CS26007: Introduction to Wireless Networking

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Department of Computer Sciences,

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Course Information

- Course Information
  - Course #: CS26007
  - Lecture: T8:55 - 11:40 pm @陈瑞球楼207
  - Course homepage: http://www.cs.sjtu.edu.cn/~xue-gt/wireless/wireless.html
- Xue's Office hour: W 2-4pm or by appt. @ SEIEE 3.129
- Teaching assistant: Guang Yang, glfpes@sjtu.edu.cn
  - Office hour: W 11am-noon SEIEE 3.129

Course Workload

- Grading

  -Class participation: 20% (include in-class exercises)

  -Homework: 30%

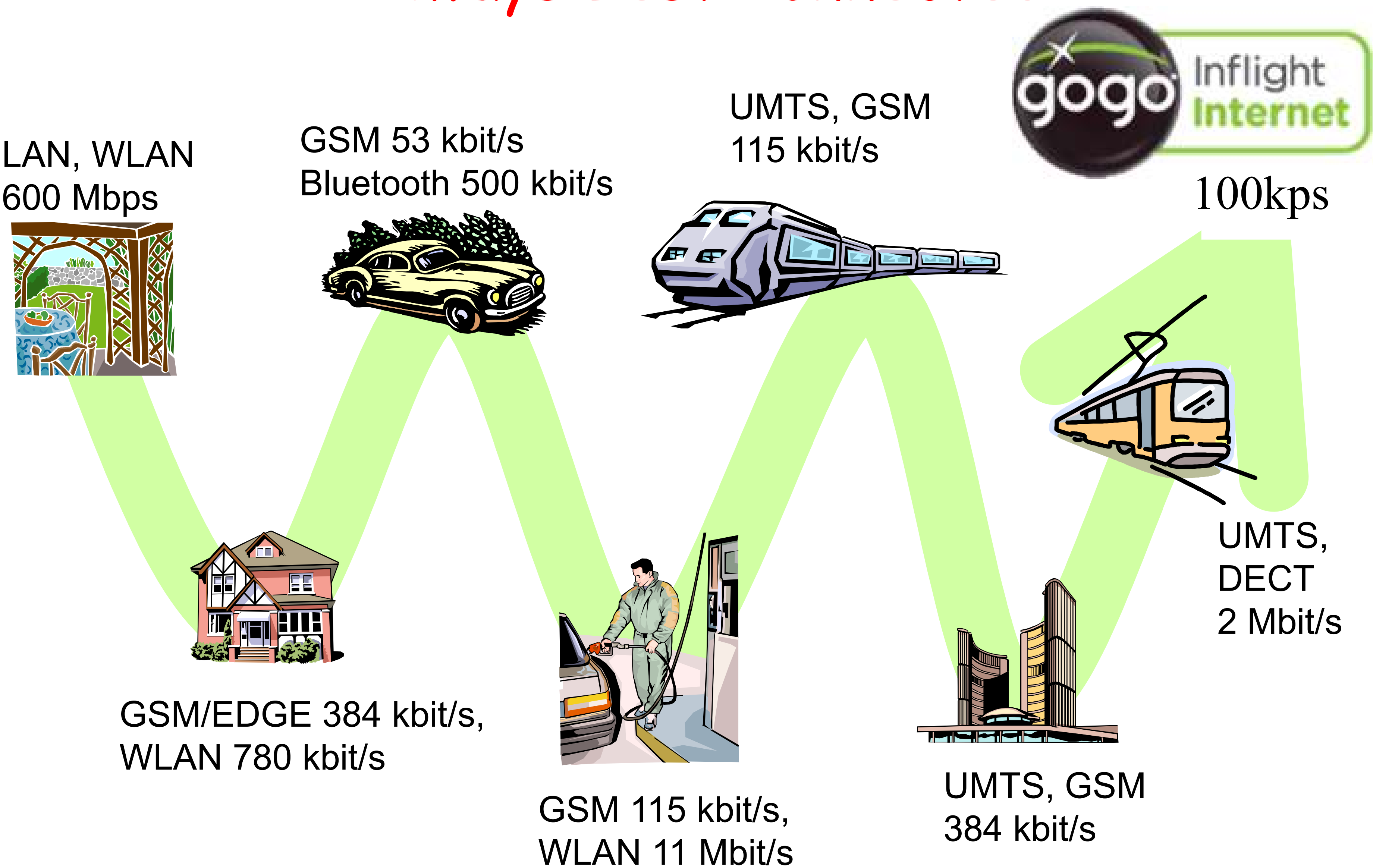
  -Project: 50%

Course Material

- Required textbook
  - Ad Hoc Wireless Networks: Architectures and Protocols by C. Siva Ram Murthy and B.S. Manoj
  - 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
  - Wireless Communications Principles and Practice by Ted Rappaport
  - Ad Hoc Networking by Charles E. Perkins

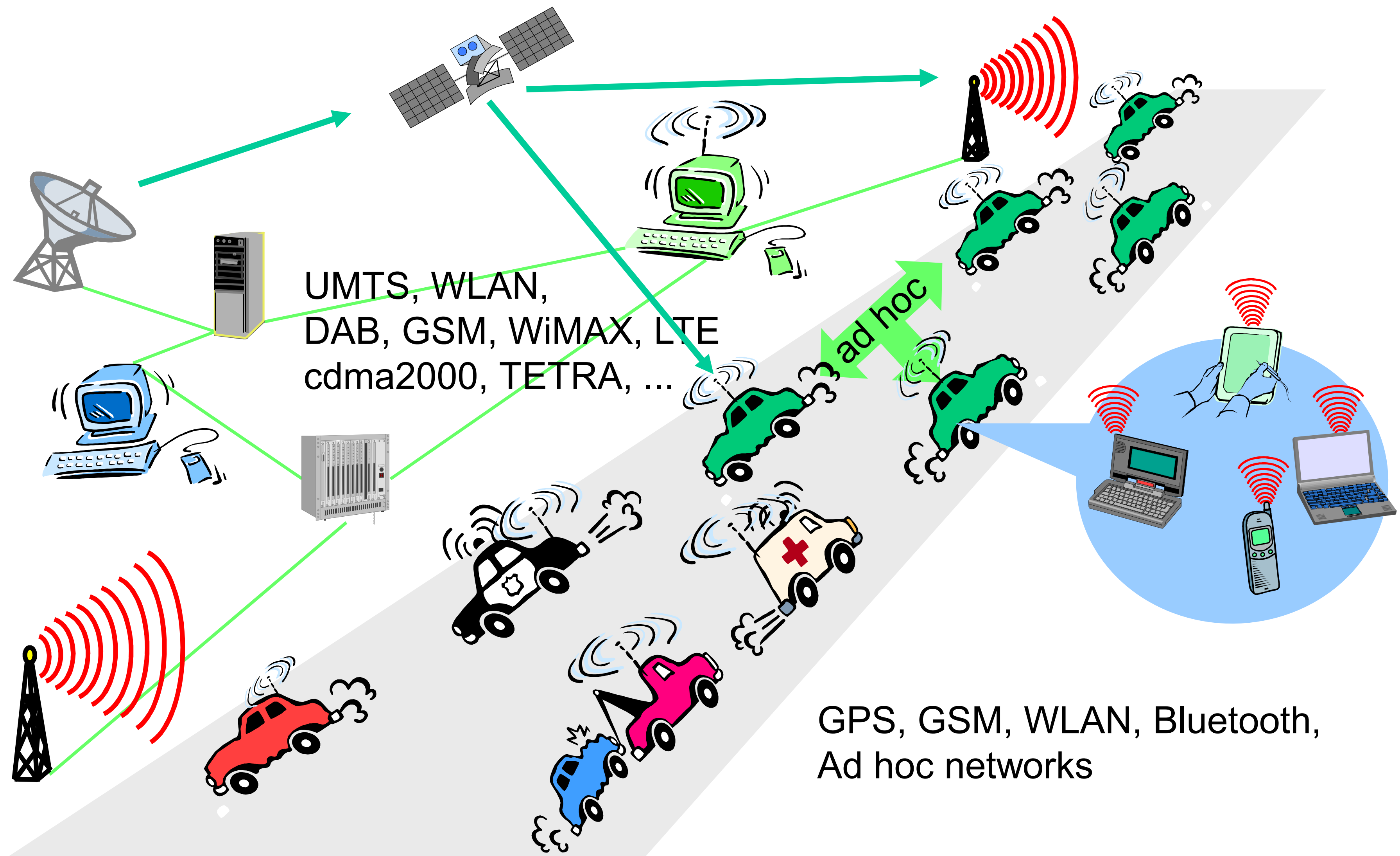
Motivation

Mobile and Wireless Services – Always Best Connected

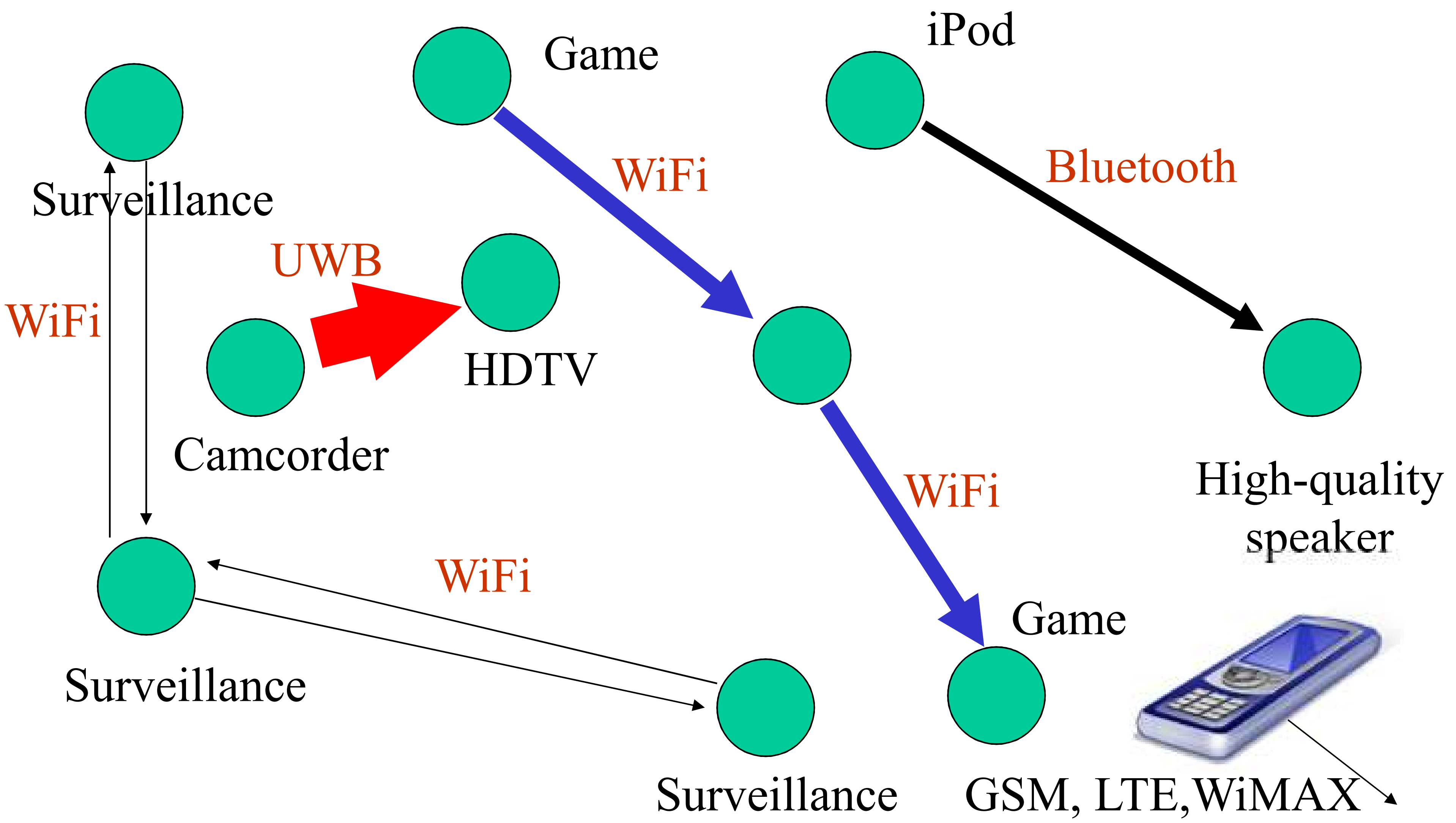


On the road

On the Road


UMTS, WLAN,
DAB, GSM, WiMAX, LTE
cdma2000, TETRA, ...
ad hoc
GPS, GSM, WLAN, Bluetooth,
Ad hoc networks

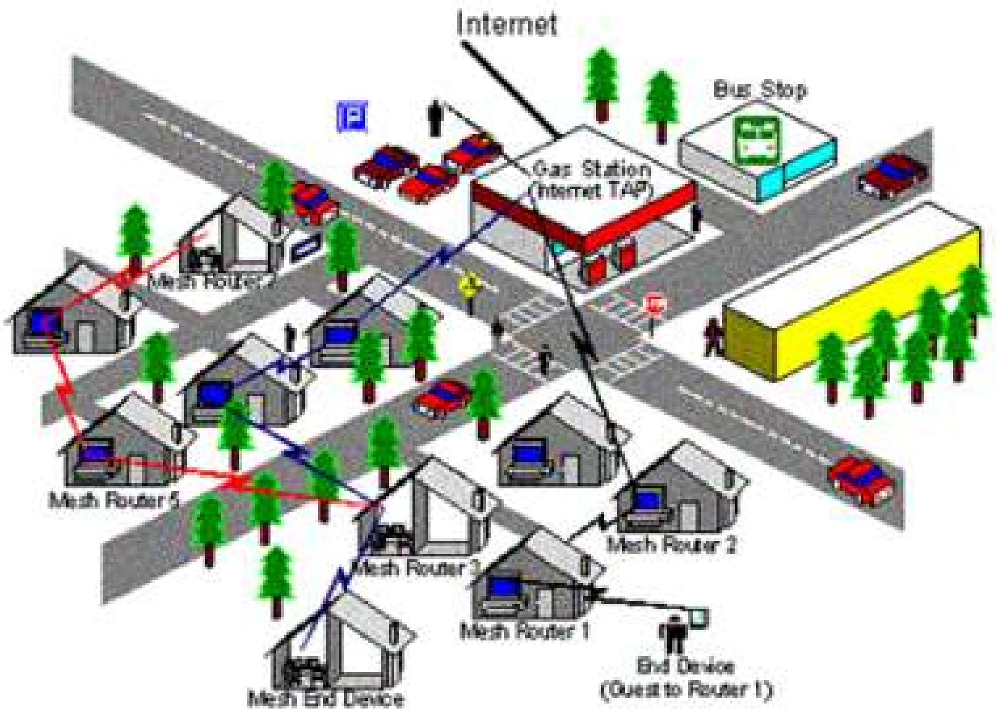
Home Networking



Last-Mile

Rank	Country	DSL p.p.	Cable p.p.	Other p.p.	Total p.p.	H.p.	Total subscribers	Date
—	*World*	4.0%	1.3%	0.8%	6.1%	N/A	349,980,000	Dec. 2007
1	China	3.9%	N/A	N/A	5.0%[3]	N/A	93,500,000	Dec. H1, 2009
2	US	9.3%	11.5%	1.3%	22.1%	N/A	83,968,547	Jun. Q1, 2009
3	Japna	10.8%	2.9%	7.6%	21.3%	N/A	30,631,900	Jun. Q1, 2009
4	Germany	20.2%	1.0%	0.1%	29.4%	N/A	24,144,350	Jun. Q1, 2009
5	Mexico	13.7%	2.1%	0.0%	15.8%	N/A	17,267,285	Q4, 2009
6	France	21.4%	1.1%	0.0%	22.5%	N/A	18,009,500	Jun. Q1, 2009
7	UK	18.4%	5.3%	0.0%	23.7%	N/A	17,661,100	Jun. Q1, 2009
8	South Korea	10.1%	10.6%	9.2%	29.9%	N/A	15,709,771	Jun. Q1, 2009
9	Italy	15.4%	0.0%	0.4%	15.8%	N/A	12,447,533	Jun. Q1, 2009
10	India	N/A	N/A	N/A	1%	N/A	10,520,000	Oct. 2010

Last-Mile



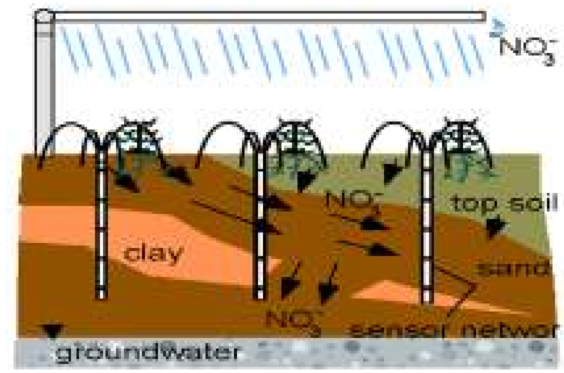
- Many users still don't have broadband
  - Reasons: out of service area; some consider expensive
- Broadband speed is still limited
  - DSL: 300Kbps – 6Mbps
  - Cable modem: depends on your neighbors
  - Insufficient for several applications (e.g., high-quality video streaming)

Disaster Recovery Network

- 9/11, Tsunami, Irene, Hurricane Katrina, China, South Asian, Haidi earthquakes …
- Wireless communication capability can make a difference between life and death!
- How to enable efficient, flexible, and resilient communication?
  - Rapid deployment
  - Efficient resource and energy usage
  - Flexible: unicast, broadcast, multicast, anycast
  - Resilient: survive in unfavorable and untrusted environment

Environmental Monitoring

Ecosystems, Biocomplexity

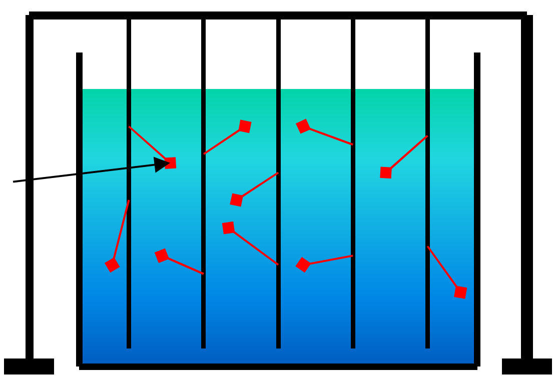


Contaminant Transport

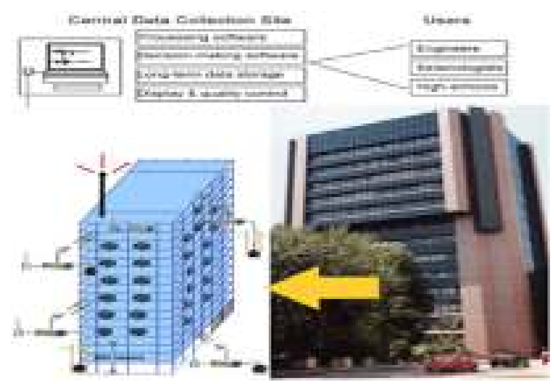
- Micro-sensors, on-board processing, wireless interfaces feasible at very small scale--can monitor phenomena "up close"
- Enables spatially and temporally dense environmental monitoring

Embedded Networked Sensing will reveal previously unobservable phenomena

Marine Microorganisms



Seismic Structure Response



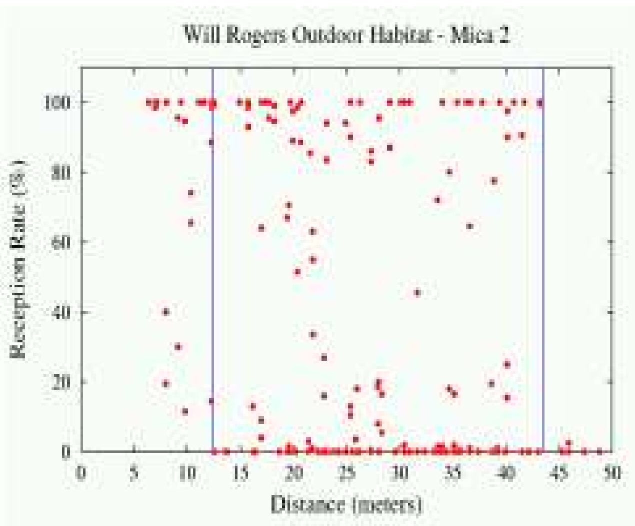
Wearable Computing

Challenges in Wireless Networking Research

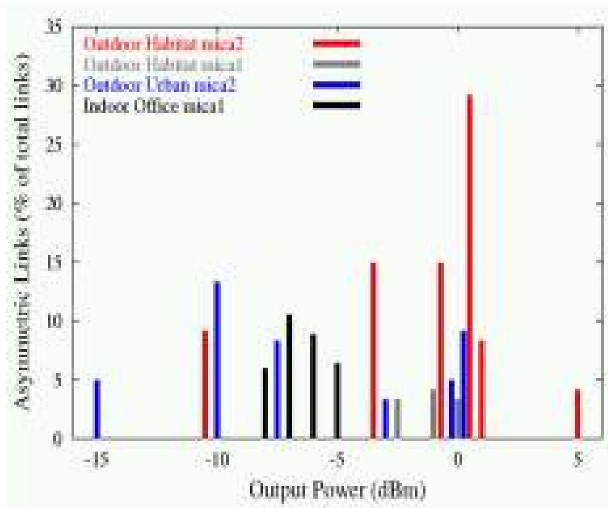
Challenge 1: Unreliable and Unpredictable Wireless Links

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

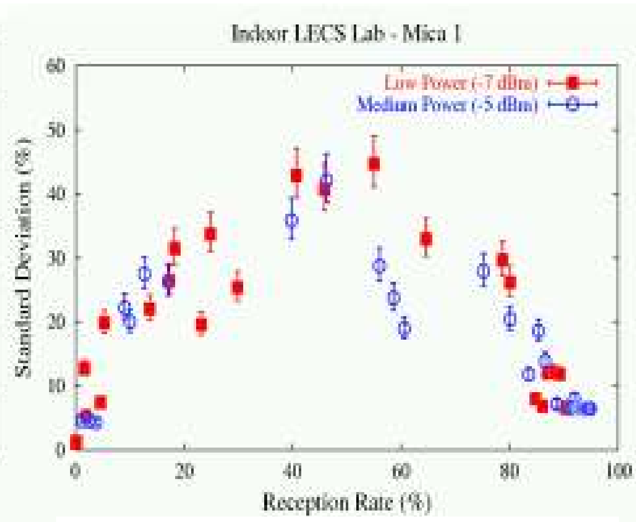
Reception v. Distance



Asymmetry vs. Power



Standard Deviation v. Reception rate



*Cerpa, Busek et. al

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

Challenge 2: Open Wireless Medium

- Wireless interference

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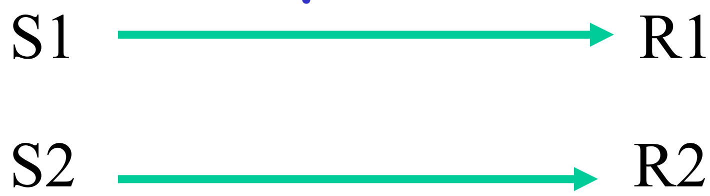
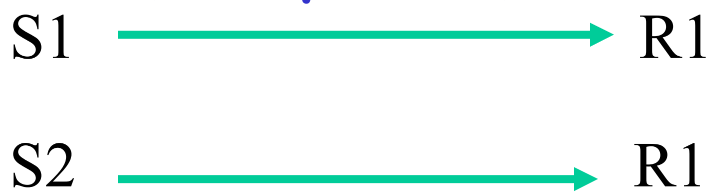
- Wireless interference



- Hidden terminals

Challenge 2: Open Wireless Medium

- Wireless interference

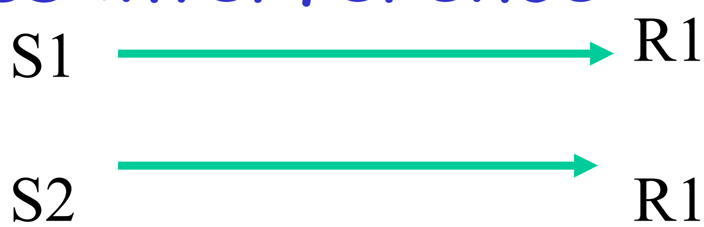


- Hidden terminals

- Exposed terminal

Challenge 2: Open Wireless Medium

- Wireless interference



- Hidden terminals

- Exposed terminal

- 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 displays
- GSM

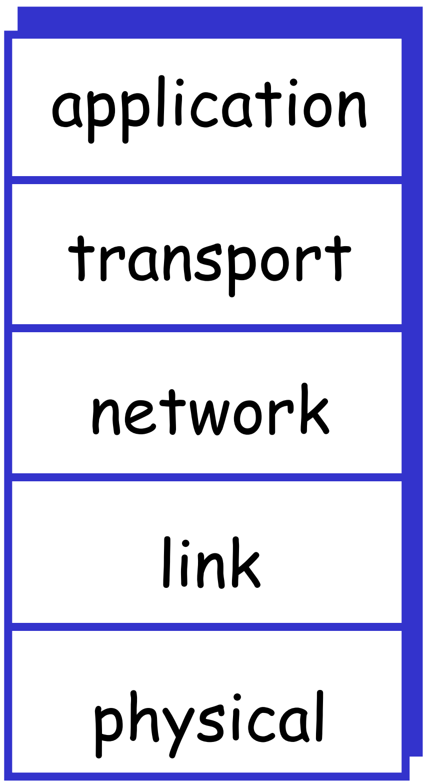
PDA
- data
- simpler graphical displays
- 802.11

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

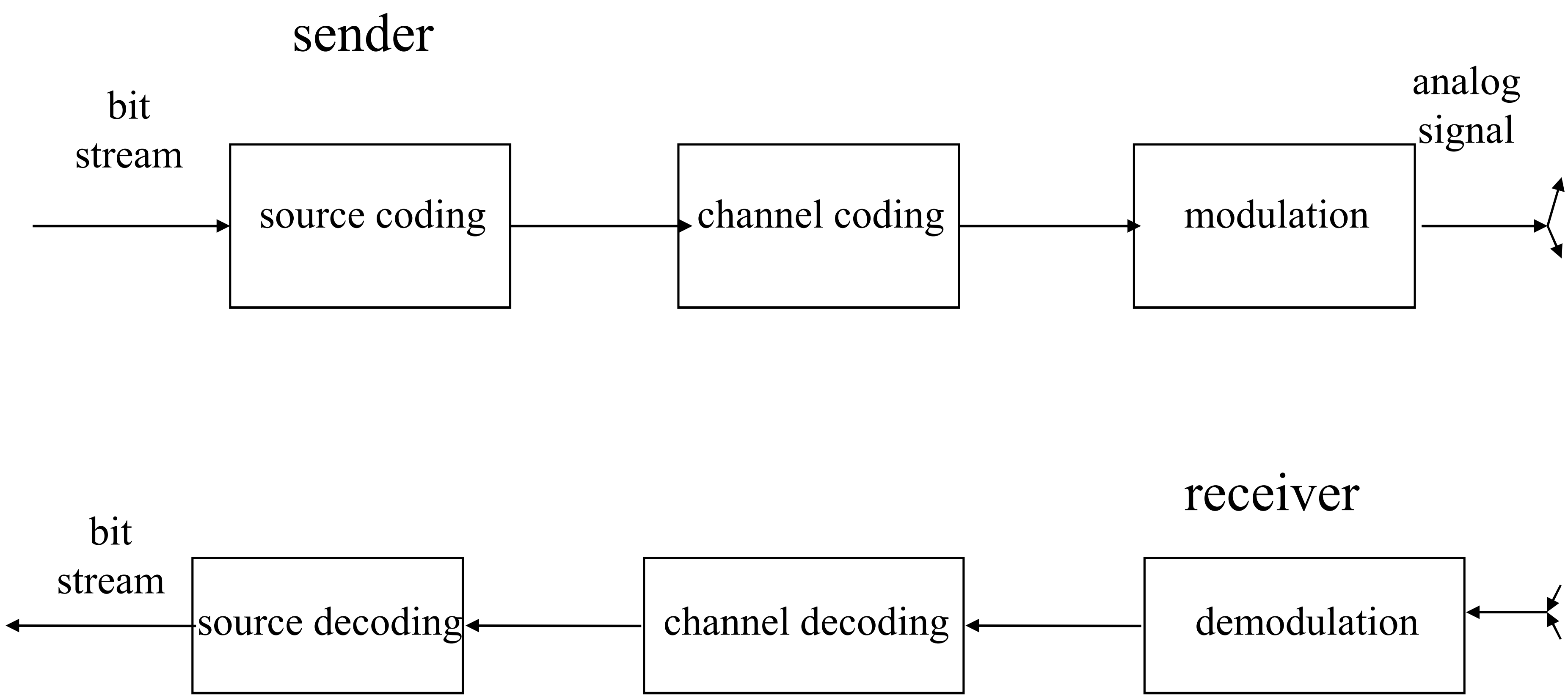


Physical Layer

Outline

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

Overview of Wireless Transmissions



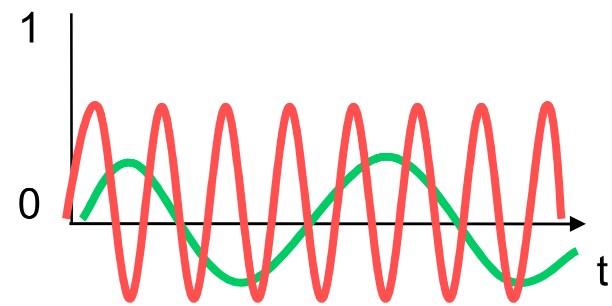
Signals

- 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.)

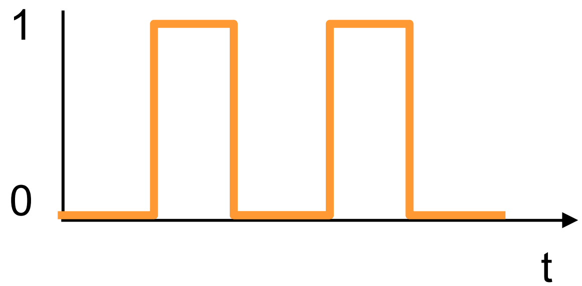
- Signal parameters of periodic signals:
  - period T, frequency f=1/T
  - amplitude A
  - phase shift φ
  - sine wave as special periodic signal for a carrier:

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

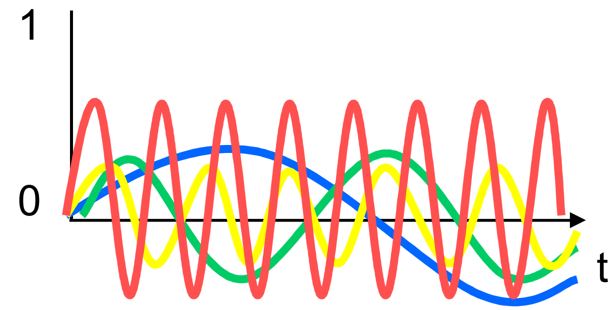


Fourier Transform: Every Signal Can be Decomposed as a Collection of Harmonics

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

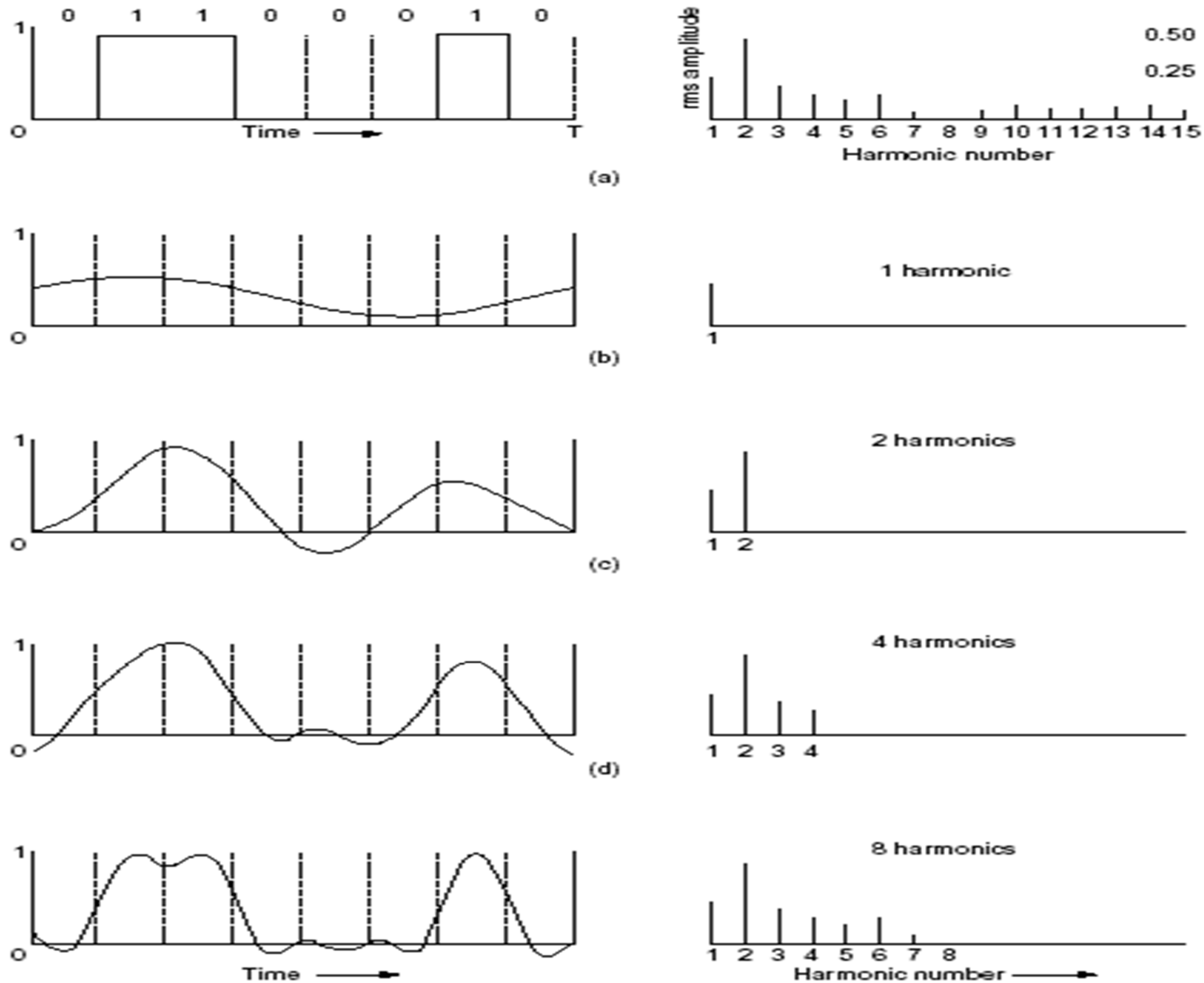


ideal periodical digital signal



decomposition

The more harmonics used, the smaller the approximation error.

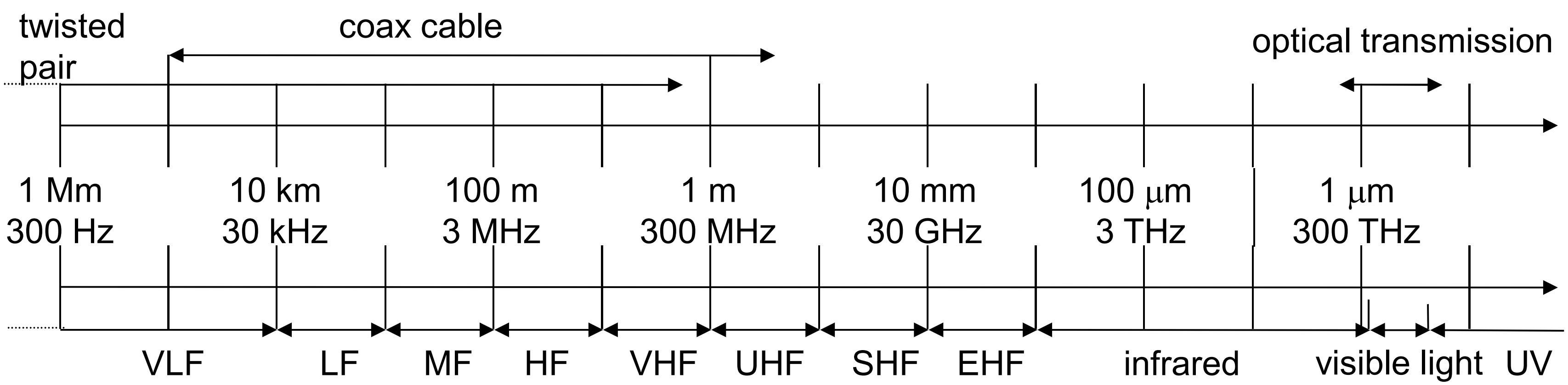


0 1 1 0 0 0 1 0
1
0
Time
T
rms amplitude
0.50
0.25
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Harmonic number
(a)
1 harmonic
(b)
2 harmonics
(c)
4 harmonics
(d)
8 harmonics
Time
Harmonic number

Why Not Send Digital Signal in Wireless Communications?

- Digital signals need
  - infinite frequencies for perfect transmission
  - however, we have limited frequencies in wireless communications

Frequencies for Communication



VLF = Very Low Frequency

LF = Low Freq., submarine

MF = Medium Freq., radio

HF = High Freq., radio

VHF = Very High Frequency, TV

UHF = Ultra High Frequency

SHF = Super High Frequency

EHF = Extra High Frequency

Visible light

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:

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

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

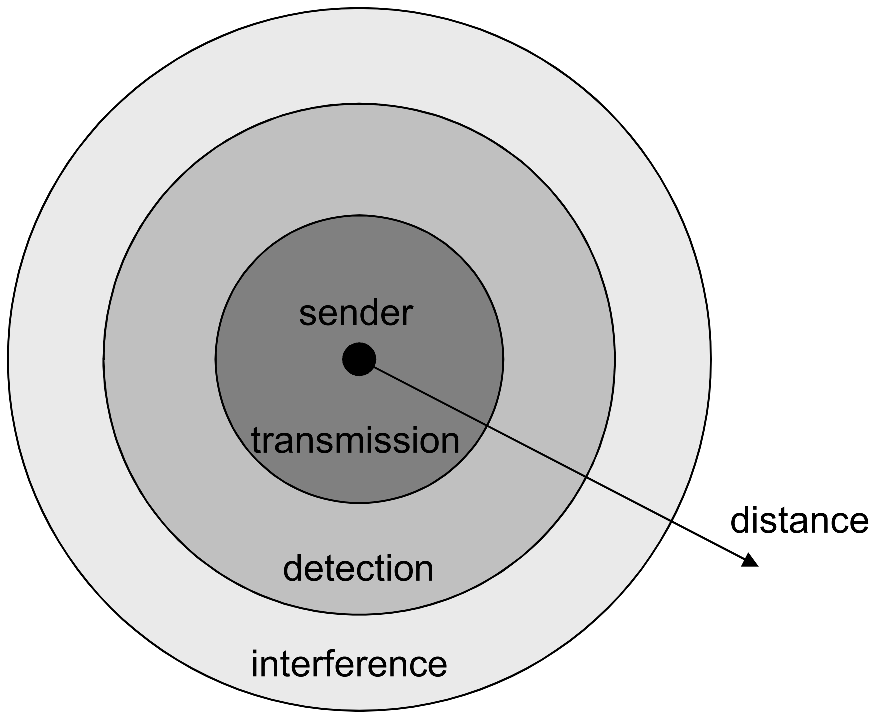
- dB
  - Denote the difference between two power levels
  - $(P2/P1)[dB] = 10 * \log_{10}(P2/P1)$
  - $P2/P1 = 10^{(A/10)}$
  - Example: P2 = 100 P1 [Answer: 20dB], P2/P1=10 dB [Answer: P2/P1 = 10]
- dBm and dBW
  - Denote the power level relative to 1 mW or 1 W
  - $P[dBm] = 10*\log_{10}(P/1mW)$
  - $P[dBW] = 10*\log_{10}(P/1W)$
  - Example: P = 0.001 mW [Answer: -30dBm], P = 100 W [Answer: 20dBW]

Outline

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

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

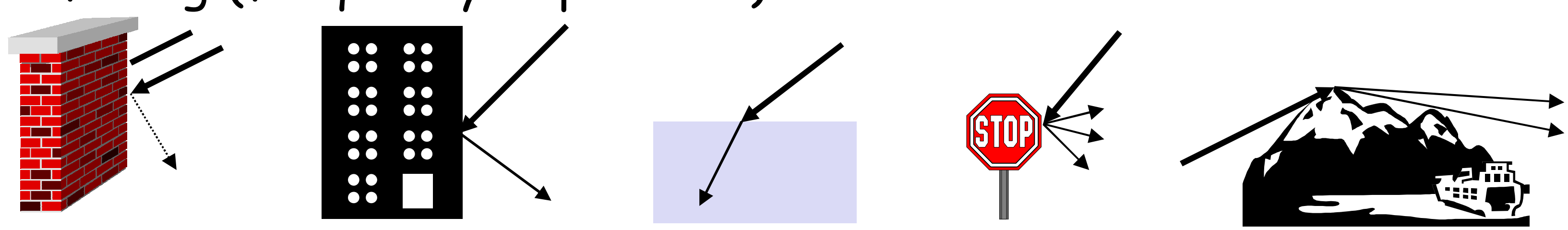


Signal Propagation

- Does signal propagation via a straight line?

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

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

- 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

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

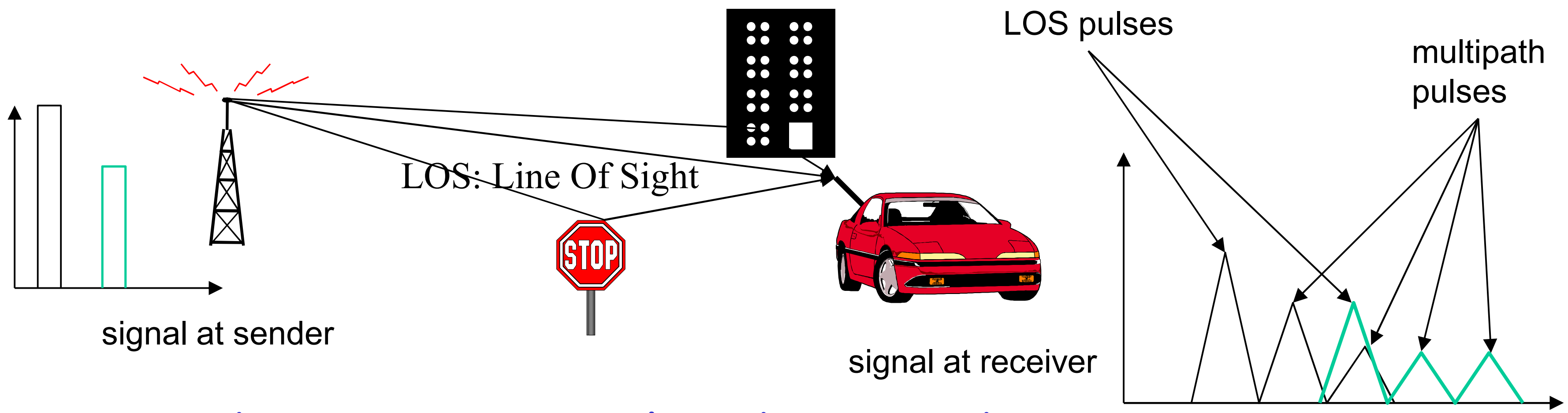
- Indoor model

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

- 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



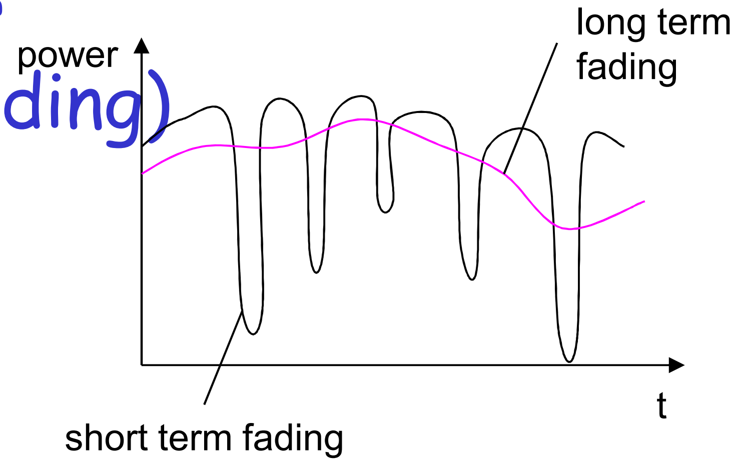
- Time dispersion: signal is dispersed over time

  → interference with "neighbor" symbols, Inter Symbol Interference (ISI)
- The signal reaches a receiver directly and phase shifted

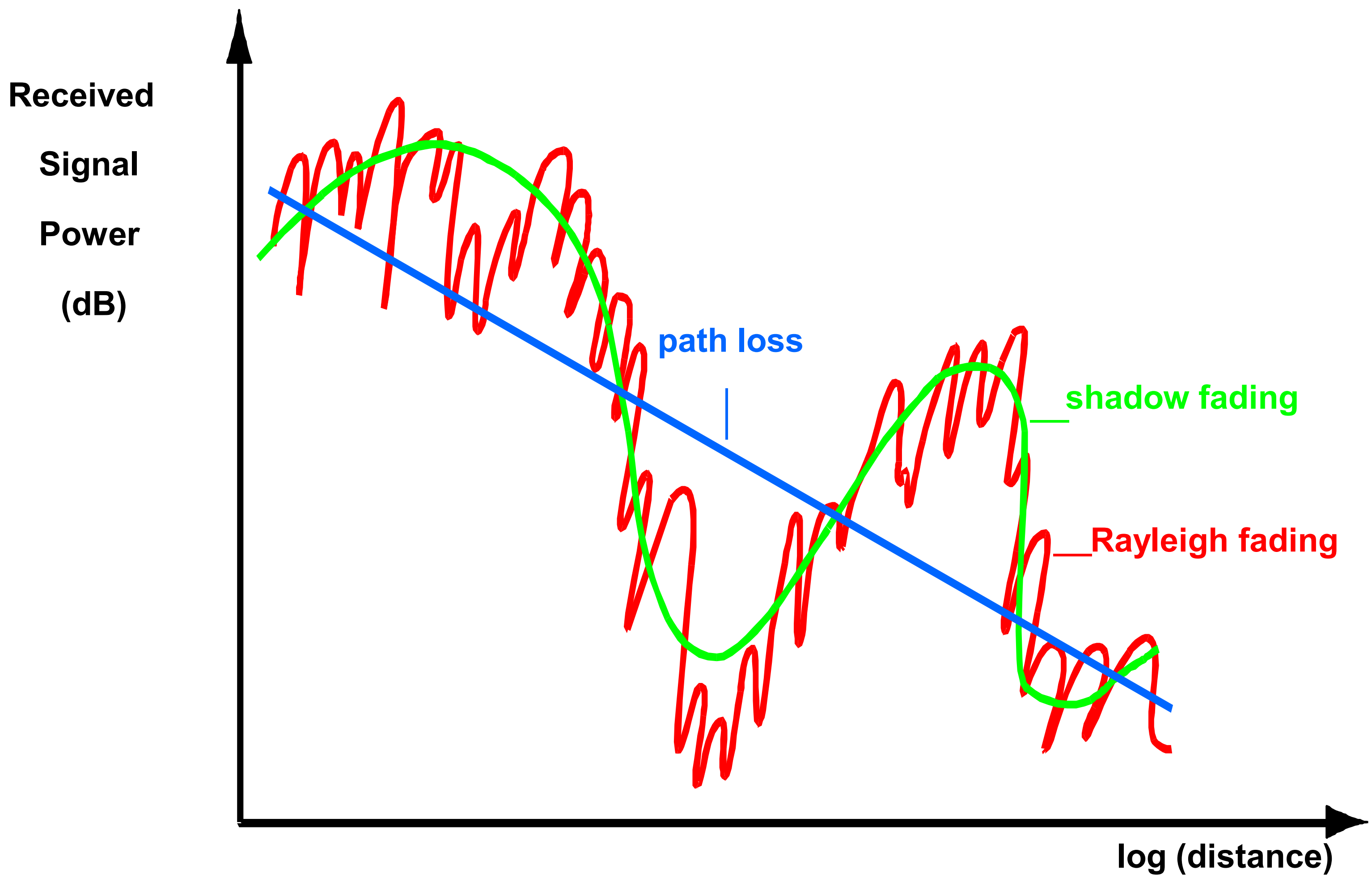
  → distorted signal based on the phases of different parts

Fading

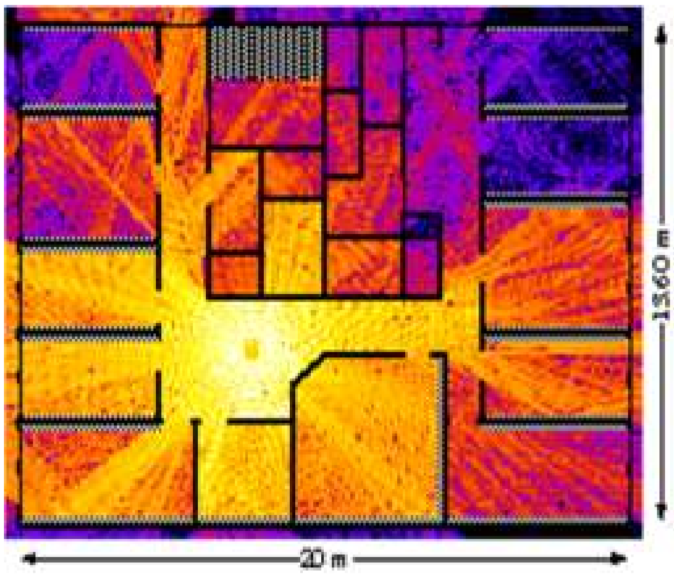
- Channel characteristics change over time and location
  - e.g., movement of sender, receiver and/or scatters
- ➔ quick changes in the power received (short term/fast fading)
- Additional changes in
  - distance to sender
  - obstacles further away
- ➔ slow changes in the average power received (long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

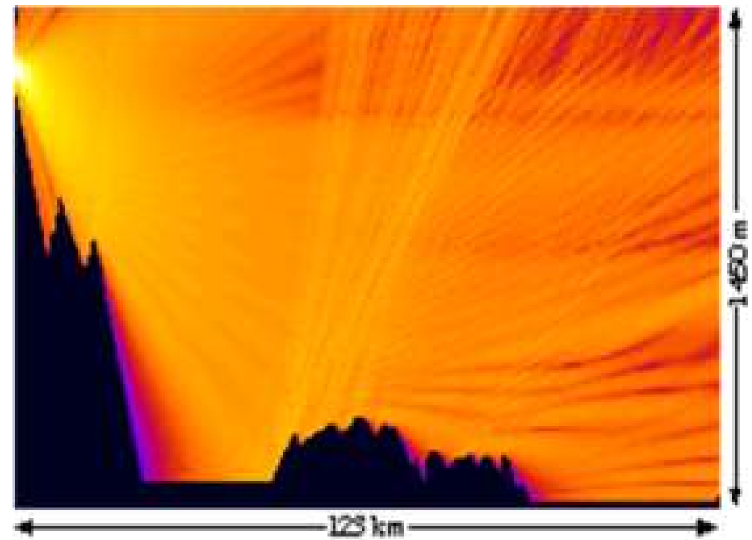


Typical Picture



Real world example





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How to allow multiple nodes share the spectrum?

Multiplexing

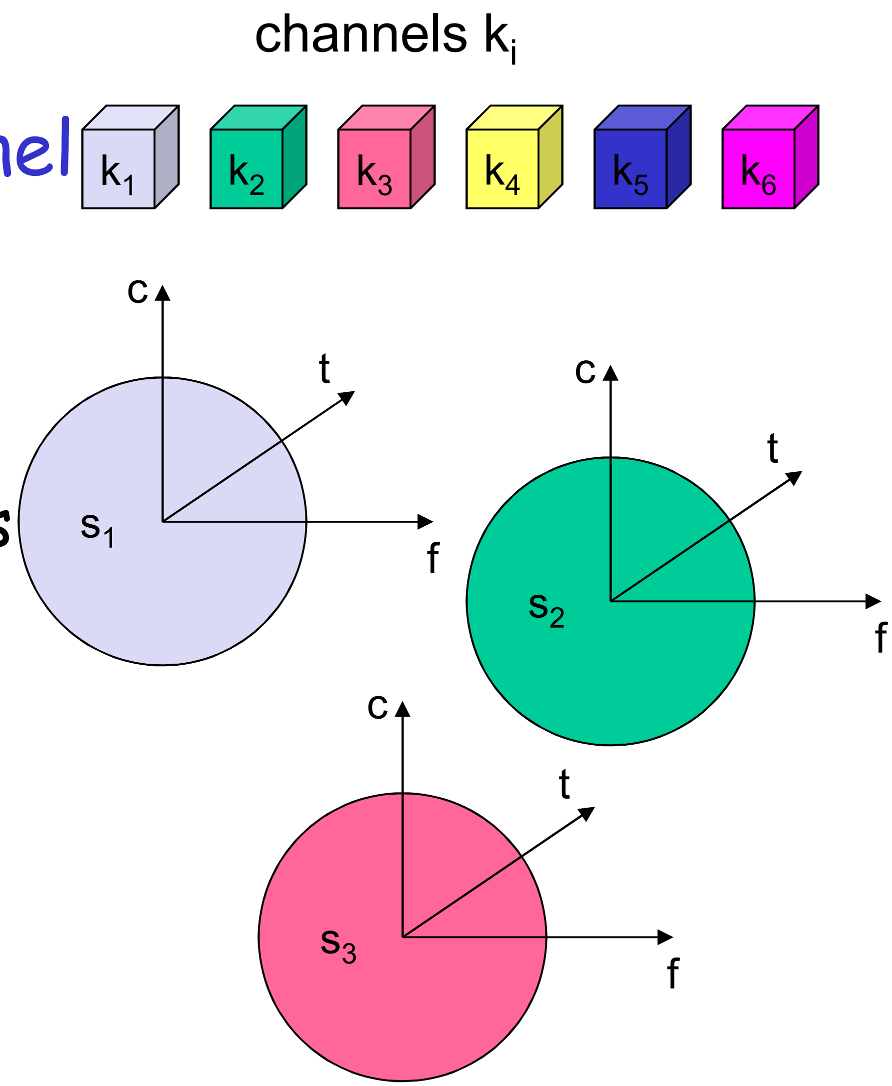
- Goal: multiple use of a shared medium

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

- Important: guard spaces needed!

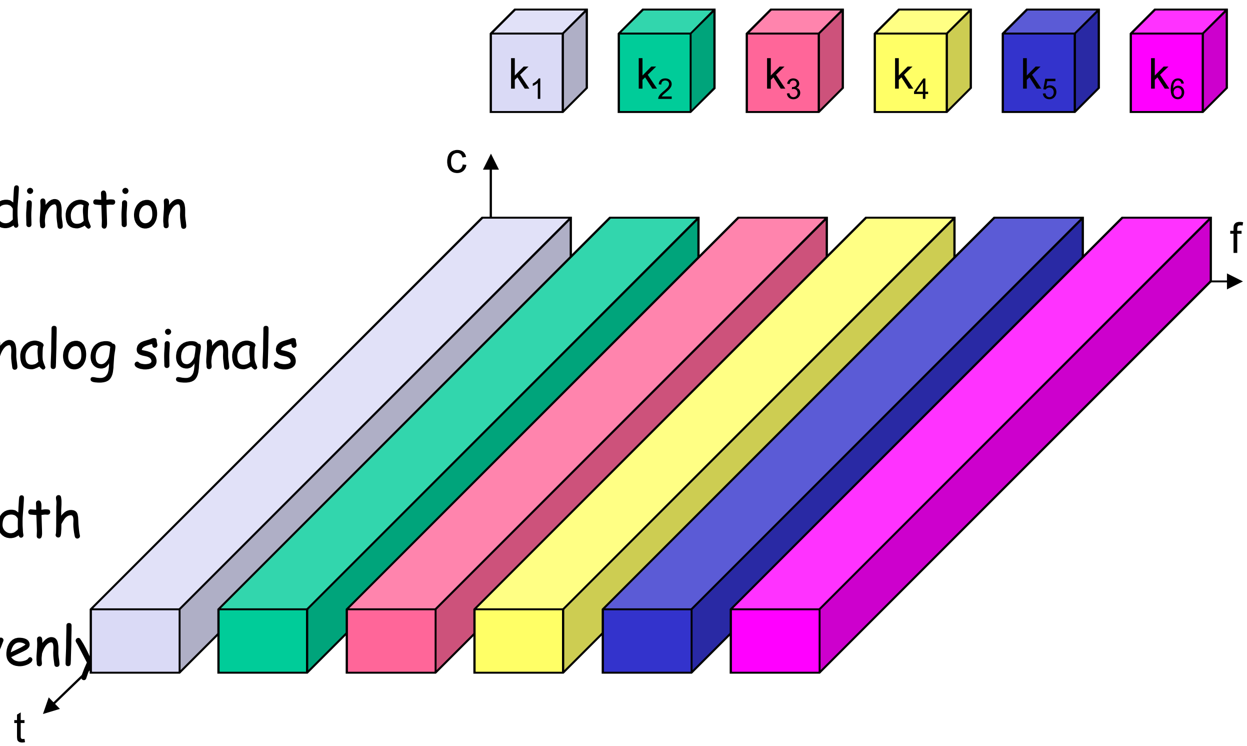
Space Multiplexing

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



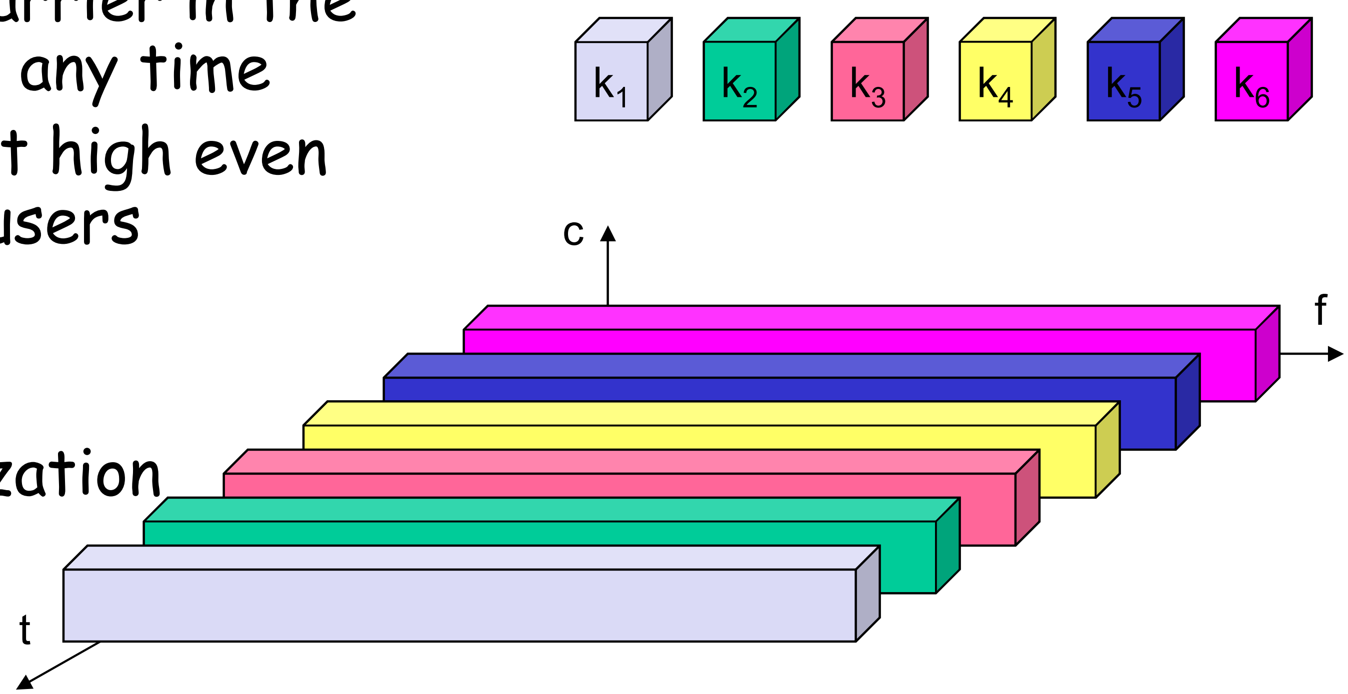
Frequency Multiplexing

- 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



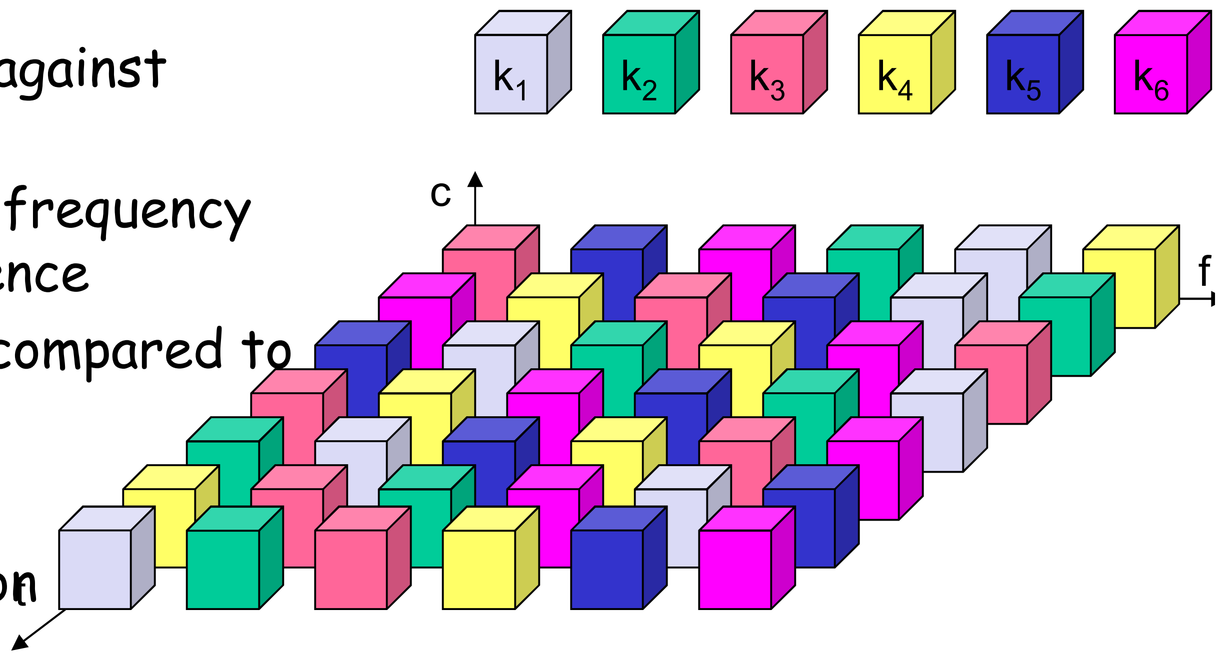
Time Multiplex

- 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



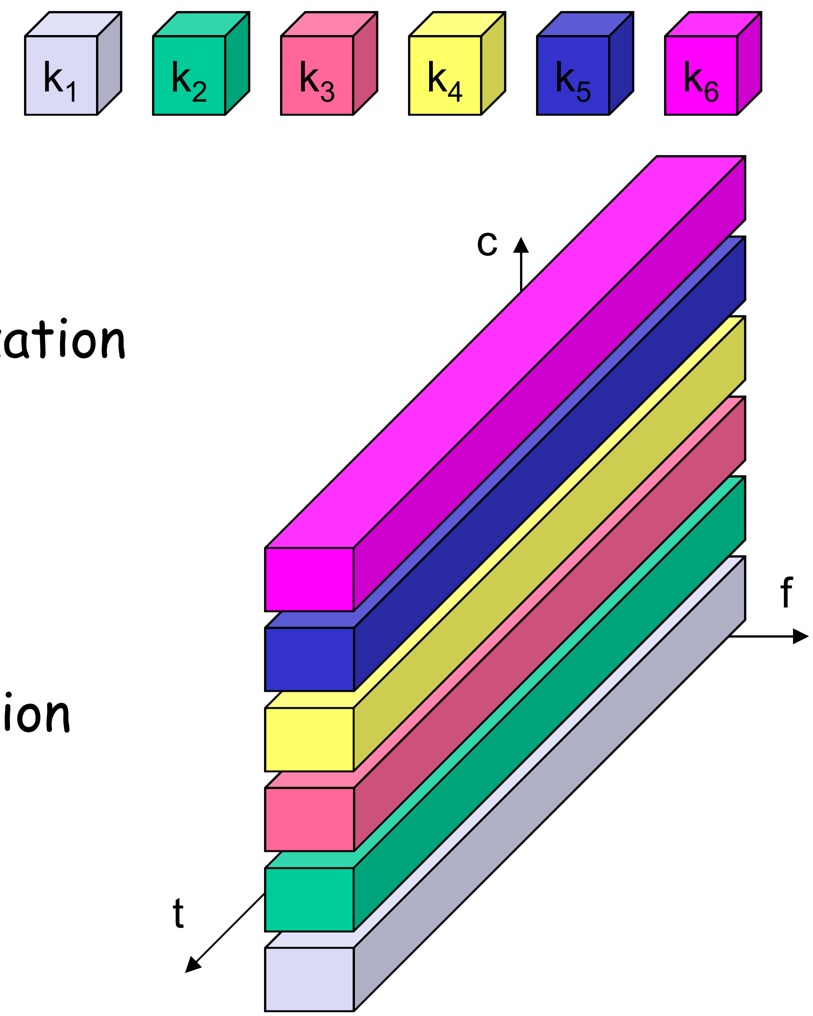
Time and Frequency Multiplexing

- 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



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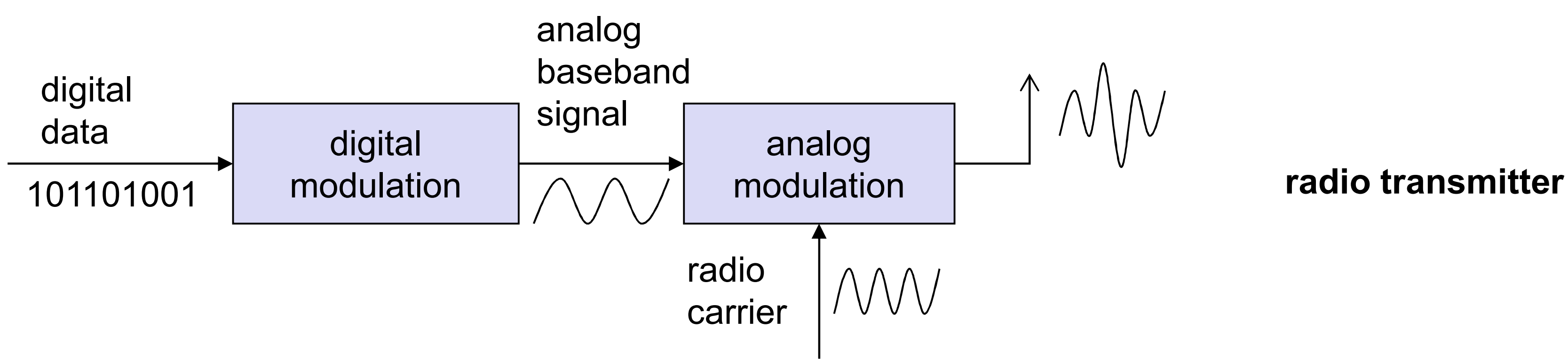
Modulation I

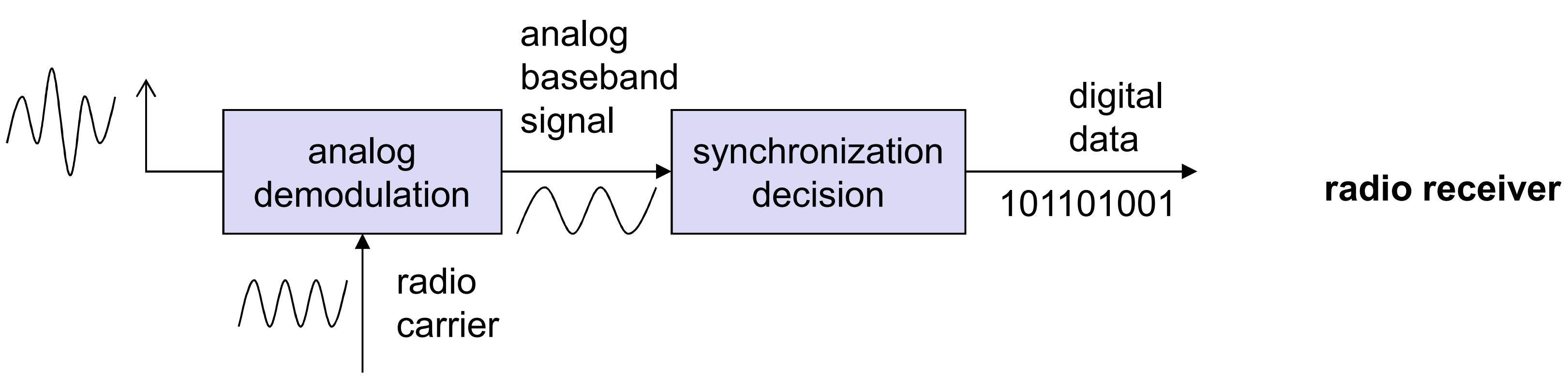
- Digital modulation
  - Digital data is translated into an analog signal (baseband)
  - Difference in spectral efficiency, power efficiency, robustness
- Analog modulation
  - Shifts center frequency of baseband signal up to the radio carrier
  - Reasons?

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



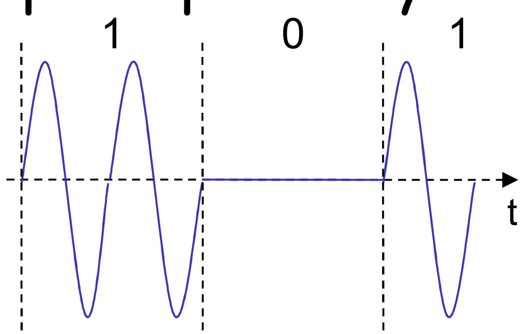


Modulation Schemes

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

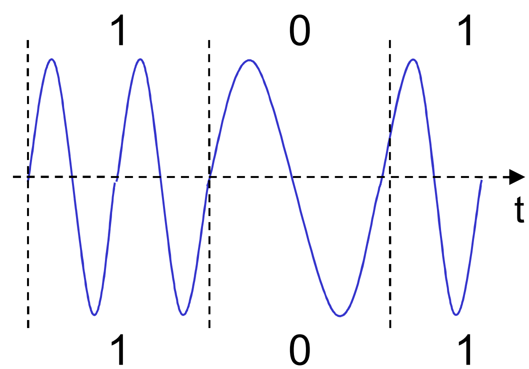
Digital Modulation

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



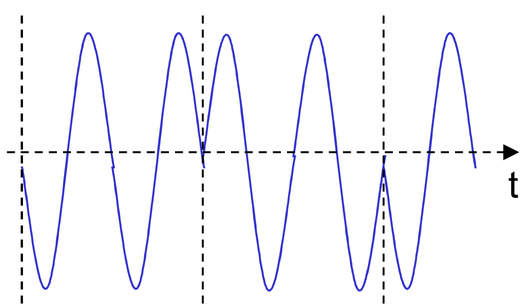
Digital Modulation II

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



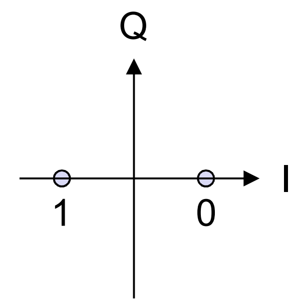
Digital Modulation III

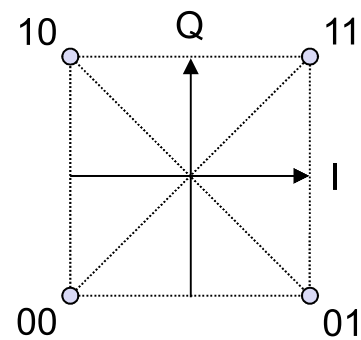
- Phase Shift Keying (PSK):
  - Pros:
    - Less susceptible to noise
    - Bandwidth efficient
  - Cons:
    - Require synchronization in frequency and phase ➔ complicates receivers and transmitter

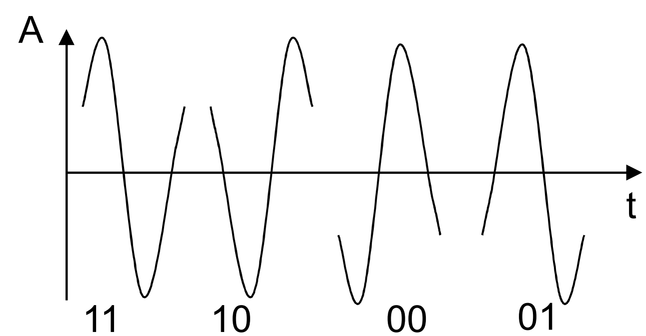


Phase Shift Keying

- 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
- 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

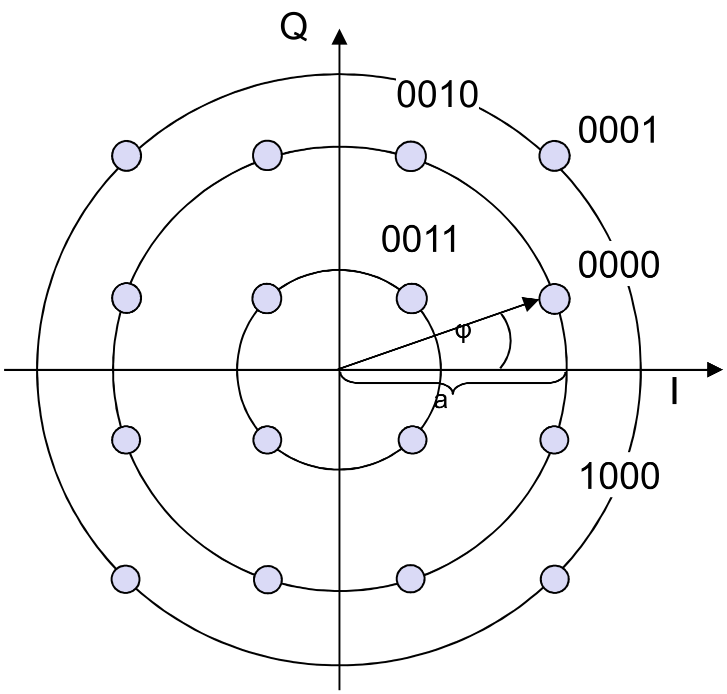






Quadrature Amplitude Modulation

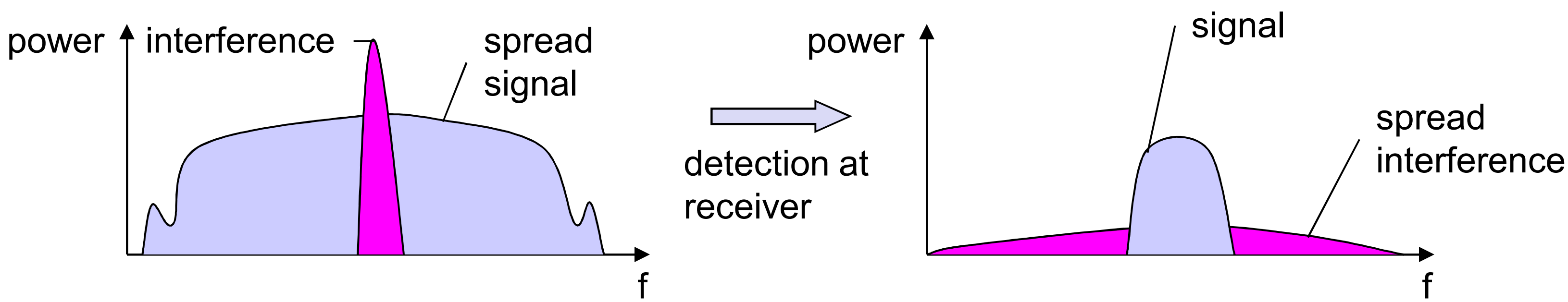
- Quadrature Amplitude Modulation (QAM): combines amplitude and phase modulation
- It is possible to code n bits using one symbol
  - 2^n discrete levels
- bit error rate increases with n



- 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

Spread spectrum technology

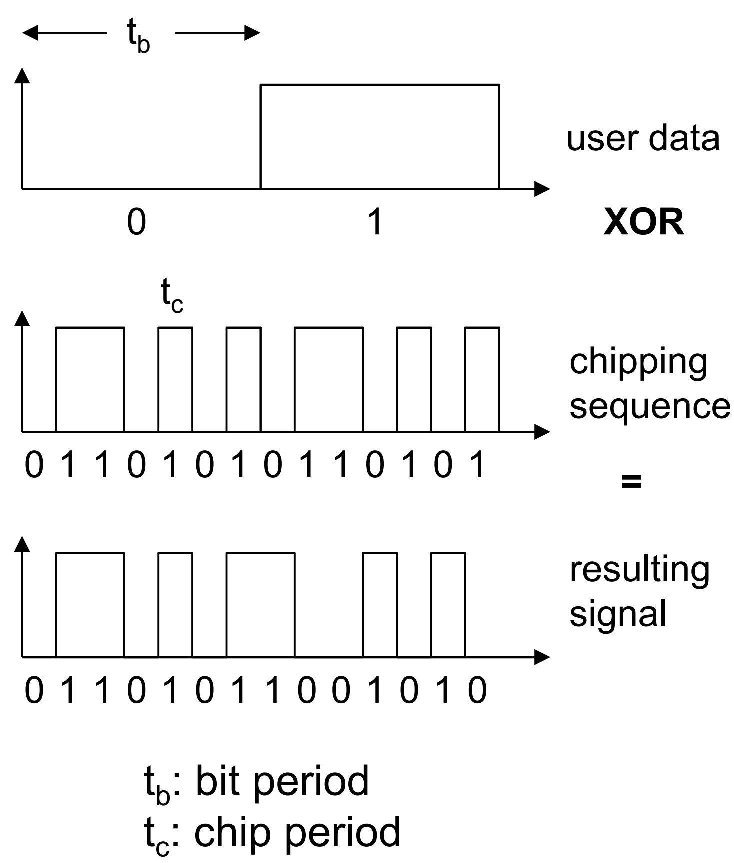
- Problem of radio transmission: frequency dependent fading can wipe out narrow band signals for duration of the interference
- Solution: spread the narrow band signal into a broad band signal using a special code



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

DSSS
(Direct Sequence Spread Spectrum)

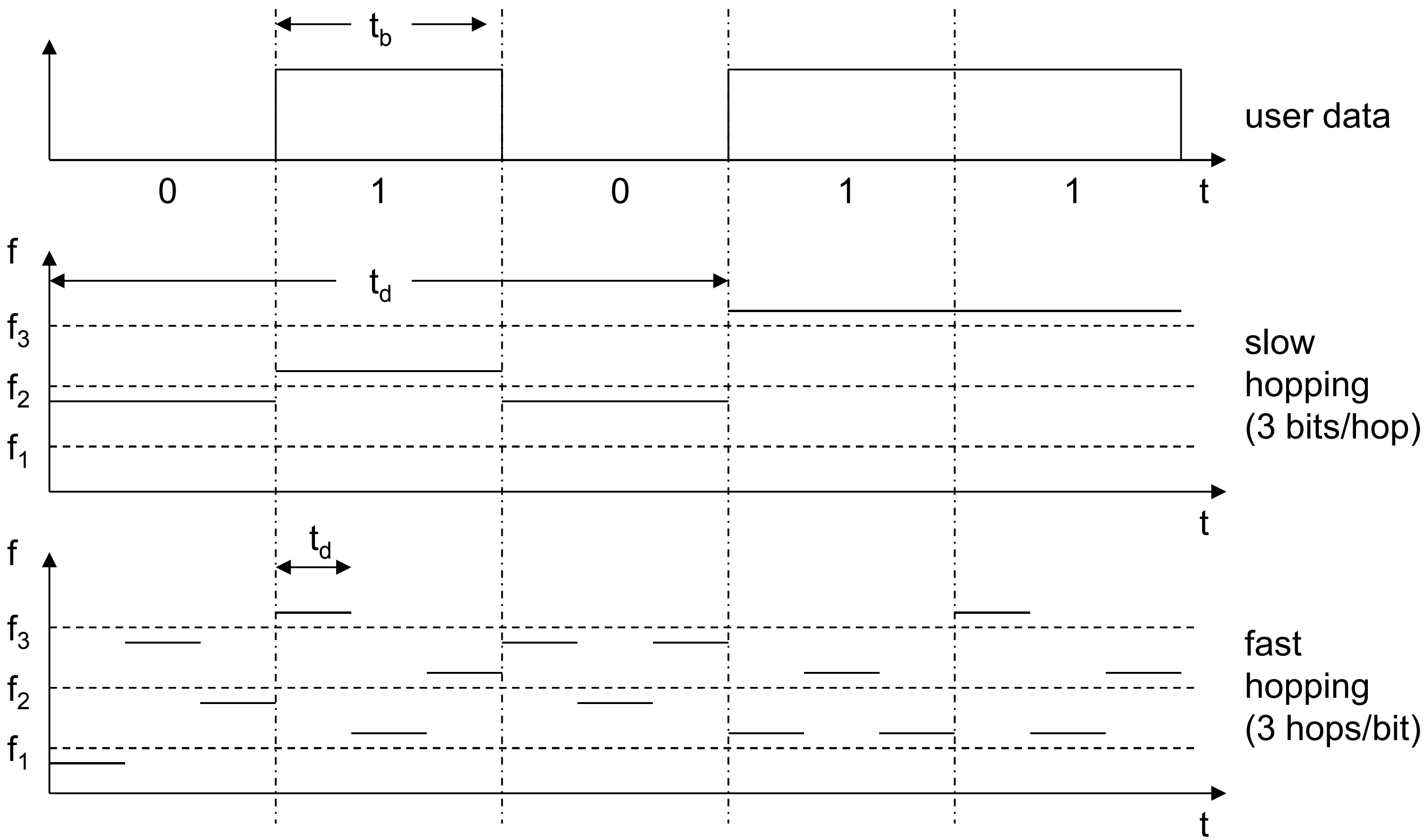
- XOR of the signal with pseudo-random number (chipping sequence)
  - generate a signal with a wider range of frequency: spread spectrum



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