An Introduction to Wireless Technologies
Part 1

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2010/2011

Content

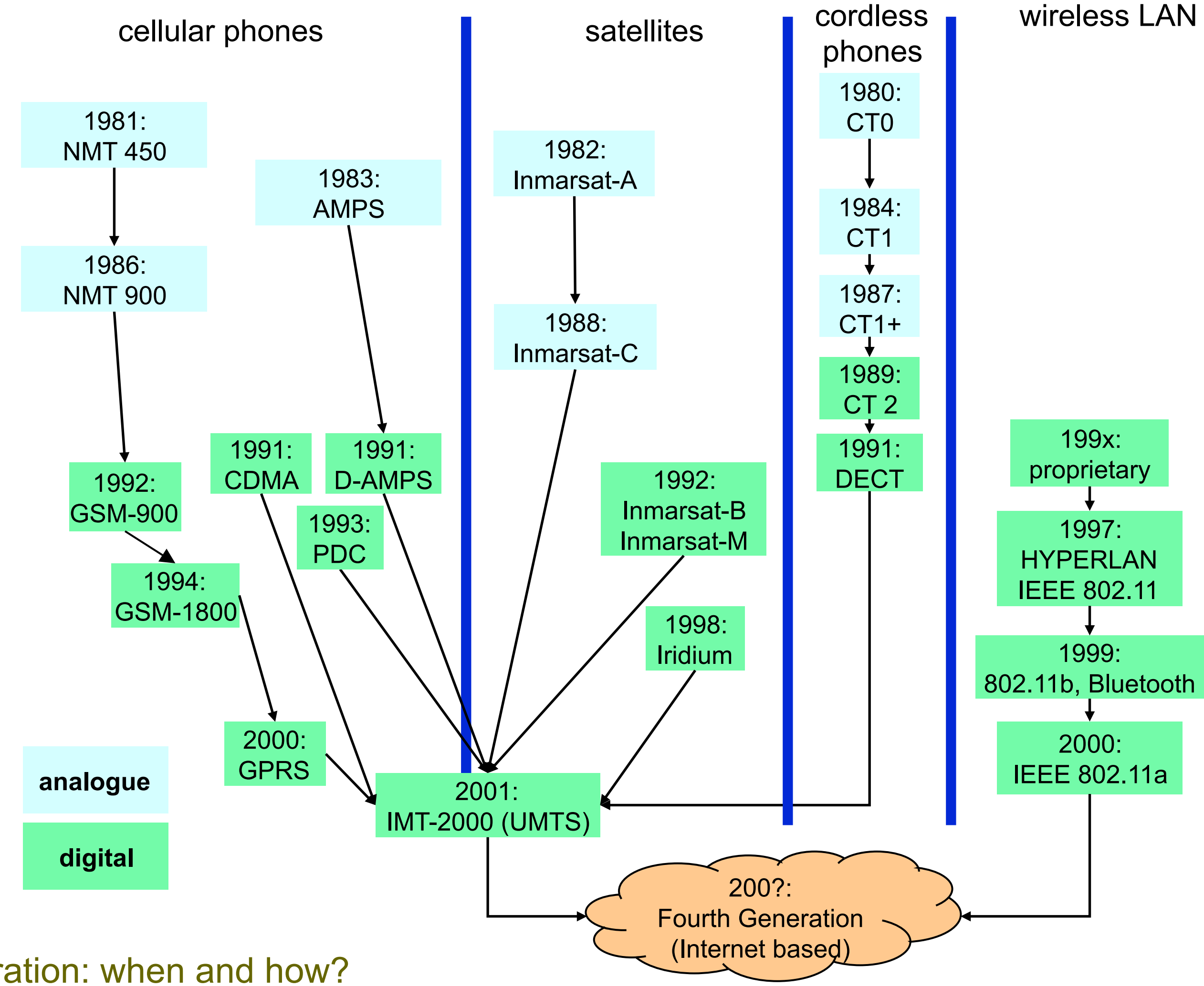
- Wireless communication standards
- Computer Networks
- Reference model for a network architecture
- Frequencies and regulations
- Wireless communication technologies
- Signals
- Bandwidth limited signals
- Signal modulation
- Data transfer rate
- Signal propagation

Most of the slides of this lecture come from **prof. Jochen Schiller's** didactical material for the book **"Mobile Communications", Addison Wesley, 2003.**

Analogue vs. Digital

- **Analogue transmission of analogue data**
  - The air pressure variations (analogue data) are converted (microphone) into an electrical analog signal in which either the instantaneous voltage or current is directly proportional to the instantaneous air pressure and then transmitted (e.g., traditional phone or radio)
- **Analogue transmission of digital data**
  - The electric analog signal is digitized, or converted to a digital signal, through an Analog-to-Digital converter and then modulated into analogue signals and trasmitted (e.g., digital phones as GSM).

Wireless systems: overview



4G – fourth generation: when and how?

Cellular Generations

- **First**
  - Analog, circuit-switched (AMPS, TACS)
- **Second**
  - Digital, circuit-switched (GSM) 10 Kbps
- **Advanced second**
  - Digital, circuit switched (HSCSD High-Speed Circuit Switched Data), Internet-enabled (WAP) 10 Kbps
- **2.5**
  - Digital, packet-switched, TDMA (GPRS, EDGE) 40-400 Kbps
- **Third**
  - Digital, packet-switched, Wideband CDMA (UMTS)
    0.4 – 2 Mbps
- **Fourth**
  - Data rate 100 Mbps; achieves "telepresence"

Nokia N95

- **Operating Frequency:** WCDMA2100 (HSDPA), EGSM900, GSM850/1800/1900 MHz (EGPRS)
- **Memory:** Up to 160 MB internal dynamic memory; memory card slot - microSD memory cards (up to 2 GB)
- **Display:** 2.6" QVGA (240 x 320 pixels) TFT – ambient light detector - up to 16 million colors
- **Data Transfer:**
  - WCDMA 2100 (HSDPA) with simultaneou voice and packet data (Packet Switching max speed UL/DL= 384/3.6MB, Circuit Switching max speed 64kbps)
  - Dual Transfer Mode (DTM) support for simultaneous voice and packet data connection in GSM/EDGE networks - max speed DL/UL: 177.6/118.4 kbits/s
  - EGPRS class B, multi slot class 32, max speed DL/UL= 296 / 177.6 kbits/s

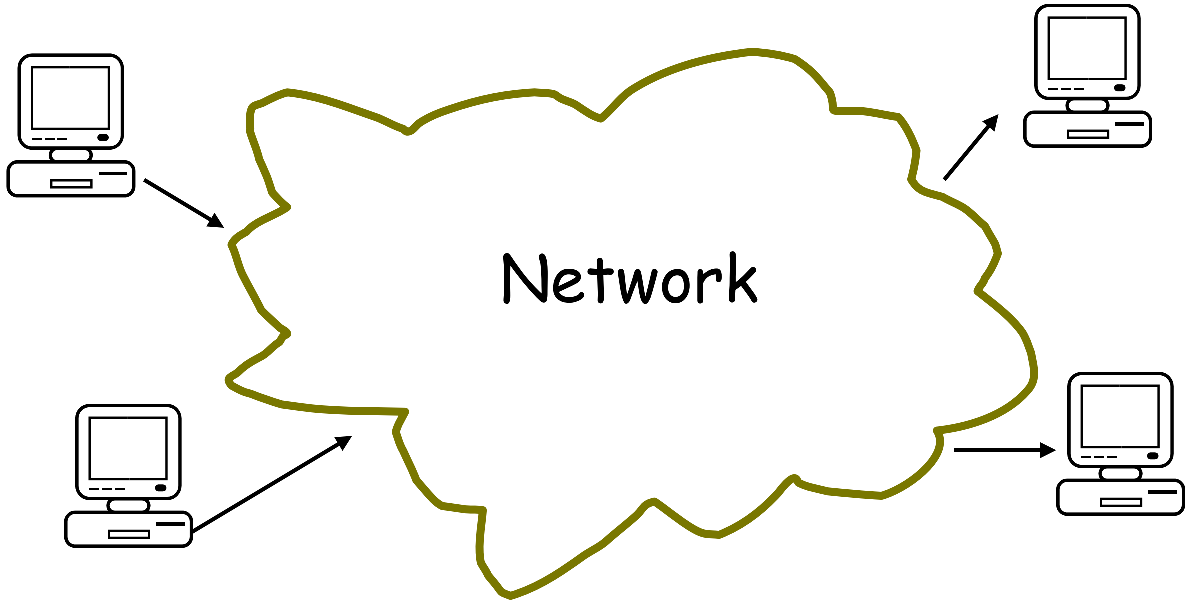
Speed

Services	2G	PSTN	ISDN	2G+	UMTS/3G
E-mail file 10 Kbyte	8 sec	3 sec	1 sec	0.7 sec	0.04 sec
Web Page 9 Kbyte	9 sec	3 sec	1 sec	0.8 sec	0.04sec
Text File 40 Kbyte	33 sec	11 sec	5 sec	3 sec	0.2 sec
Large Report 2 Mbyte	28 min	9 min	4 min	2 min	7 sec
Video Clip 4 Mbyte	48 min	18 min	8 min	4 min	14 sec
Film with TV Quality	1100 hr	350 hr	104 hr	52 hr	>5hr

Source: UMTS Forum

Computer Networks

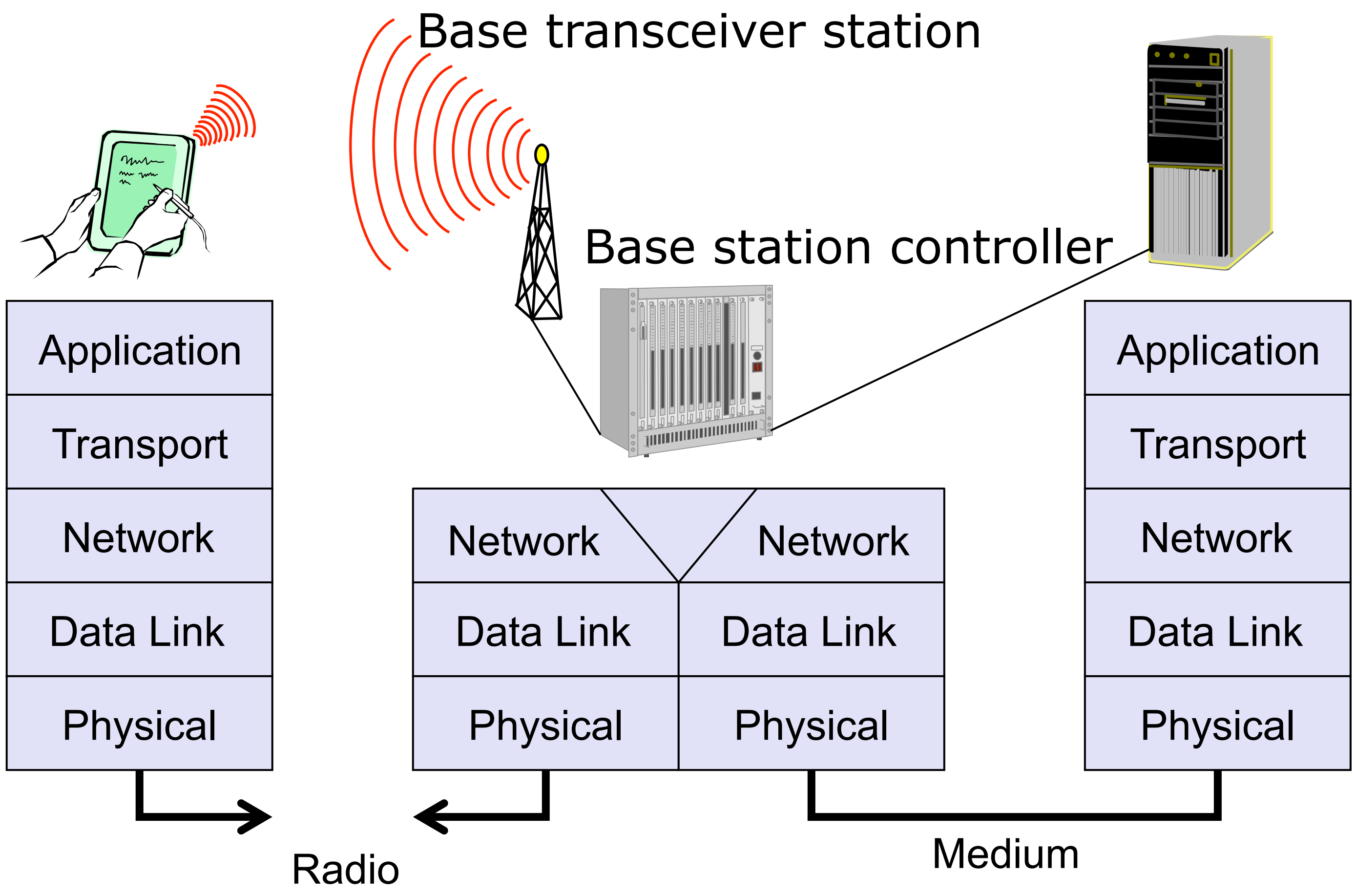
- A **computer network** is two or more computers connected together using a telecommunication system for the purpose of communicating and sharing resources
- Why they are interesting?
  - Overcome geographic limits
  - Access remote data
  - Separate clients and server
- Goal: Universal Communication (any to any)



Type of Networks

- **PAN:** a **personal area network** is a computer network (CN) used for communication among computer devices (including telephones and personal digital assistants) close to one person
  - **Technologies:** USB and Firewire (wired), IrDA and Bluetooth (wireless)
- **LAN:** a **local area network** is a CN covering a small geographic area, like a home, office, or group of buildings
  - **Technologies:** Ethernet (wired) or Wi-Fi (wireless)
- **MAN: Metropolitan Area Networks** are large CNs usually spanning a city
  - **Technologies:** Ethernet (wired) or WiMAX (wireless)
- **WAN: Wide Area Network** is a CN that covers a broad area, e.g., cross metropolitan, regional, or national boundaries
  - **Examples:** Internet
  - **Wireless Technologies:** HSDPA, EDGE, GPRS, GSM.

Reference Model



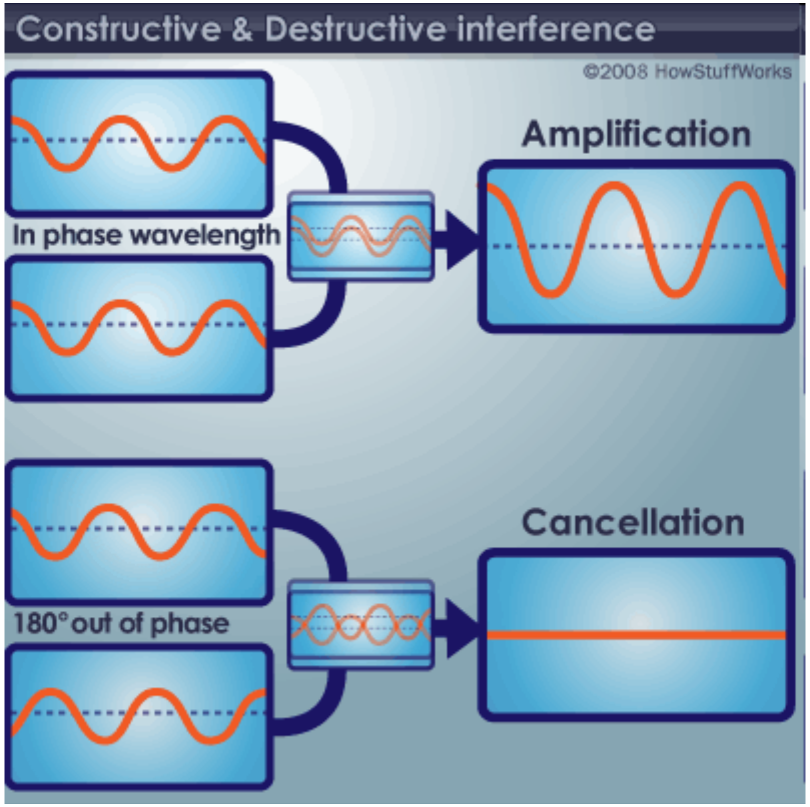
Reference model

- **Physical layer:** conversion of stream of bits into signals – carrier generation - frequency selection – signal detection – encryption
- **Data link layer:** accessing the medium – multiplexing - error correction – synchronization
- **Network layer:** routing packets – addressing - handover between networks
- **Transport layer:** establish an end-to-end connection – quality of service – flow and congestion control
- **Application layer:** service location – support multimedia – wireless access to www

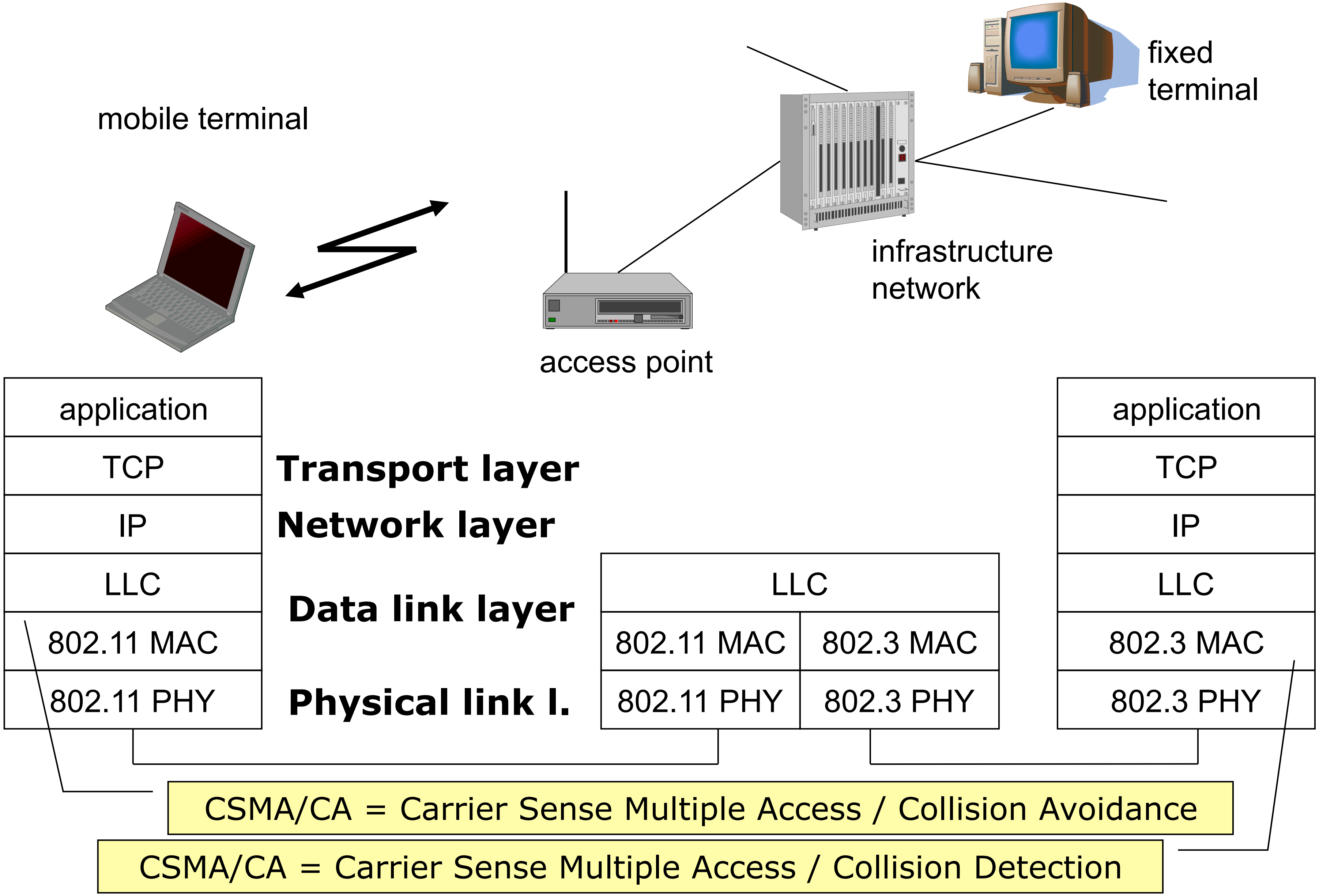
Wireless Network

- The difference between wired and wireless is the **physical layer** and the **data link layer**
- Wired network technology is based on wires or fibers
- Data transmission in wireless networks take place using **electromagnetic waves** which propagates through space (scattered, reflected, attenuated)
- Data are **modulated onto carrier frequencies** (amplitude, frequency)
- The **data link layer** (accessing the medium, multiplexing, error correction, synchronization) requires more complex mechanisms.

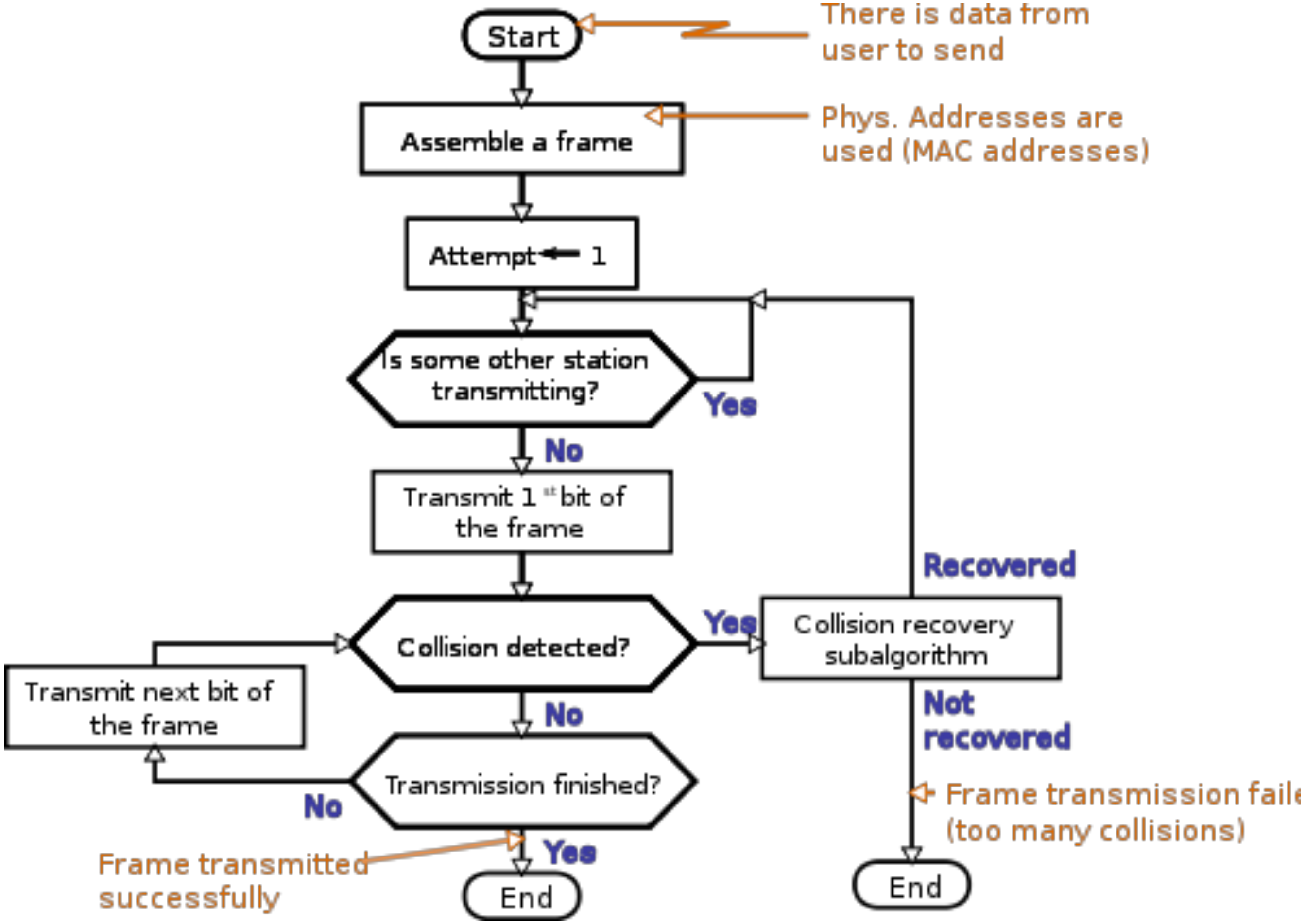
Waves' interference



IEEE standard 802.11

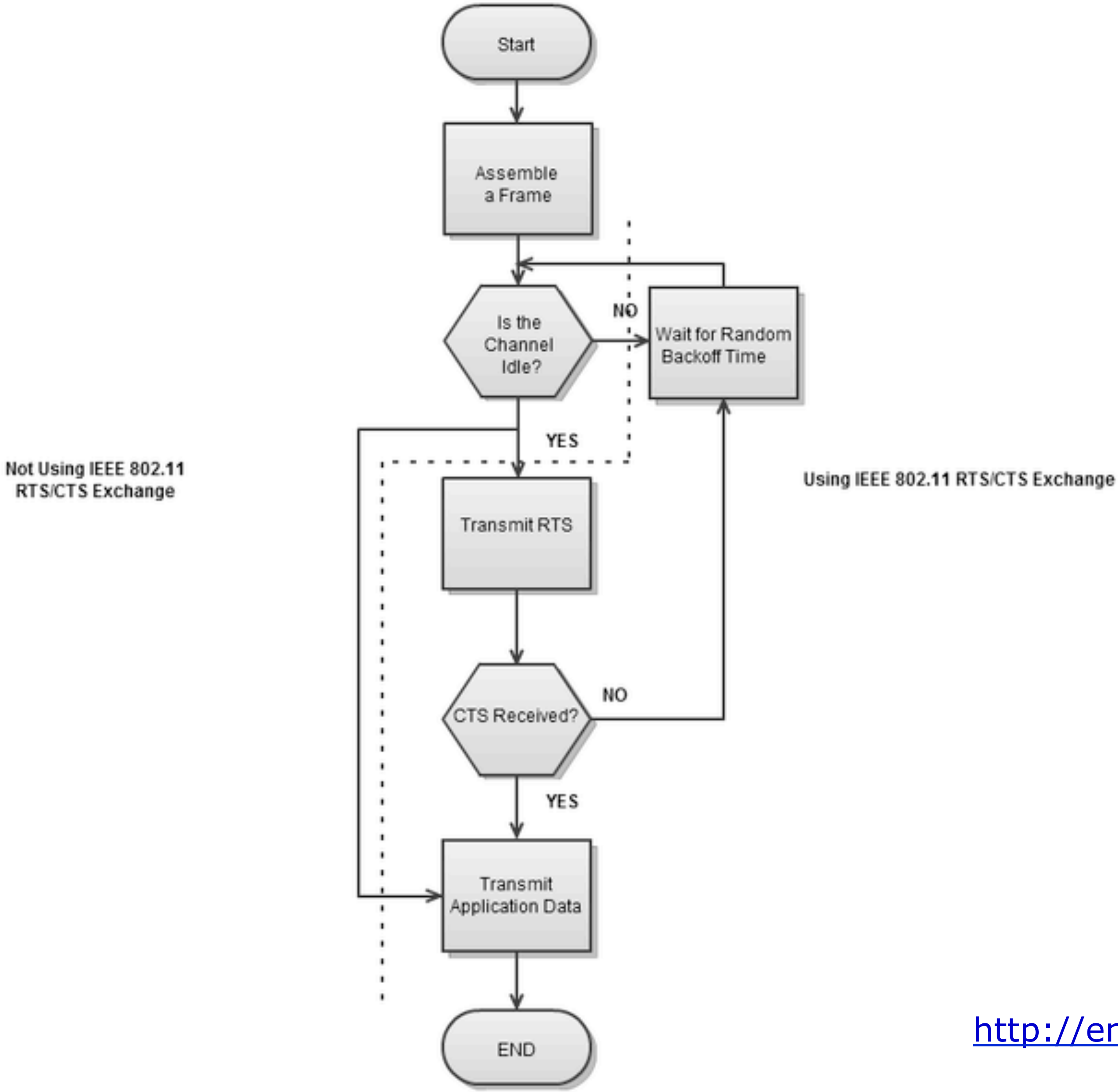


CSMA/CD



http://en.wikipedia.org/wiki/CSMA/CD

CSMA/CA



Request to Send (RTS) packet sent by the sender S, and a **Clear to Send** (CTS) packet sent by the intended receiver R.

Alerting all nodes within range of the sender, receiver or both, to not transmit for the duration of the main transmission.

http://en.wikipedia.org/wiki/

Mobile Communication Technologies

Local wireless networks
WLAN 802.11

WiFi

802.11a → 802.11h
802.11i/e/…/w
802.11b → 802.11g

Personal wireless nw
WPAN 802.15

ZigBee

802.15.4 → 802.15.4a/b
802.15.5
802.15.3 → 802.15.3a/b
802.15.2
802.15.1
Bluetooth

Wireless distribution networks
WMAN 802.16 (Broadband Wireless Access)

WiMAX

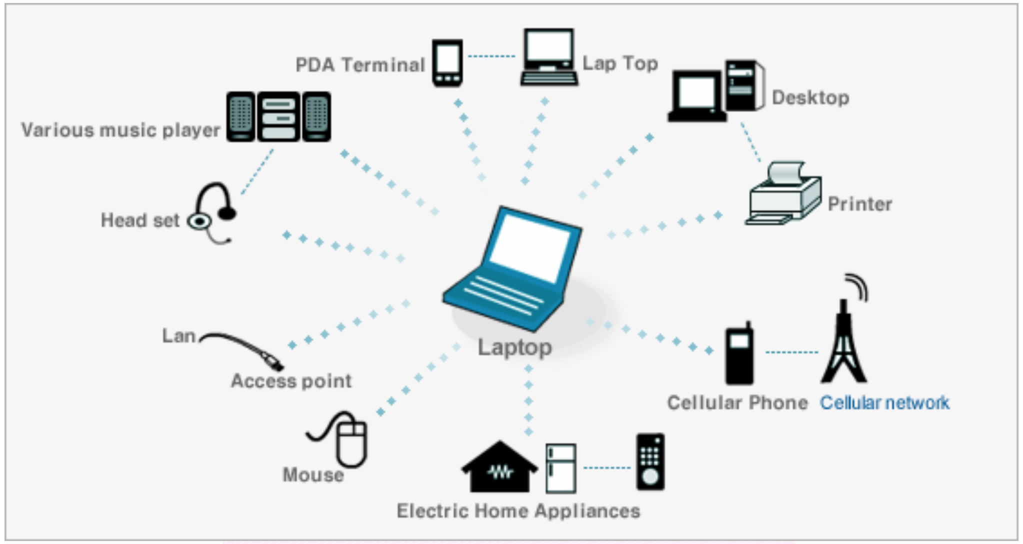
+ Mobility

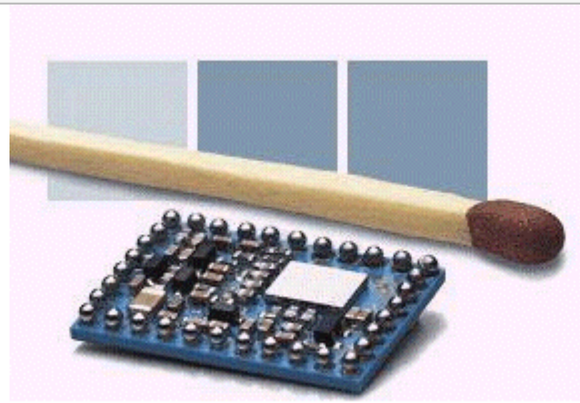
802.20 (Mobile Broadband Wireless Access)

Bluetooth

A standard permitting wireless connection of:

- Personal computers
- Printers
- Mobile phones
- Handsfree headsets
- LCD projectors
- Modems
- Wireless LAN devices
- Notebooks
- Desktop PCs
- PDAs





Bluetooth Characteristics

- Operates in the **2.4 GHz band - Packet switched**
- **1 milliwatt** - as opposed to 500 mW cellphone
- **Low cost**
- **10m** to **100m** range
- **Uses Frequency Hop** (FH) spread spectrum, which divides the frequency band into a number of hop channels. During connection, devices hop from one channel to another 1600 times per second
- **Data transfer rate 1-2 megabits/second** (GPRS is ~50kbits/s)
- Supports up to **8 devices in a piconet** (= two or more Bluetooth units sharing a channel).
- Built-in security
- Non line-of-sight transmission through walls and briefcases
- Easy integration of TCP/IP for networking.

http://www.bluetooth.com/English/Technology/Pages/Basics.aspx

Wi-Fi

- **Wi-Fi** is a technology for WLAN based on the IEEE 802.11 (a, b, g) specifications
- Originally developed for PC in WLAN
- Increasingly used for more services:
  - Internet and VoIP phone access, gaming, …
  - and basic connectivity of consumer electronics such as televisions and DVD players, or digital cameras, …
- In the **future** Wi-Fi will be used by cars in highways in support of an Intelligent Transportation System to increase safety, gather statistics, and enable mobile commerce (IEEE 802.11p)
- Wi-Fi supports structured (access point) and ad-hoc networks (a PC and a digital camera).

Wi-Fi

- An access point (AP) **broadcasts** its SSID (Service Set Identifier, "Network name") via packets (beacons) broadcasted every 100 ms at 1 Mbit/s
- Based on the settings (e.g. the SSID), the client may decide whether to connect to an AP
- Wi-Fi transmission, as a non-circuit-switched wired Ethernet network, can generate collisions
- Wi-Fi uses **CSMA/CA** (Carrier Sense Multiple Access with Collision Avoidance) to avoid collisions
- **CSMA** = the sender before transmitting it senses the carrier – if there is another device communicating then it waits a random time an retry
- **CA** = the sender before transmitting contacts the receiver and ask for an acknowledgement – if not received the request is repeated after a random time interval.

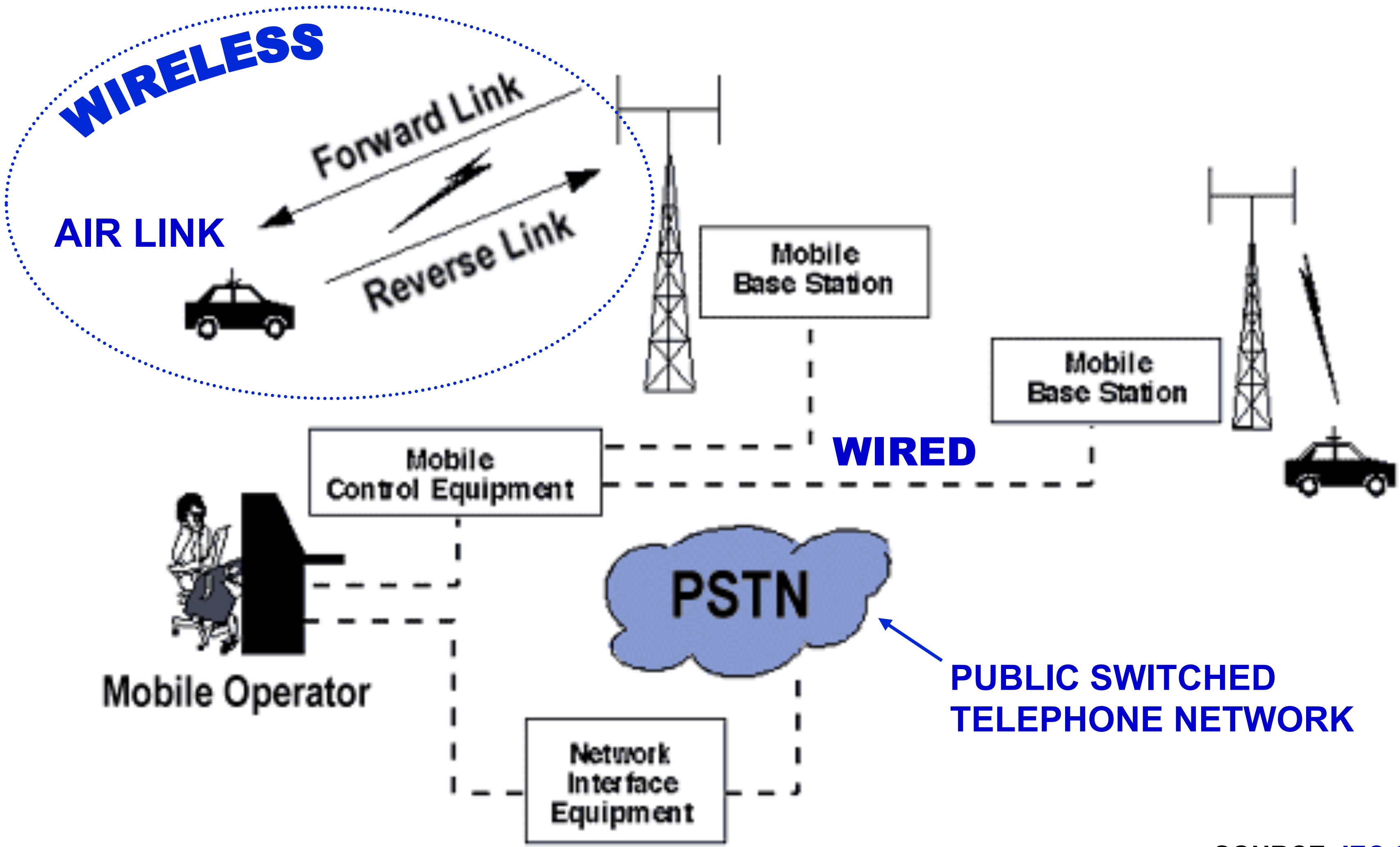
WiMAX

- IEEE 802.16: Broadband Wireless Access / WirelessMAN / WiMax (**W**orldwide **I**nteroperability for **M**icrowave **Acc**ess)
- Connecting Wi-Fi hotspots with each other and to other parts of the Internet
- Providing a **wireless alternative to cable and DSL** for last mile broadband access
- Providing high-speed mobile data and telecommunications services
- Providing Nomadic connectivity
- 75 Mbit/s up to 50 km LOS, up to 10 km NLOS; 2-5 GHz band
- Initial standards without roaming or mobility support
- 802.16e adds mobility support, allows for roaming at 150 km/h.

http://wimax.retelit.it/index.do

http://www.wimax-italia.it/

Wireless Telephony



SOURCE: IEC.ORG

Advantages of wireless LANs

- Very flexible within the reception area
- Ad-hoc networks without previous planning possible
- (almost) no wiring difficulties (e.g. historic buildings, firewalls)
- More robust against disasters like, e.g., earthquakes, fire - or users pulling a plug...

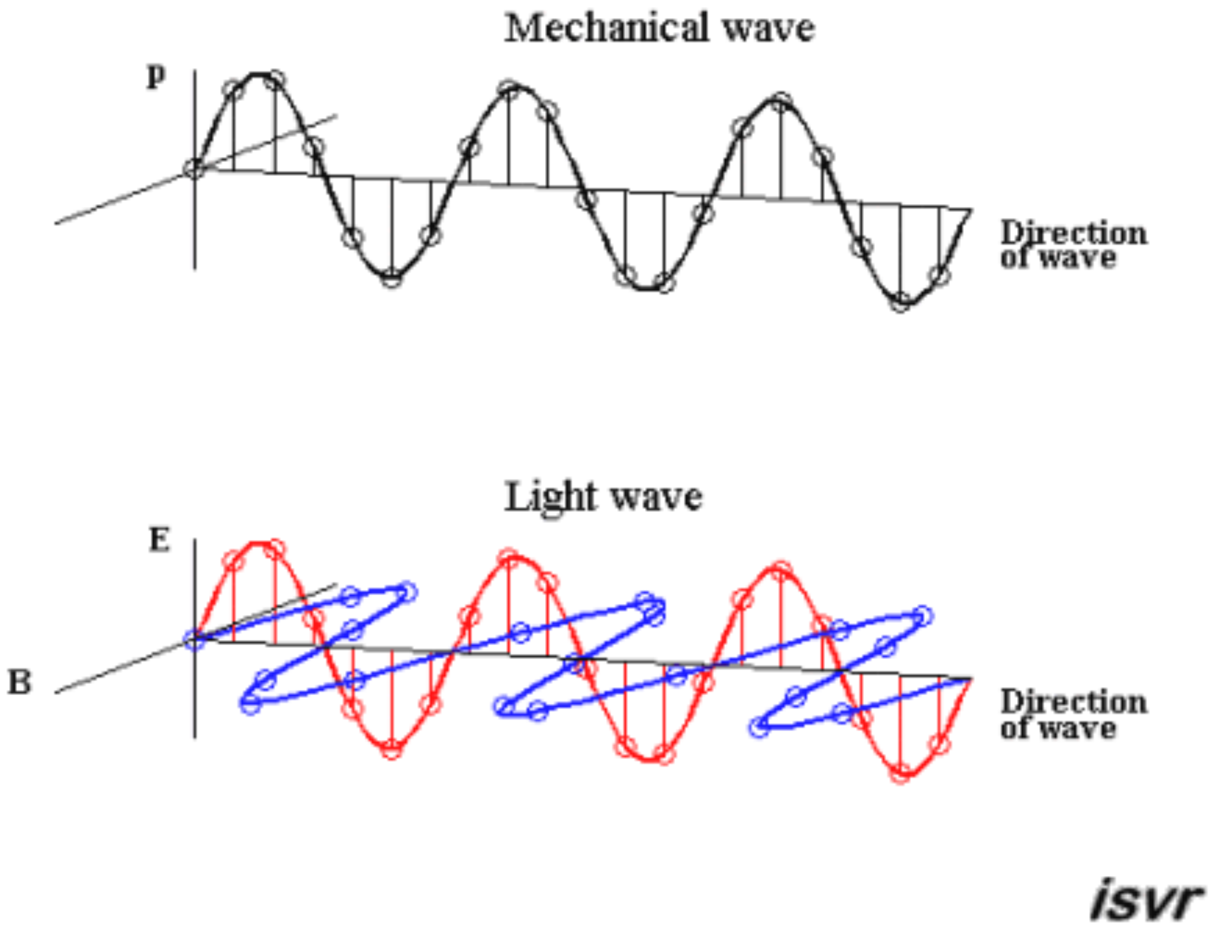
Wireless networks disadvantages

- **Higher loss-rates due to interference**
  - emissions of, e.g., engines, lightning
- **Restrictive regulations of frequencies**
  - frequencies have to be coordinated, useful frequencies are almost all occupied
- **Low data transmission rates**
  - local some Mbit/s, regional currently, e.g., 53kbit/s with GSM/GPRS
- **Higher delays, higher jitter**
  - connection setup time with GSM in the second range, several hundred milliseconds for other wireless systems
- **Lower security, simpler active attacking**
  - radio interface accessible for everyone, base station can be simulated, thus attracting calls from mobile phones
- **Always shared medium**
  - secure access mechanisms important

Electromagnetic Waves

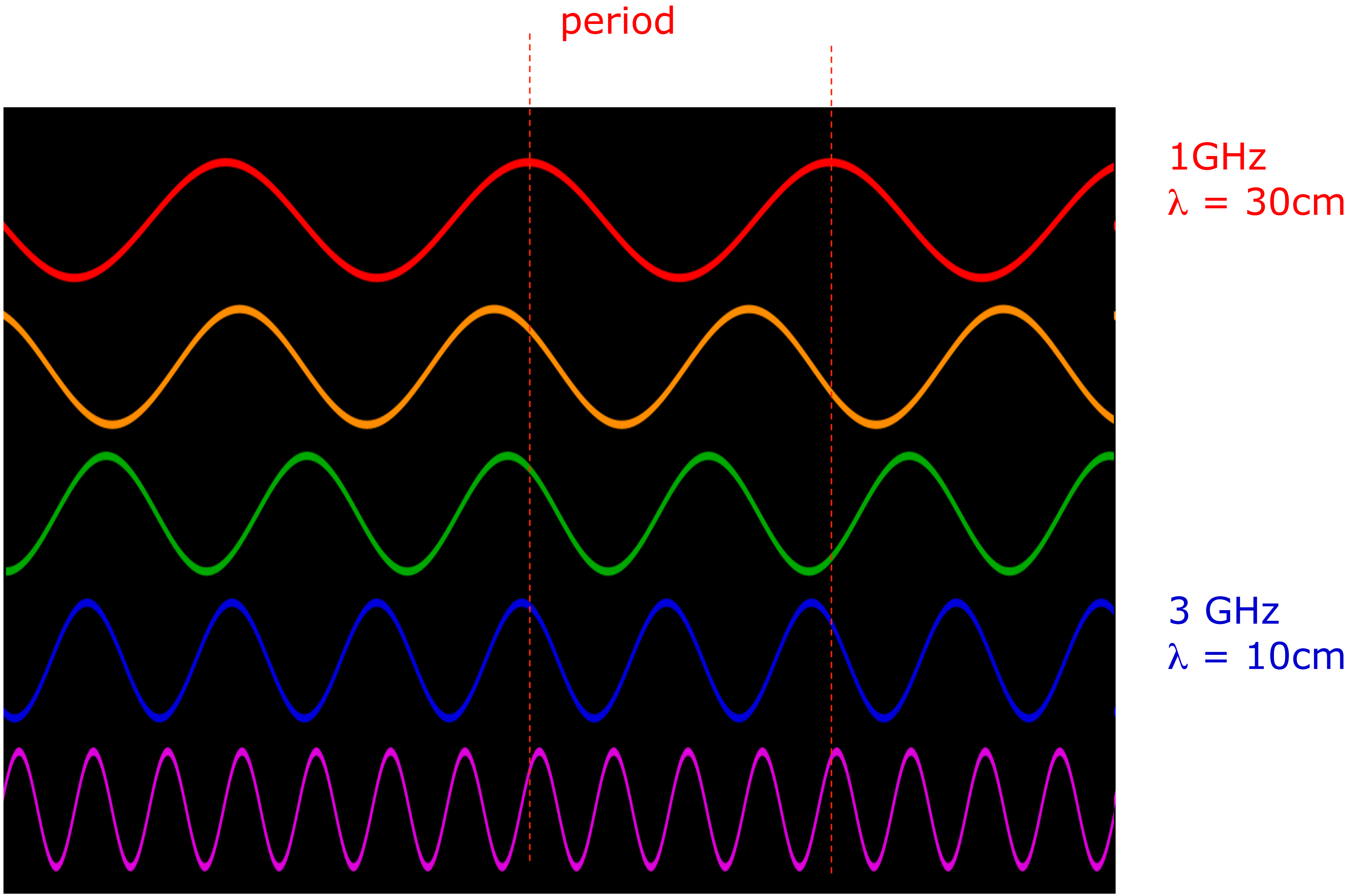
- **Electromagnetic radiation** (EMR) takes the form of self-propagating waves in a vacuum or in matter
- It consists of **electric** and **magnetic field** components which oscillate in phase perpendicular to each other and **perpendicular** to the direction of energy propagation
- A **wave** is a disturbance that propagates through space and time, usually with transference of energy
- The **wavelength** (denoted as λ) is the distance between two sequential crests
- The **period** *T* is the time for one complete cycle for an oscillation of a wave
- The **frequency** *f* is how many periods per unit time (for example one second) and is measured in hertz: $f=1/T$
- the **velocity of a wave** is the velocity at which variations in the shape of the wave's amplitude propagate through space: $v = \lambda * f$

Wave propagation

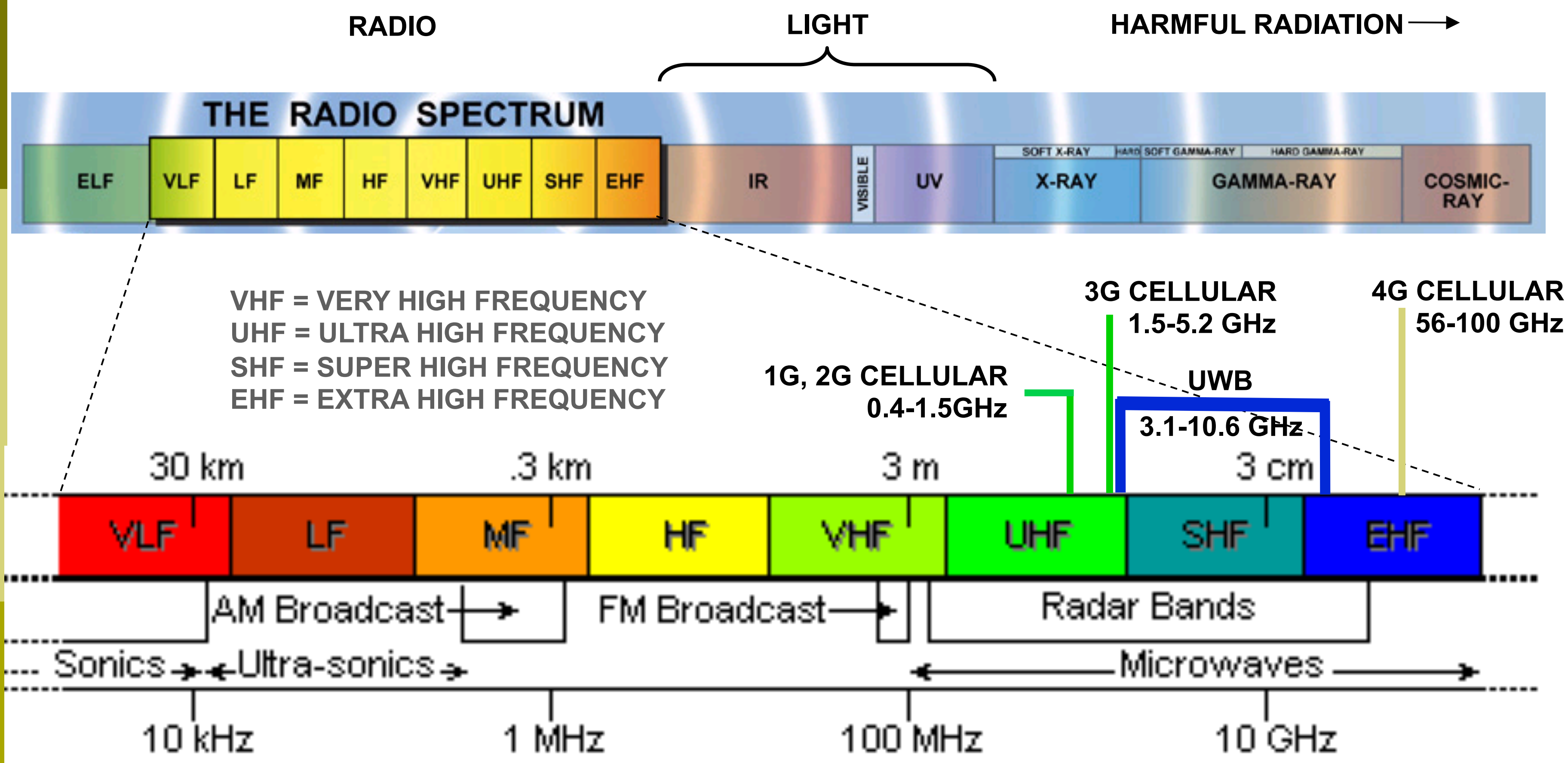


http://www.isvr.soton.ac.uk/SPCG/Tutorial/Tutorial/StartCD.htm

Waves with different frequencies and length



Electromagnetic Spectrum



SOURCE: JSC.MIL

$c = \lambda * f$

$c = 299\,792\,458$ m/s ~ $3*10^8$ m/s

Frequencies and regulations

- ITU-R (International Telecommunication Union – Radiocommunication) holds auctions for new frequencies, manages frequency bands worldwide

	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

Values in MHz

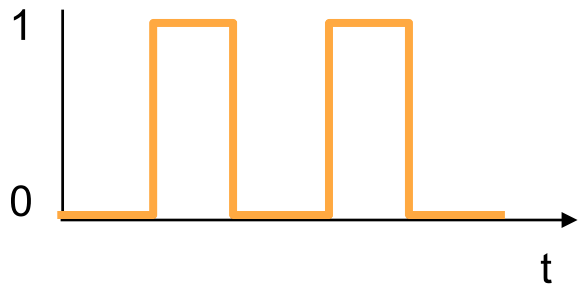
Signals I

- **Signals are a function of time and location**
- **Physical representation of data**
- Users can **exchange data** through the **transmission of signals**
- The **Layer 1** is responsible for conversion of data, i.e., bits, into signals and viceversa
- 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:
    $s(t) = A_t \sin(2 \pi f_t t + \varphi_t)$
- Sine waves are of special interest as it is possible to construct every periodic signal using only sine and cosine functions (Fourier equation).

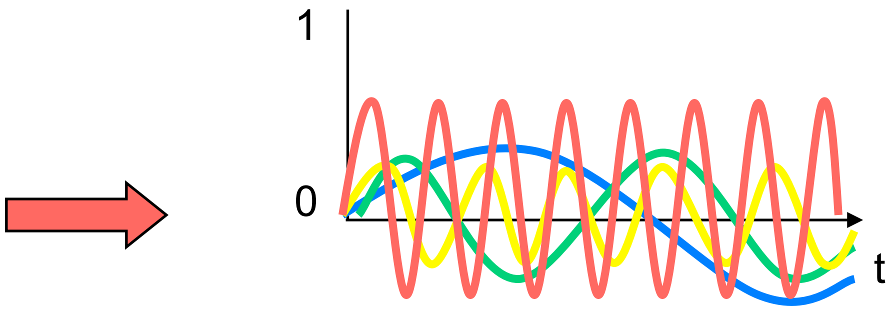
http://en.wikipedia.org/wiki/Fourier_series
http://en.wikipedia.org/wiki/Fourier_transform

Fourier analysis of periodic signals

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



ideal periodic signal

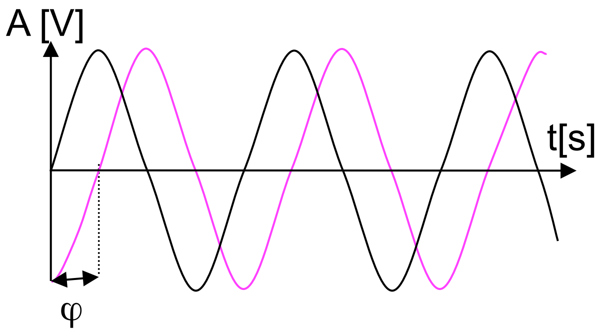


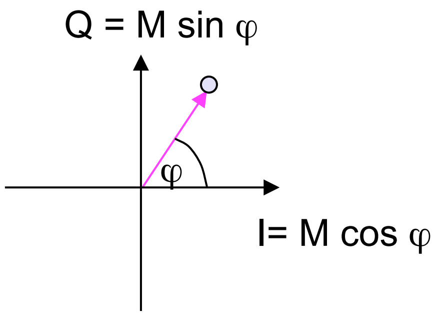
real composition
(based on harmonics)

f=1/T is the fundamental frequency = first harmonic
It is the lowest frequency present in the spectrum of the signal.

Signals II

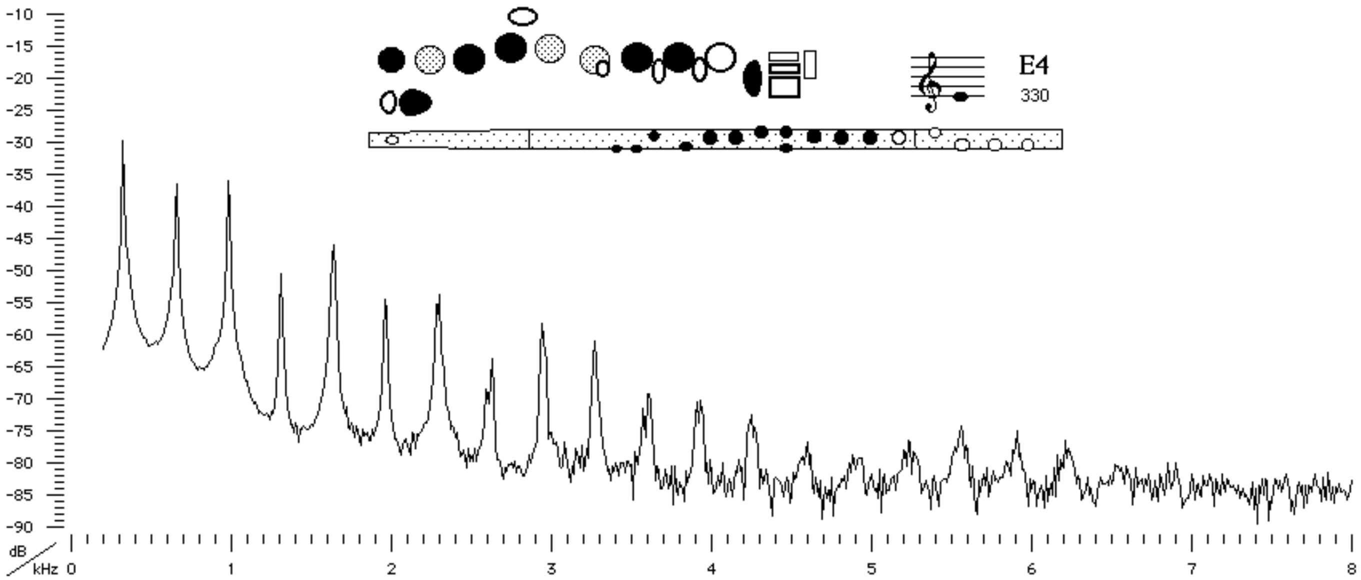
- Different representations of signals
  - amplitude (amplitude domain)
  - frequency spectrum (frequency domain)
  - phase state diagram (amplitude M and phase φ in polar coordinates)

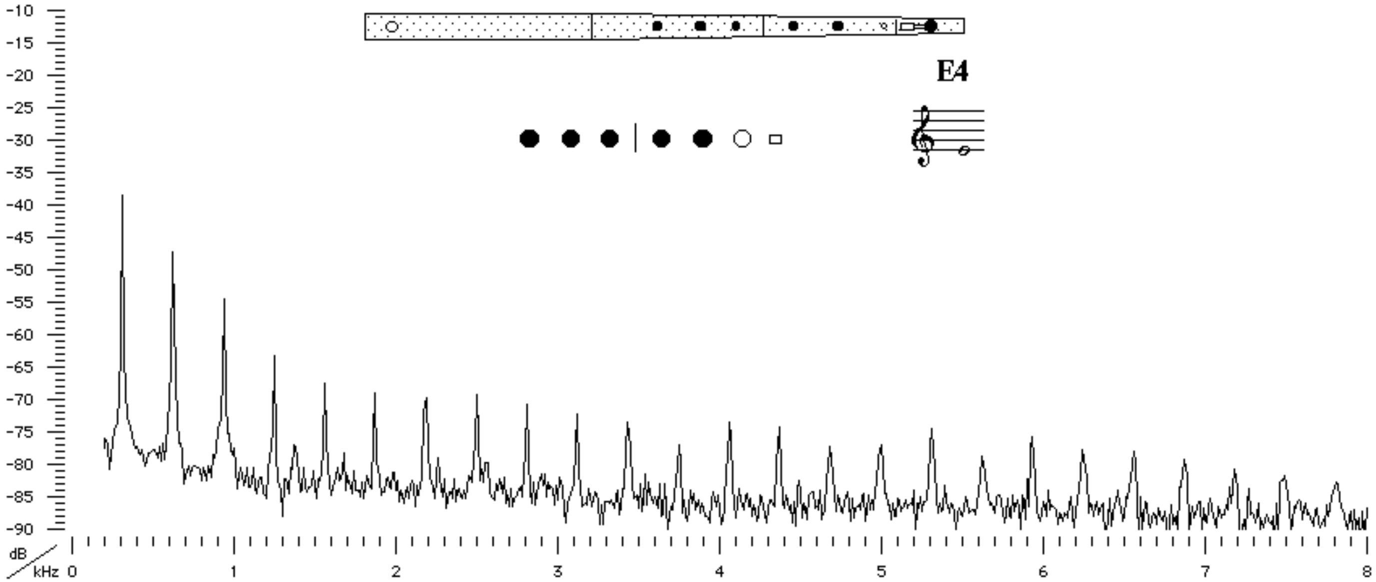




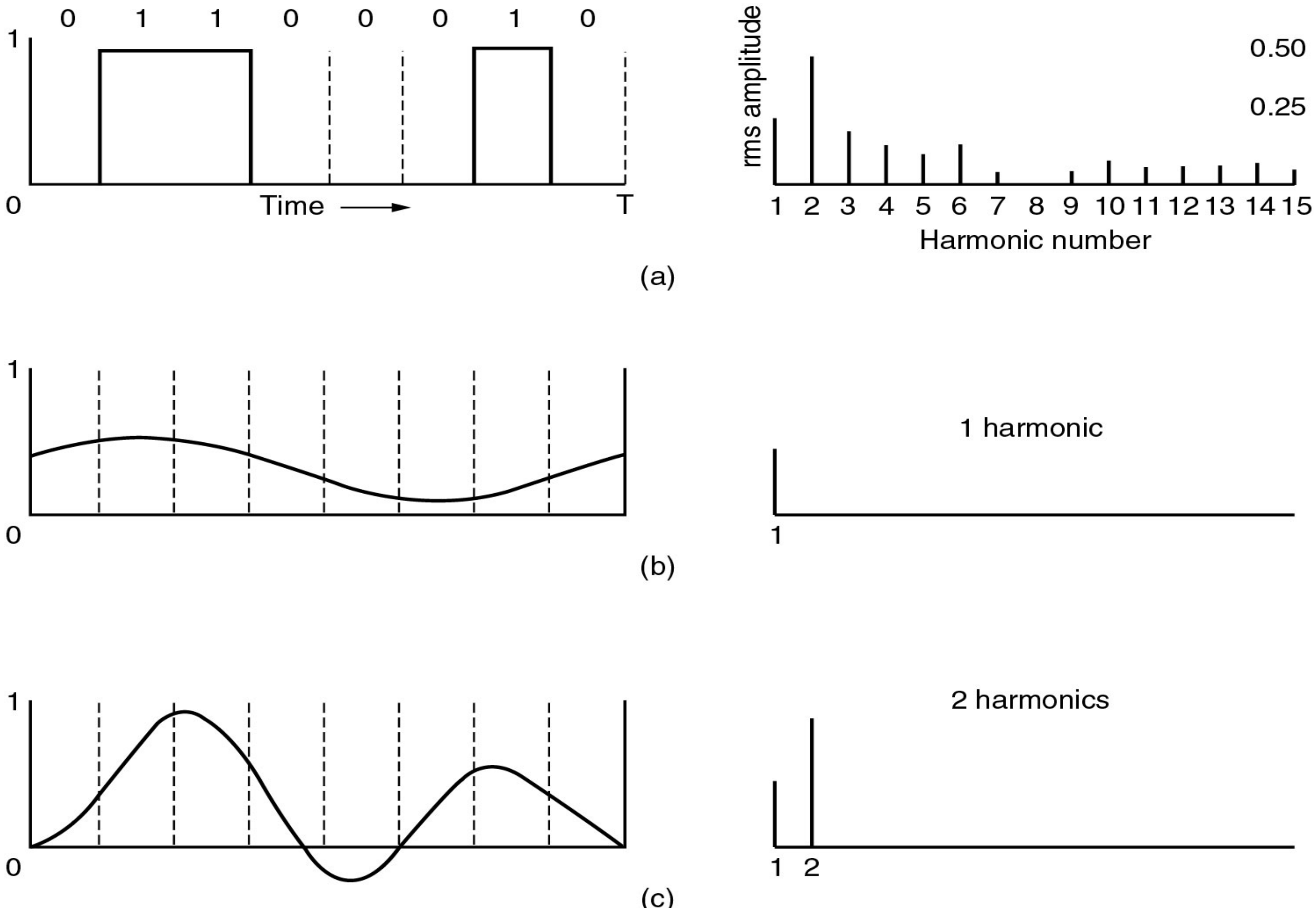
- Composed signals transferred into frequency domain using Fourier transformation
- **Digital signals need:**
  - infinite frequencies for perfect transmission
  - modulation with a carrier frequency for transmission (analog signal!)

Sound spectrum of two flutes



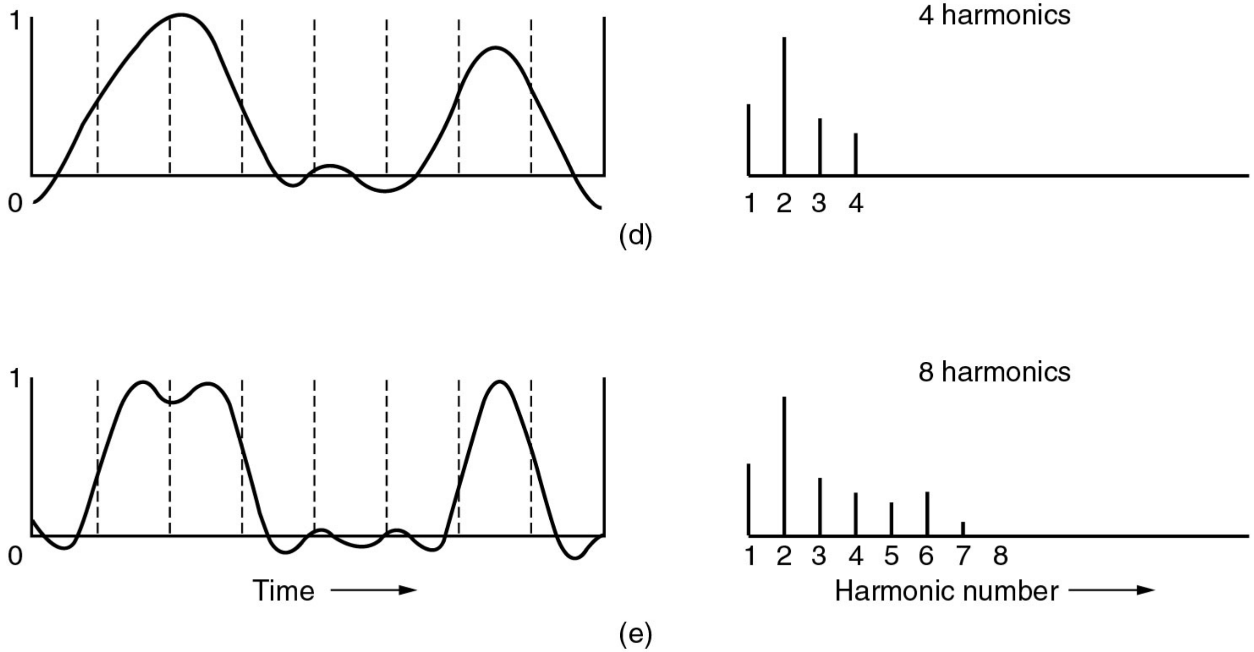


Bandwidth-Limited Signals



- A binary signal and its root-mean-square Fourier amplitudes.
- (b) – (c) Successive approximations to the original signal
- f=1/T is the fundamental frequency = first harmonic

Bandwidth-Limited Signals (2)



(d) – (e) Successive approximations to the original signal.

Bandwidth-Limited Signals (3)

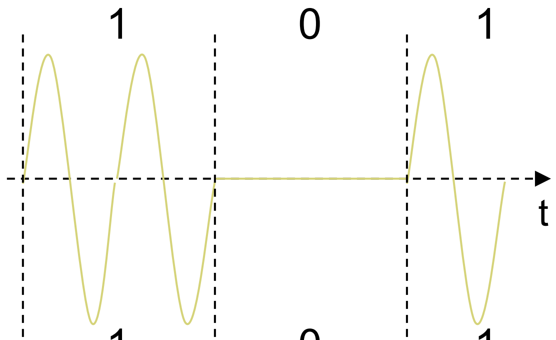
Relation between data rate and harmonics

Bps	T (msec)	First harmonic (Hz)	# Harmonics sent
300	26.67	37.5	80
600	13.33	75	40
1200	6.67	150	20
2400	3.33	300	10
4800	1.67	600	5
9600	0.83	1200	2
19200	0.42	2400	1
38400	0.21	4800	0

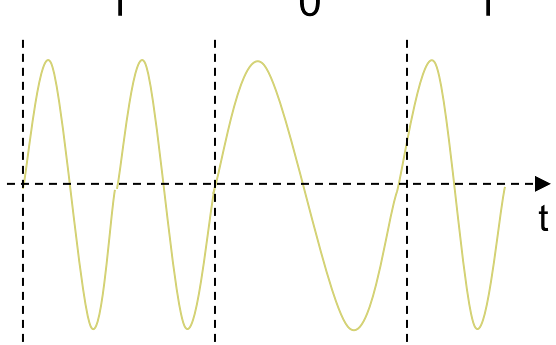
- **8 bits** sent through a channel with **bandwidth** equal to **3000Hz**
- For instance, if we want to send at **2400bps** we need
- T=8/2400 = 3.33 msec – this is the period of the first harmonic (the longest) – hence the frequency of the first harmonic is 1000/3.3=300
- The number of harmonic passing through the channel (3000Hz) is 3000/300 = 10.

Digital modulation

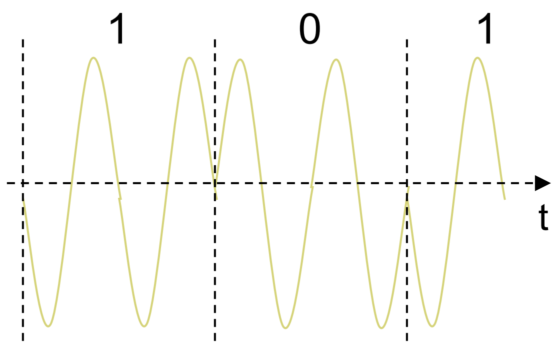
- Modulation of digital signals known as Shift Keying
- Amplitude Shift Keying (ASK):
  - very simple
  - low bandwidth requirements
  - very susceptible to interference



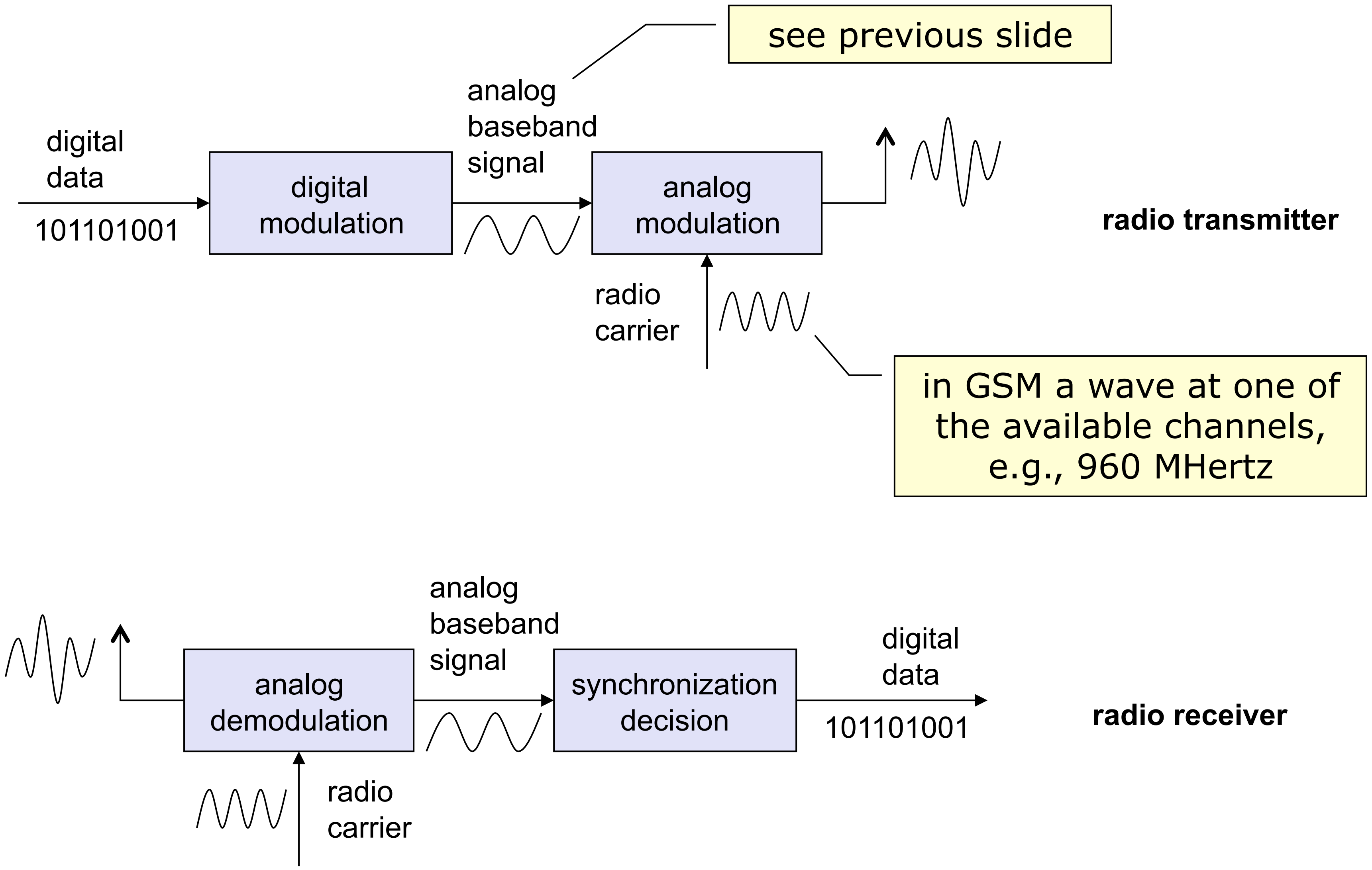
- Frequency Shift Keying (FSK):
  - needs larger bandwidth
  - WHY?



- Phase Shift Keying (PSK):
  - more complex
  - robust against interference



Modulation and demodulation



Modulation

- **Digital modulation**
  - digital data is translated into an analog signal (baseband) with: ASK, FSK, PSK
  - differences in spectral efficiency, power efficiency, robustness
- **Analog modulation:** shifts center frequency of baseband signal up to the radio carrier
  - Motivation
    - smaller antennas (e.g., $\lambda/4$)
    - Frequency Division Multiplexing -it would not be possible if we use always the same band
    - medium characteristics
  - Basic schemes
    - Amplitude Modulation (AM)
    - Frequency Modulation (FM)
    - Phase Modulation (PM)

Frequency of Signals: Summary

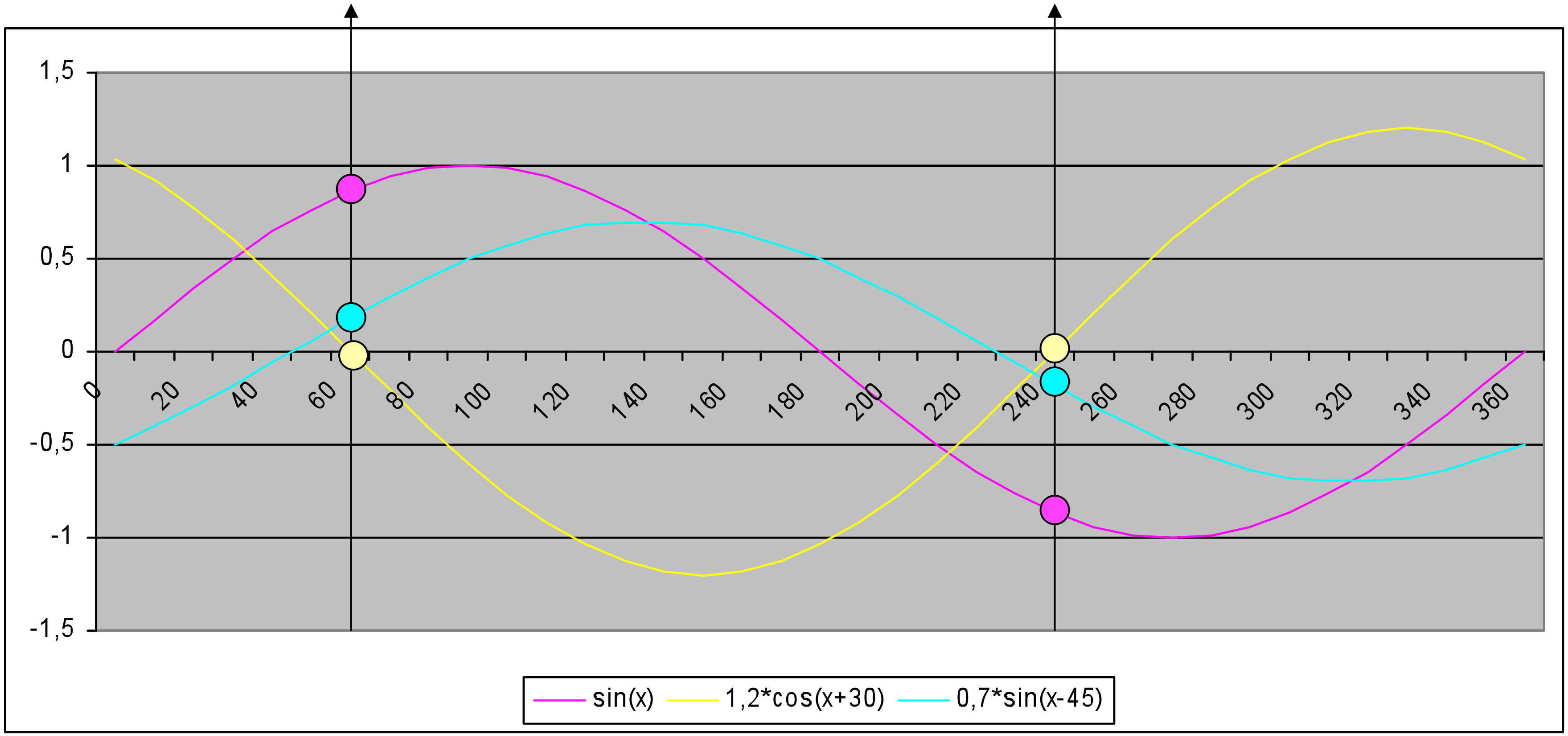
- *Frequency is measured in **cycles per second**, called **Hertz.***
- Electromagnetic radiation can be used in ranges of increasingly higher frequency:
  - Radio (< GHz)
  - Microwave (1 GHz – 100 GHz)
  - Infrared (100 GHz - 300 THz)
  - Light (380-770 THz)
- Higher frequencies are more directional and (generally) more affected by weather
- Higher frequencies can carry more bits/second (*see next*)
- A signal that changes over time can be represented by its energy at different *frequencies (Fourier)*
- *The **bandwidth** of a signal is the difference between the maximum and the minimum significant frequencies of the signal*

100GHz -> 3mm wavelength - ~1Gb/s throughput - Why?

Nyquist Sampling Theorem

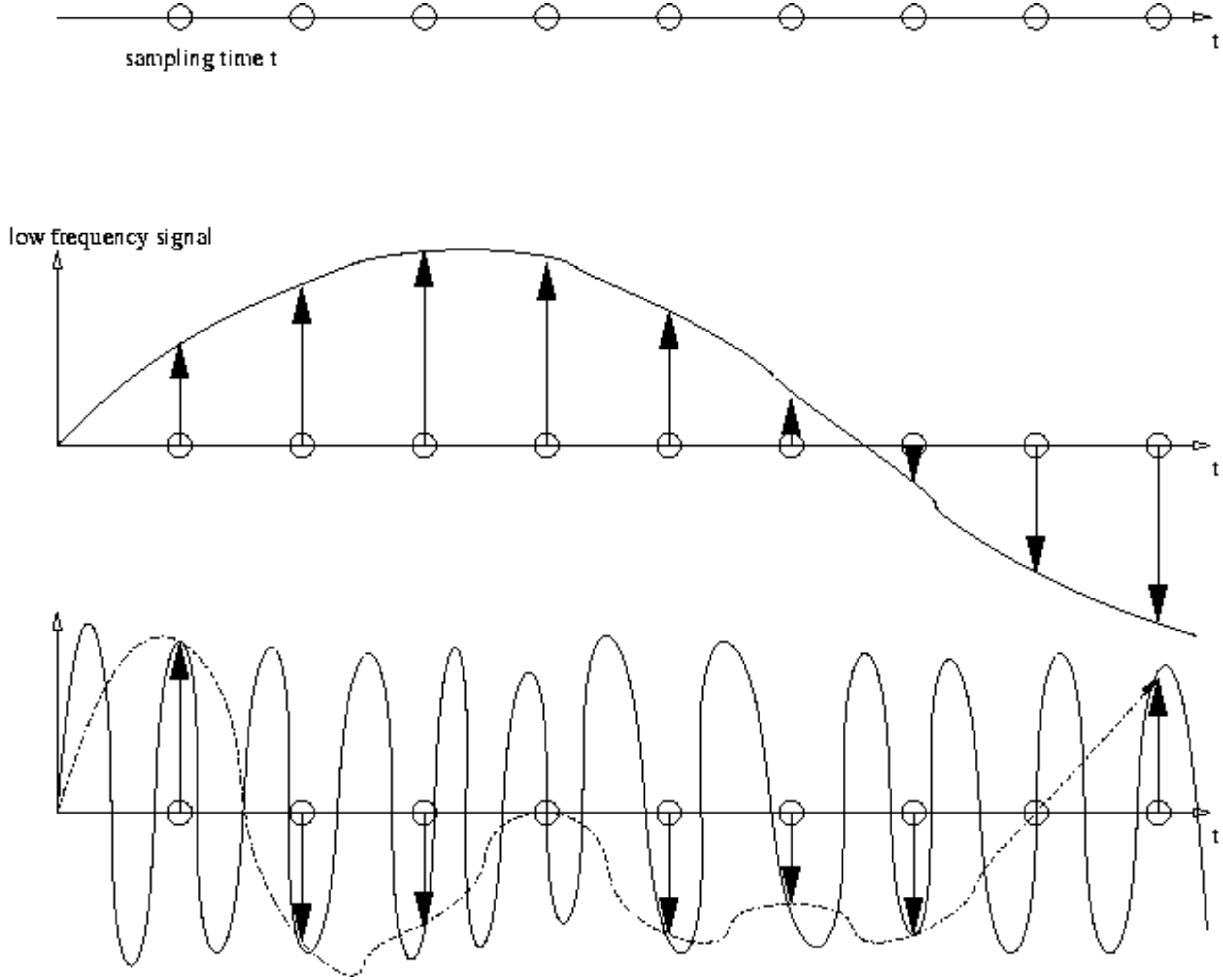
- **Nyquist Sampling Theorem:**
  - **if** all significant frequencies of a signal are less than B (*observe the Fourier spectrum*)
  - and **if** we sample the signal with a frequency 2B or higher,
  - **then** we can exactly reconstruct the signal
  - anything sampling rate less than 2B will lose information
- Proven by Shannon in 1949
- This also says that the maximum amount of information transferred through a channel with bandwidth B Hz is 2B bps (using 2 symbols – binary signal). **WHY?**

Example



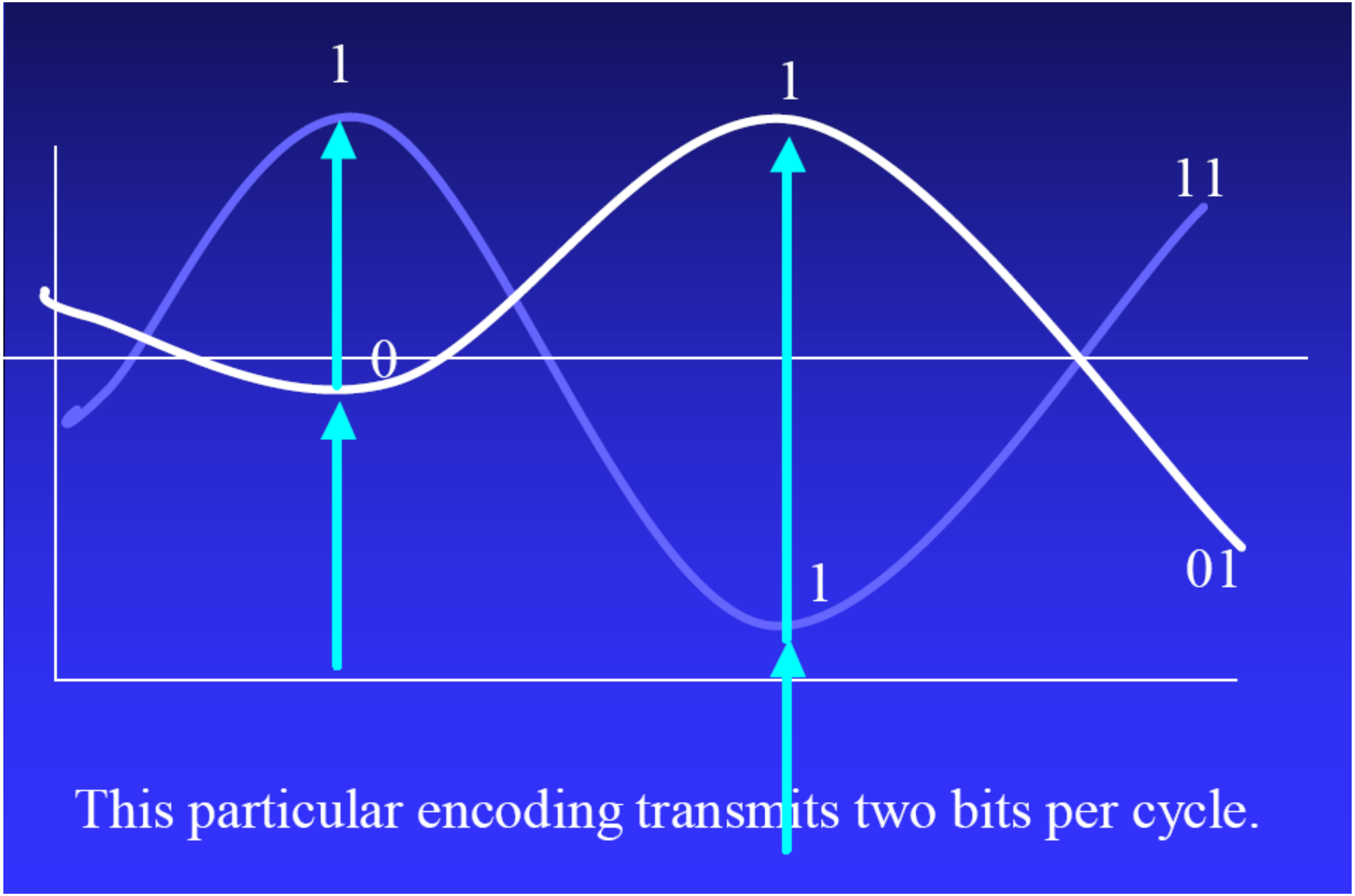
- We must sample in two points to understand the amplitude and phase of the sine function

Example



- With a signal for which the maximum frequency is higher than twice the sampling rate, the reconstructed signal may not resemble the original signal.

Example



1
1
11
0
1
01
This particular encoding transmits two bits per cycle.

Idea

- The larger the bandwidth the more complex signals can be transmitted
- More complex signals can encode more data
- What is the relationship between bandwidth and maximum data rate?
- See next slide…

Data Transmission Rate

- Assume data are encoded digitally using **K** symbols (e.g., just two 0/1), the bandwidth is **B**, then the maximum data rate is:
  - **$D = 2B \log_2 K$ bits/s** (Nyquist Theorem)
- For example, with 32 symbols and a bandwidth B=1MHz, the maximum data rate is $2*1M*\log_2 32$ bits/s or 10Mb/s
- A symbol can be encoded as a unique signal level (AM), or a unique phase (PM), or a unique frequency (FM)
- In theory, we could have a very large number of symbols, allowing very high transmission rate without high bandwidth … BUT
- In practice, we cannot use a high number of symbols because we cannot tell them apart: all real circuits suffer from **noise.**

Shannon's Theorem

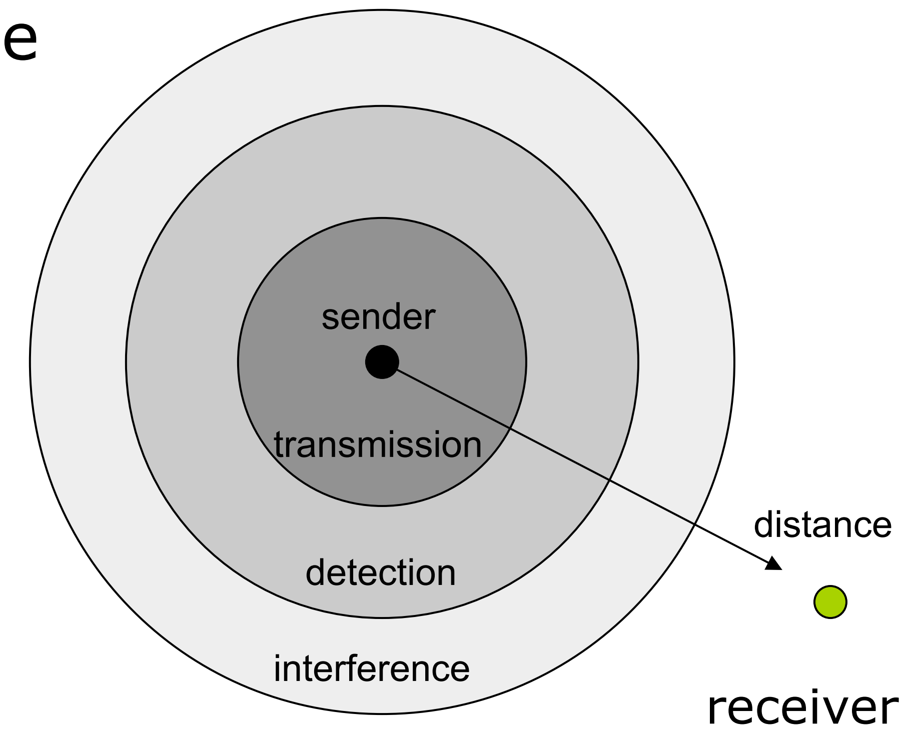
- It is **impossible** to reach very high data rates on band-limited circuits in the presence of **noise**
- Signal power **S**, noise power **N**
- **SNR signal-to-noise ratio in Decibel:**
  - **SNR = 10 $\log_{10}$ (S/N) dB**
- For example SNR = 20dB means the signal is 100 times more powerful than the noise
- **Shannon's theorem:** the capacity C of a channel with bandwidth B (Hz) is:
  - **$C = B \log_2(1+S/N)$ b/s**
- For example if SNR = 20dB and the channel has bandwidth B = 1MHz:
  - $C = 1M*\log_2(1+100)$ b/s = 6.66 Mb/s
  - Theoretical capacity is $2*1M*\log_2(K)$ - Nyquist – but even if we use 16 symbols we cannot reach the capacity
    - $2*1M*\log_2(16) = 2*1M*4=8$Mb/s.

Signal in wired networks

- There is a sender and a receiver
- The wire determine the propagation of the signal (the signal can only propagate through the wire
  - twisted pair of copper wires (telephone)
  - or a coaxial cable (TV antenna)
- As long as the wire is not interrupted everything is ok and the signal has the same characteristics at each point
- For wireless transmission this predictable behavior is true only in a vacuum – without matter between the sender and the receiver.

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

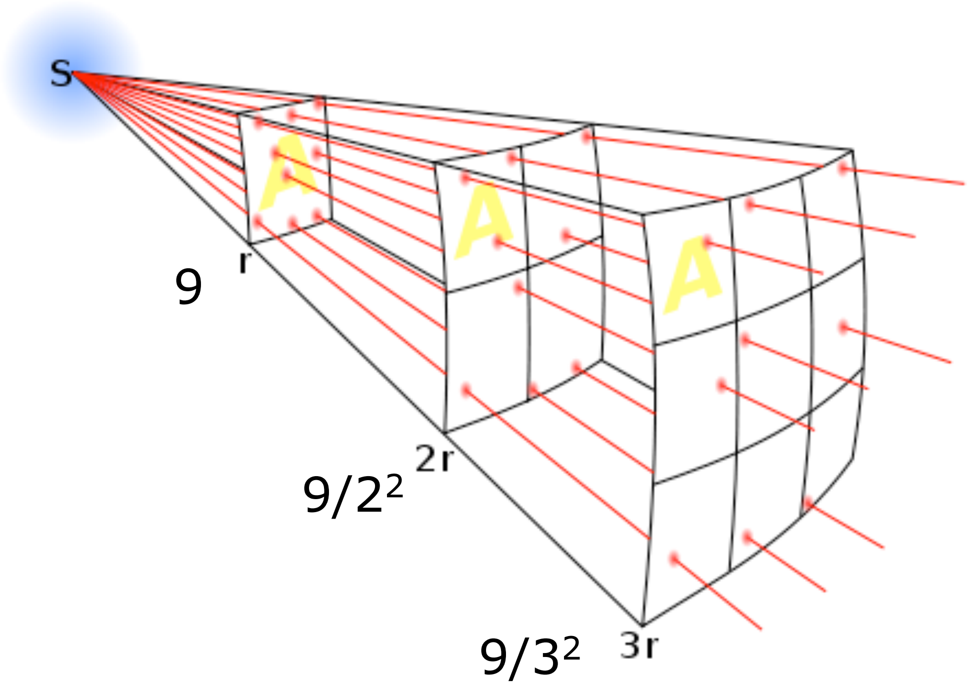


Path loss of radio signals

- In **free space** radio signal propagates as light does – straight line
- Even without matter between the sender and the receiver, there is a **free space loss**
  - Receiving power proportional to $1/d^2$ (d = distance between sender and receiver)
- **If there is matter** between sender and receiver
  - The **atmosphere** heavily influences transmission over long distance
  - **Rain** can absorb radiation energy
  - Radio waves can **penetrate objects** (the lower the frequency the better the penetration – higher frequencies behave like light!)

Inverse-square law

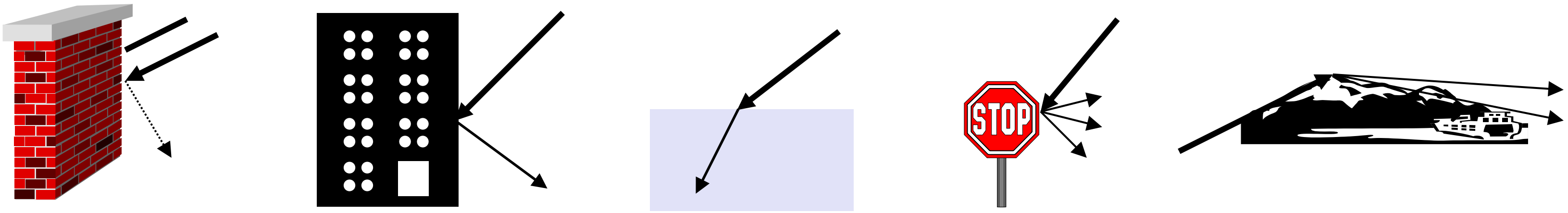
- The lines represent the flux emanating from the source
- The total number of flux lines depends on the strength of the source and is constant with increasing distance
- A greater density of flux lines (lines per unit area) means a stronger field



- The density of flux lines is inversely proportional to the square of the distance from the source because the surface area of a sphere increases with the square of the radius.
- Thus the strength of the field is inversely proportional to the square of the distance from the source.

Signal propagation

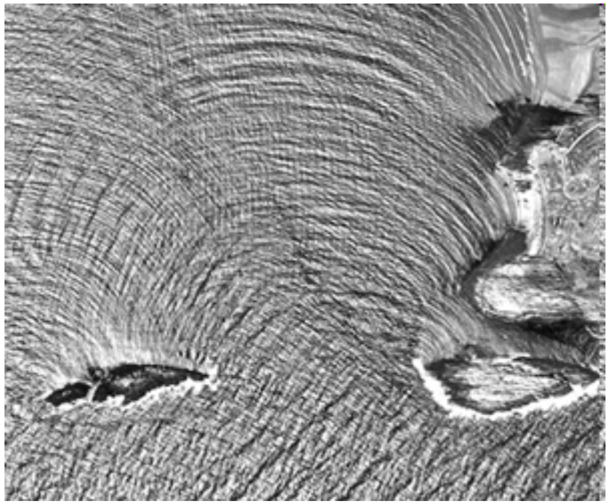
- In real life we rarely have a line-of-sight (LOS) between sender and receiver
- Receiving power additionally influenced by
  - fading (frequency dependent)
  - shadowing
  - reflection at large obstacles
  - refraction depending on the density of a medium
  - scattering at small obstacles (size in the order of the wavelength)
  - diffraction at edges

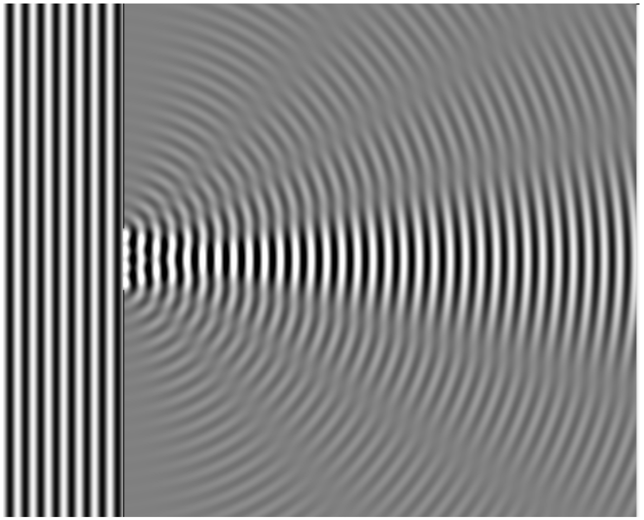


shadowing reflection refraction scattering diffraction

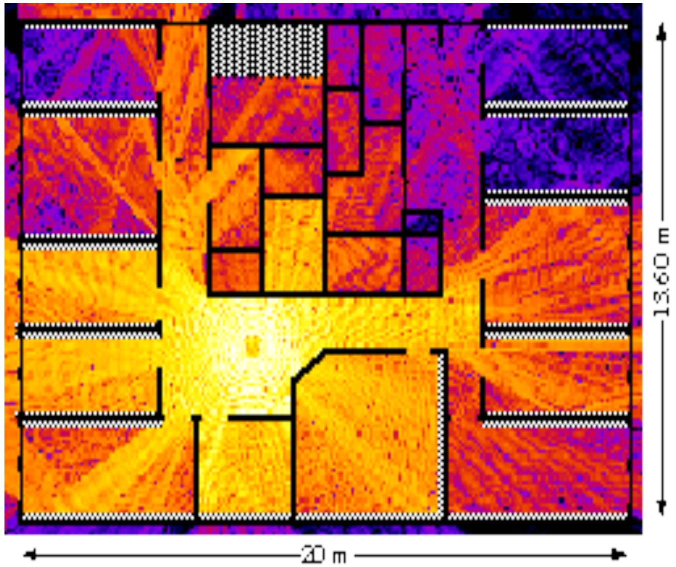
Diffraction

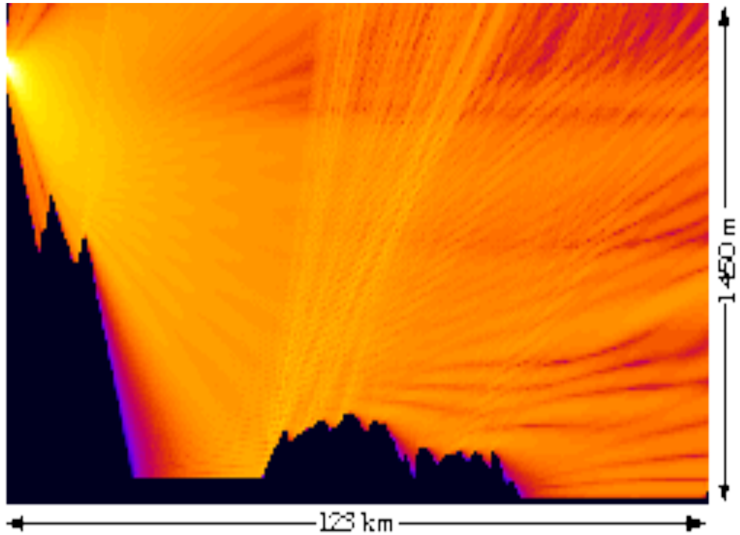
- Diffraction: the bending of waves when they pass near the edge of an obstacle or through small openings
- Example: http://www.ngsir.netfirms.com/englishhtm/Diffraction.htm

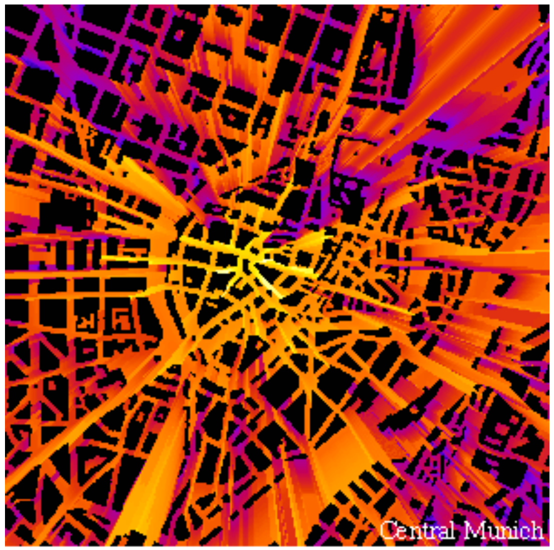




Real world example

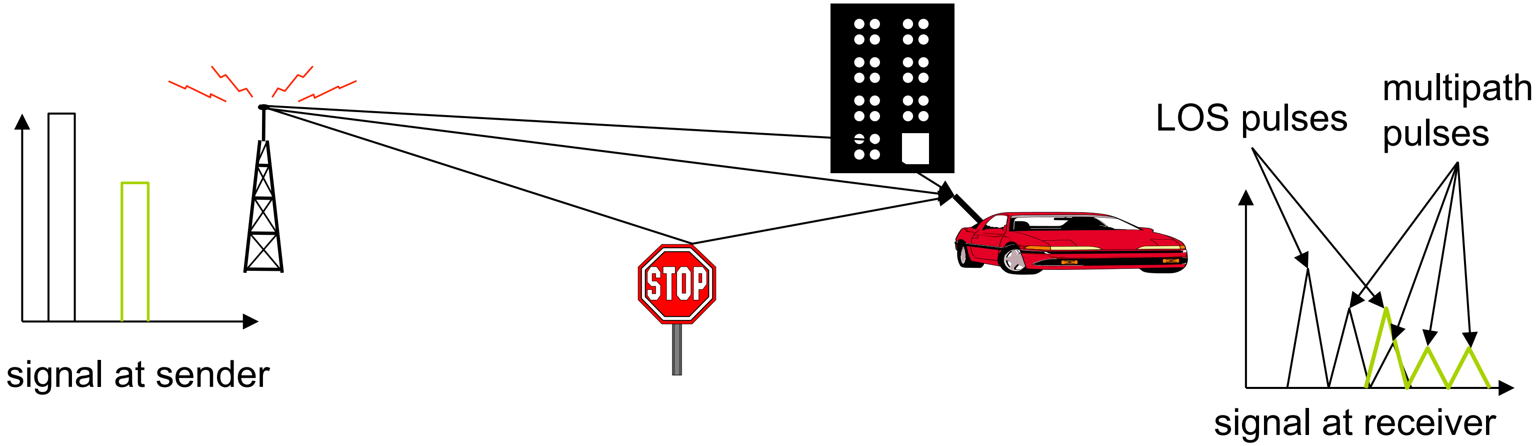






Multipath propagation

- 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 depending on the phases of the different parts