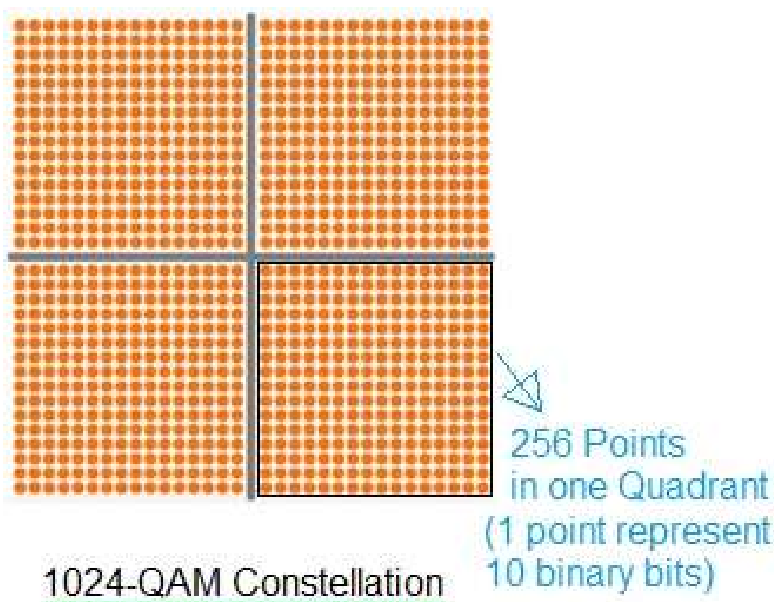
- Example: 16-QAM (4 bits = 1 symbol)
- Symbols 0011 and 0001 have the same phase φ, but different amplitude; 0000 and 1000 have same amplitude but different phase
- Used in Modem

More QAMs





512-QAM Constellation



1024-QAM Constellation

Why not always use the highest QAM?

How do we decide which modulation to use?

What is FFT

- Fast Fourier Transform (FFT) is an efficient algorithm to compute the Discrete Fourier Transform (DFT).
- Why it matters:
  - Converts signals from time domain → frequency domain
  - Reveals spectrum, bandwidth, and interference
  - Enables modern digital communication systems
- Key idea:
  - Analyze signals by frequency components instead of raw waveforms.

Why Wireless Needs FFT

- Wireless channels are
  - Multipath (many echoes)
  - Frequency selective
  - Time varying - Noisy
- FFT allows us to:
  - Separate overlapping signals
  - Design filters
  - Estimate channels
  - Handle interference
  - Build high-data-rate systems
- Without FFT → No 4G/5G/WiFi

FFT in OFDM (4G / 5G / WiFi)

- OFDM = Orthogonal Frequency Division Multiplexing
- Transmitter
  - Bits → QAM symbols → IFFT → Time signal
- Receiver
  - Time signal → FFT → QAM symbols → Bits
- Benefits:
  - Turns one hard channel into many easy subchannels
  - Simple equalization
  - High spectral efficiency

Channel & Filtering with FFT

- Channel modeling
  - Time domain: $y(t) = x(t) * h(t)$
  - Frequency domain (via FFT): $Y(f) = X(f) \cdot H(f)$

- Filtering
  - Multiplication in frequency domain
  - Easier filter design
  - Noise suppression
  - Band selection

FFT in Practice

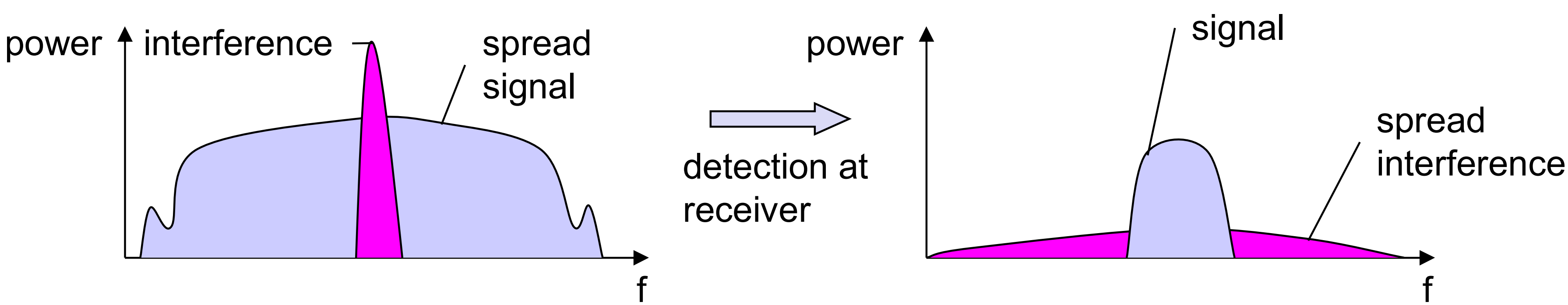
- Used in:
  - Spectrum analyzers
  - Channel estimation
  - Doppler estimation
  - Beamforming (mmWave)
- Radar & wireless sensing
  - Typical parameters:
  - Sample rate: 16–48 kHz (audio), MHz-GHz (RF)
  - Frame size: 64–4096 points
  - Complexity: O(N log N)

Take-away

- FFT is the mathematical engine behind modern wireless systems.
- It enables:
  - OFDM
  - High data rates
  - Robust transmission
  - Efficient spectrum usage
- In one sentence:
  - FFT turns complex wireless channels into manageable frequency components.

Spread spectrum technology

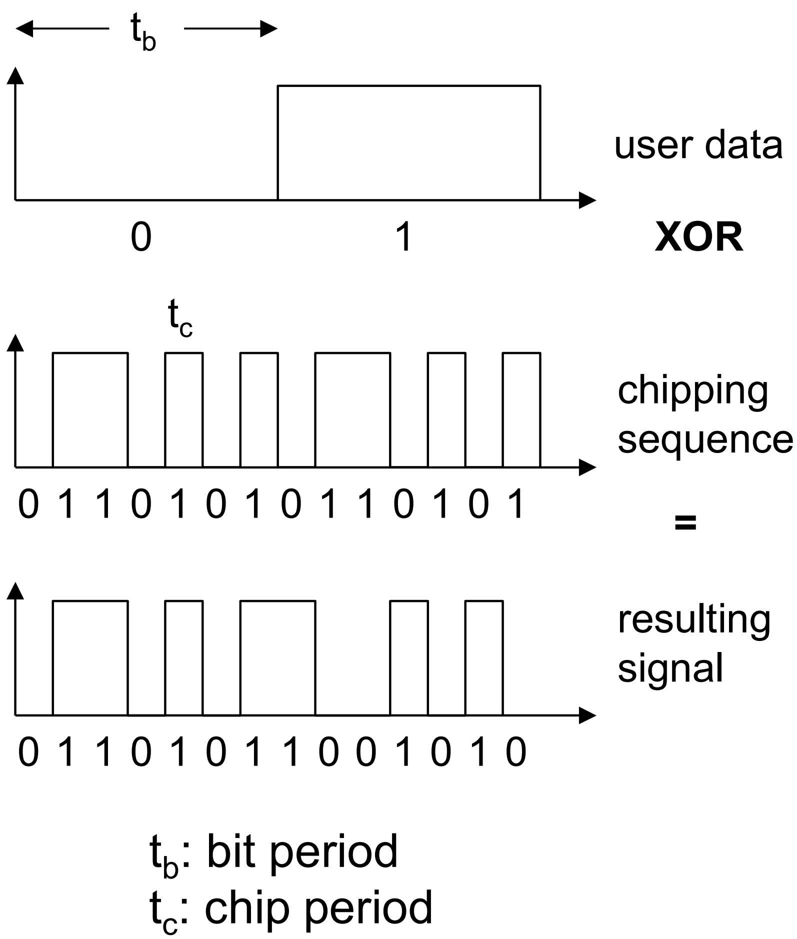
- Problem of radio transmission: frequency dependent fading can wipe out narrow band signals for duration of the interference
- Solution: spread the narrow band signal into a broad band signal using a special code



- Side effects:
  - coexistence of several signals without dynamic coordination
  - tap-proof
- Alternatives: Direct Sequence, Frequency Hopping

DSSS
(Direct Sequence Spread Spectrum)

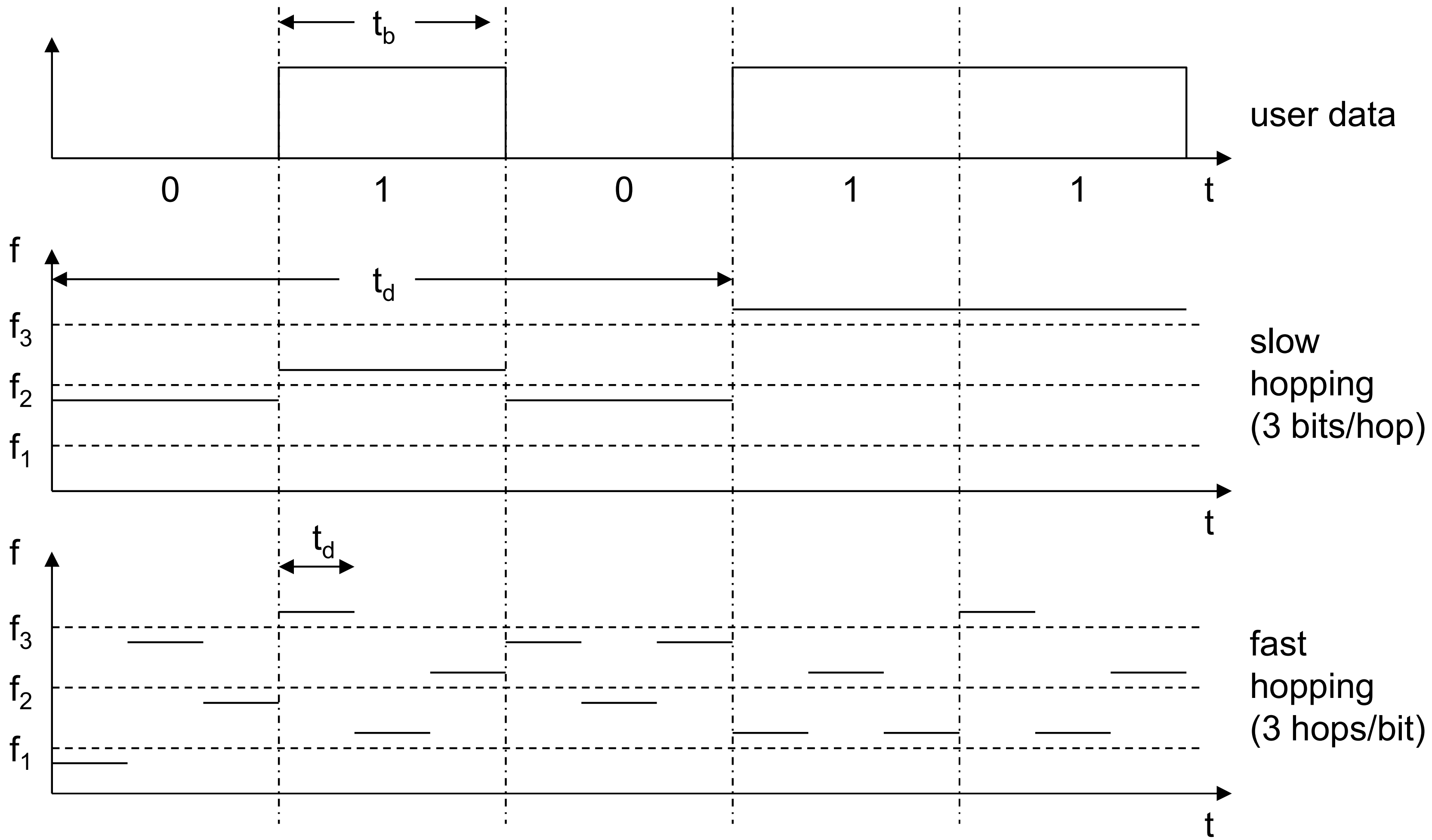
- XOR of the signal with pseudo-random number (chipping sequence)
  - generate a signal with a wider range of frequency: spread spectrum



FHSS
(Frequency Hopping Spread Spectrum)

- Discrete changes of carrier frequency
  - sequence of frequency changes determined via pseudo random number sequence
- Two versions
  - Fast Hopping:
    several frequencies per user bit
  - Slow Hopping:
    several user bits per frequency
- Advantages
  - frequency selective fading and interference limited to short period
  - simple implementation
  - uses only small portion of spectrum at any time

FHSS: Example



t_b: bit period t_d: dwell time

Comparison between Slow Hopping and Fast Hopping

- Slow hopping
  - Pros: cheaper
  - Cons: less immune to narrowband interference
- Fast hopping
  - Pros: more immune to narrowband interference
  - Cons: tight synchronization → increased complexity

Recap

- Name 5 layers in the Internet protocol stack.
- Pros and cons of layering.
- What is a signal?
- Difference between analog vs. digital signal?
- How do we represent different signals?
- Does a signal always follow a straight line?
- Path loss models

Recap (Cont.)

- Why do we need a wide bandwidth?
- What is multipath propagation?
- Types of multiplexing?
- Types of modulation?
- What is spread spectrum?