3. Wireless Communication Basics

Compared to a wired medium, wireless communication offers a range of additional challenges.

This subsection provides an introduction into the properties of wireless communication channels.

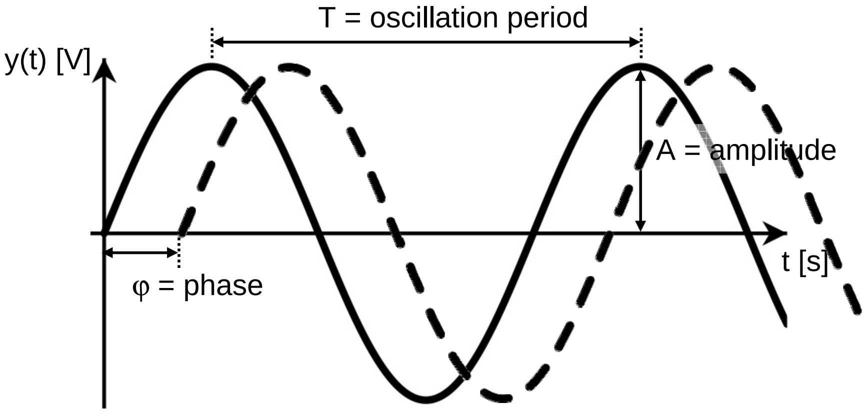
3.1. Signals

Wireless communication is about the transmission of information from A to B (usually) with electromagnectic waves which encode **signals.**

What is a signal?
A **periodic signal** is a time-dependent variation of voltage usually described by a series of **sin-** and **cos-waves** (the Fourier-representation of the signal).

A single sin- or cos-wave is described by its
- frequency f=1/T
- amplitude A
- phase φ

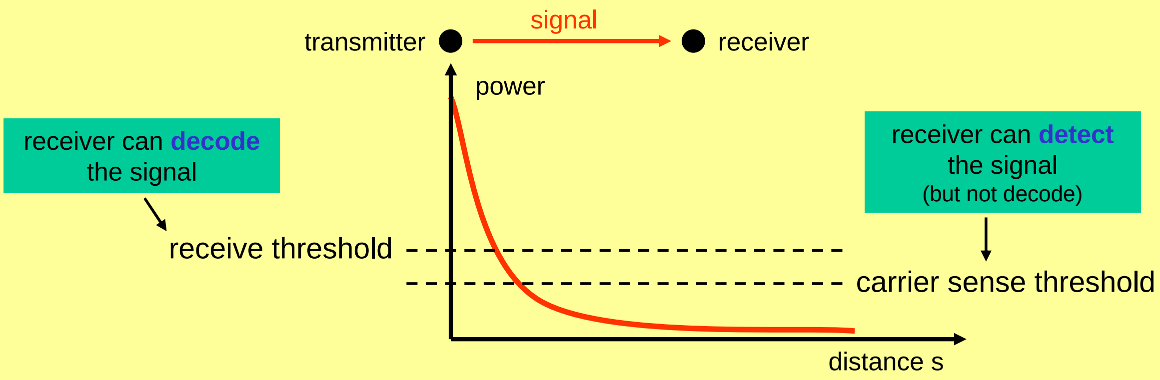
Note: The wavelength λ is proportional to the frequency f with λ=c / f



Signal Strength

For the communication with wireless transmissions, a signal must be strong enough at the receiver to decode it.

In (vacuum) free space, the signal strength at the receiver **decreases quadratically** with the distance from the transmitter.



Note: The **successful reception** of a signal does not only depend on the transmission power, but also on **environmental influences** (signal fading) and on **interference** from other sources, including background noise.

Interference

For a given receive threshold, correct reception of a signal depends on:

- the **signal strength of the actual carrier**
- the presence of **concurrent signals** (on the same frequency)
- the amount of **background noise.**

The latter two factors sum up to the **interference** at the receiver.

$$I = \sum_i I_i + N$$

I_i ~ strength of interfering signals
N ~ background noise.

The **signal-to-interference-and-noise-ratio (SINR)**, also known as the carrier-to-interference-ratio, is defined as:

$$W = \frac{C}{I}$$

C ~ carrier signal strength
I ~ total interference

Note: For a signal to be decoded successfully, the signal strength must exceed the receiver threshold **and** the SINR must be high.

Transmission Range - In Theory

For given receive thresholds and transmission powers, we have under ideal conditions:

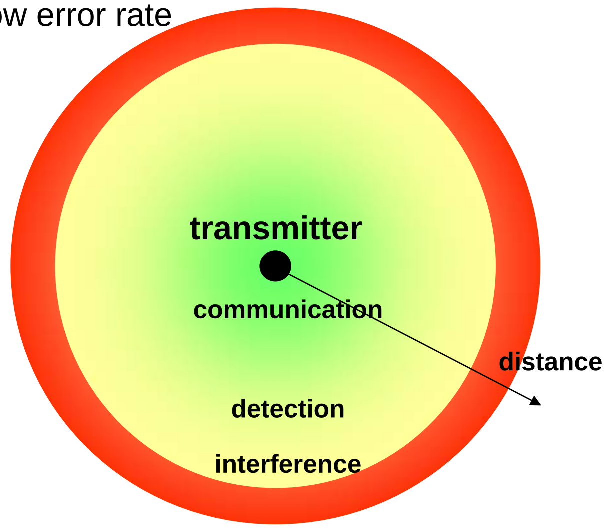
Communication range (also misleadingly known as "transmission range")

- Decoding of the signal possible with low error rate
- communication possible

Detection range

- detection of the signal possible
- no communication possible

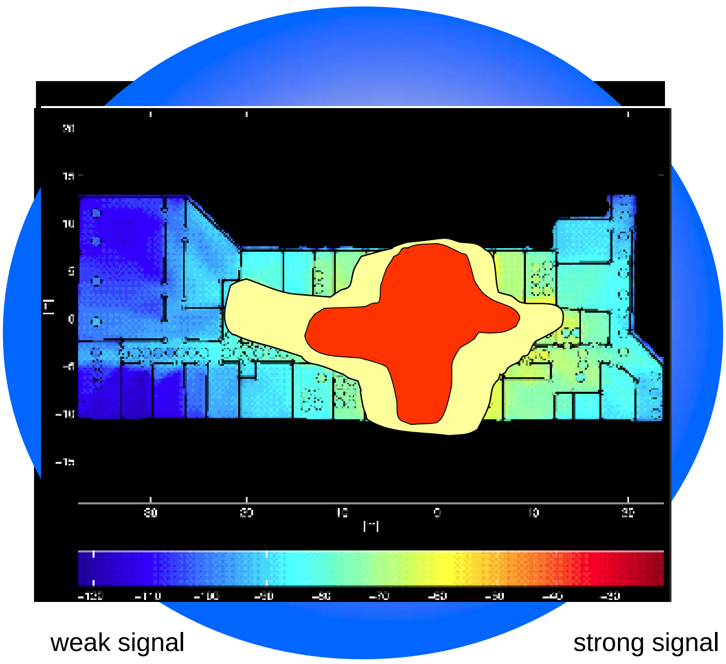
Beyond this, the signal only adds to the background noise at the receiver, possibly **interfering** with other communication.



Note: In general, a signal can always be an interfering signal.
When several communication takes place in parallel, the given „ranges“ depend on the **C/I at the receiver.**

Transmission Range - In Practice

In reality, signal propagation is **much more complex** and influenced by obstacles in between or in proximity of the sender and the receiver.



Influences on the signal strength

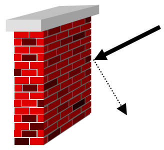
There are several factors on the transmission path between a transmitter and a receiver that influence the signal strength at the receiver:

Attenuation (German: "Dämpfung")

Additional attenuation, apart from the vacuum path loss, is caused when the signal crosses different materials, e.g. air, liquids, walls, ...

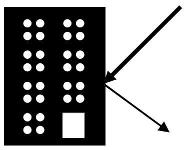
Shadowing (German: "Abschattung")

Shadowing occurs by obstacles which prohibit signals from crossing (or more precisely: which attenuate the signal so strongly that it cannot be decoded by the receiver)



Reflection (German: "Reflektion")

Reflection occurs at large obstacles (compared to the wavelength λ)

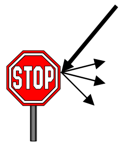


Influences on the signal strength (II)

There are several factors on the transmission path between a transmitter and a receiver that influence the signal strength at the receiver:

Scattering (German "Streuung")

Scattering occurs at small obstacles (compared to the wavelength λ)

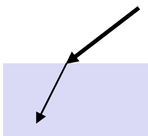


Diffraction (German "Beugung")

Diffraction occurs at edges or holes and causes a change in the propagation direction (technically a new wave is formed at the wave front). By diffraction a signal may even be received in otherwise shadowed areas.

Refraction (German "Brechung")

Refraction occurs when electromagnetic waves enter a medium with a different refraction index (e.g. from air into water). Then, part of the wave is reflected and the other part changes its propagation path.



Modelling Signal Propagation

For the analysis of wireless communication systems, it is impractical to rely solely on measurements, because:

- sample conditions might be unrepresentative
- repetition of the anlysis might be difficult (even impossible with exact same conditions)

Therefore, it is important to derive models of the signal propagation that

- abstract from a concrete environment and a detailed model of influences such as diffraction, scattering, etc.
- allow a simulation or mathematical analysis of certain aspects of the communication

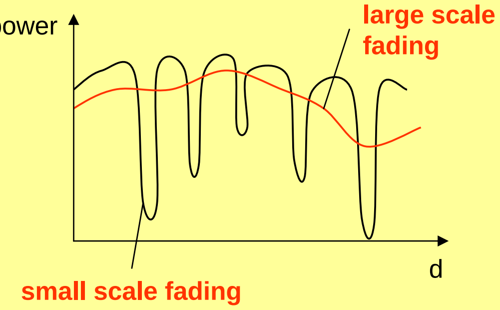
Two different kinds of models can be distinguished:

Large Scale Fading Models

Model the average signal strength for a given transmitter-receiver distance.

Small Scale Fading Models

Model the signal strength for small variations in the transmitter-receiver distance.



Large-Scale Fading

Free Space Propagation Model

Models the received signal strength when the transmitter and receiver have a **clear, unobstructed line-of-sight** path between them (e.g. satellite communication)

Friis free space equation

The expected received signal strength P_r as a function of the transmitter-receiver distance is given by:

$$P_r(d) = c\frac{P_t}{d^2}$$

P_t ~ transmitted power
d ~ trans.-recv. distance

Note: The constant c depends on the wavelength (λ), the gain of the transmitter antenna (G_t) as well as the receiver antenna (G_r), and on factors unrelated to propagation (L):

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

Path Loss

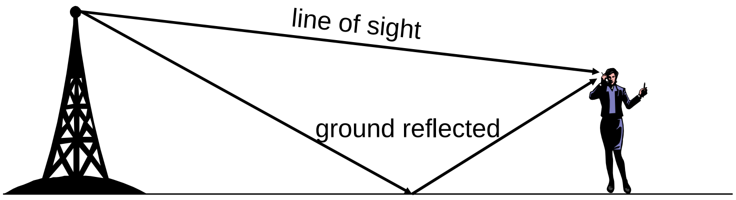
The difference between P_t and P_r is called path loss PL. It is often expressed in dB:

$$PL[dB] = 10\log\frac{P_t}{P_r}$$

Large-Scale Fading (II)

Two-Ray Ground Propagation Model

Model the received signal strength when the transmitter and receiver have an **unobstructed line-of-sight** path between them, but a second **ground-reflected** path exists (e.g. basestation-to-mobile communication) which **interferes** with the line-of-sight path.



The expected received signal strength P_r as a function of the transmitter-receiver distance is given by:

$$P_r(d) = c\,\frac{P_t}{d^4}$$

P_t ~ transmitted power
d ~ trans.-recv. distance

Note:
- This equation is only valid for large distances ($d > \frac{20\pi h_t h_r}{3\lambda}$).
- In this case, the path loss becomes independent of the frequency.
- This is a much more rapid signal loss than in free-space.

Path-Loss-Models

In a more general approach, **average path loss** is modelled
- relative to a reference distance d_0 for which the average path loss is known a-priori
- as decreasing **logarithmically** with the distance.

$$\overline{PL}(d)[dB] = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right)$$

The path loss exponent n depends on the specific propagation environment.

environment	n
free-space	2
urban	2.7-3.5
in-building (line-of-sight)	1.6-1.8
in-building (obstructed)	4-6

In reality, the actual environmental properties may heavily vary at different locations, leading to **vastly different** values than the average path loss.

Log-normal Shadowing Loss

The log-normal distribution describes the random shadowing effects which occur over a large number of measurement locations with the same distance d.

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

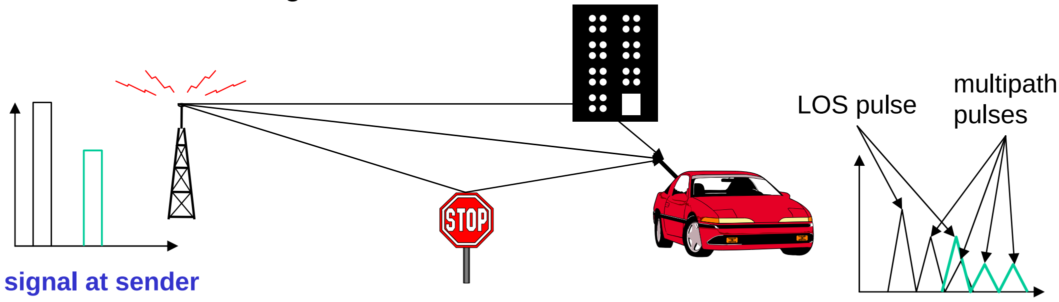
X_σ ~ normal random variable with std.dev. σ

Note: This model may also be applied to many indoor environments.

Multipath propagation

(JS)

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



Three most important effects

- rapid **changes in the signal strength** over a small travel distance or time interval due to variations in amplitude and phase of different multipath components
- **random frequency modulation** due to varying Doppler shifts on different multipath signals
- **time dispersion** (echoes) caused by multipath propagation delays which can even lead to **inter-symbol interference**

Influences on small-scale fading

There are four main influencing factors on small-scale fading:

Environment

The presence of reflecting objects and scatterers in the channel creates a constantly changing environment that dissipates the signal energy in amplitude, phase, and time.

Speed of the mobile

The relative motion between the mobile and the base station results in random frequency modulation due to different Doppler shifts on different multipath components.

Speed of surrounding objects

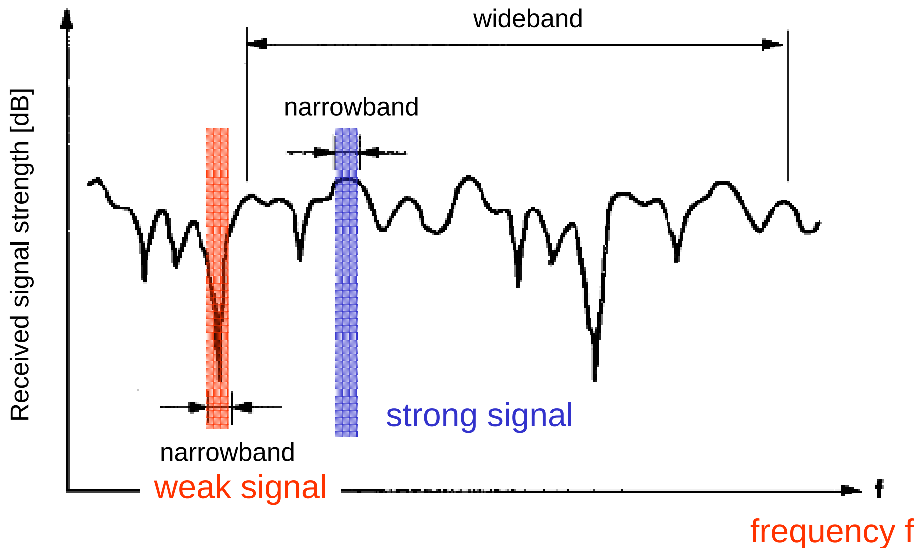
Moving objects can also induce time-varying Doppler shifts (only significant when moving faster than the mobile).

Transmission bandwidth of the signal

(see next slide).

Flat vs. Frequency Selective Channel

Multipath propagation may have different effects on different frequencies:



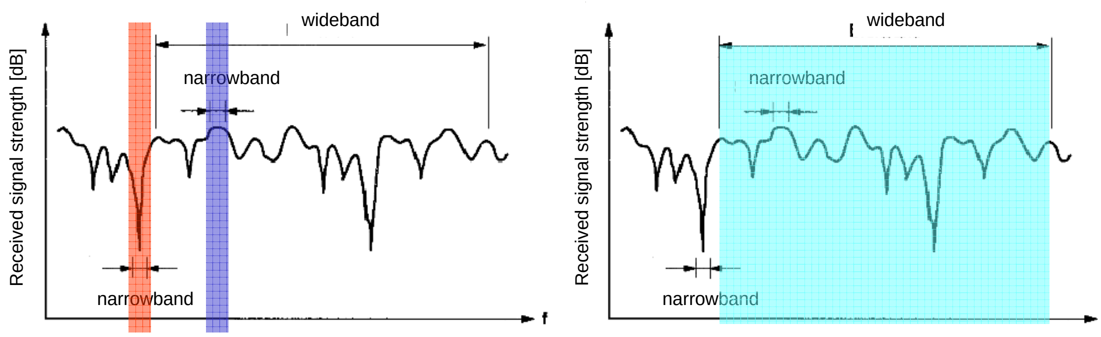
(Source: J. Eberspächer, H.-J. Vögel
GSM - Global System for Mobile Communication
B.G. Teubner Stuttgart, 1997)

A **narrowband channel** has (approx.) equal propagation characteristics over the complete bandwidth (good or bad). The channel is called **flat**.

A **wideband channel** has different propagation characteristics on different frequencies inside its bandwidth. The channel is called **frequency-selective**.

Flat vs. Frequency Selective Channel (II)

In a **frequency-selective fading** channel, the received signal strength will not change rapidly over a local area, but the signal may suffer intersymbol interference due to time dispersion (e.g. different delays in different multipath-components).



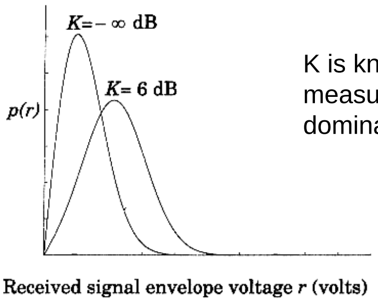
In a **flat fading** channel, the received signal strength will change rapidly, but the signal will not be distorted in time.

Note: In both cases, the channel can be either a **fast fading** channel (i.e. rapidly changing its characteristics) or a **slow fading** channel, depending on the velocity of the mobile (or surrounding objects). In practice, fast fading only occurs for very low data rates.

Flat Fading Models

To model flat fading channels, basically two situations are distinguished:

Ricean Fading:
If a **dominant multipath component** exists (e.g. line-of-sight path), small-scale fading is modelled according to a Ricean distribution.



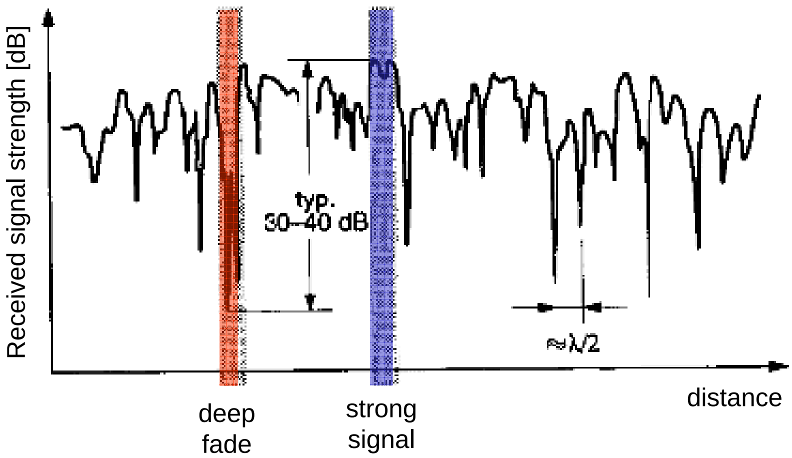
K is known as the **Ricean factor** and is a measure for the relative strength of the dominant path.

Rayleigh-Fading:
If a dominant multipath component **does not exist**, small-scale fading is modelled according to a Rayleigh-distribution. This is achieved by a degenerated Ricean distribution ($K \to -\infty$).

Note: Modelling frequency-selective fading is much more complex. One approach is to combine two independent Rayleigh components.

Periodic Deep Fades

Rayleigh fading causes **periodic deep fades** of up to 30-40dB in distances of half a wave length ($\lambda/2$) (i.e. the channel is not memoryless):



(Source: J. Eberspächer, H.-J. Vögel GSM - Globan System for Mobile Communication B.G. Teubner Stuttgart, 1997)

	frequency	wave length
D-nets	900 Mhz	33 cm
E-nets	1800 Mhz	16,65 cm
GSM USA	1900 MHz	15,78 cm

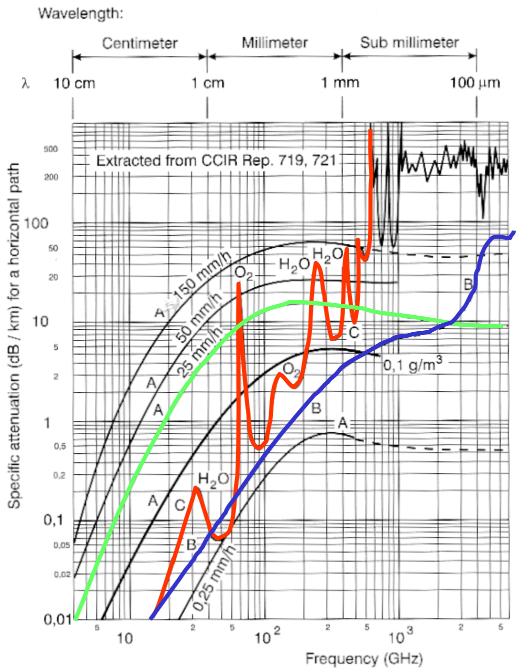
Note: To achieve the same low bit error rate as on non-fading channels, much higher transmission powers are required.

Frequency-Selective Attenuation in Different Conditions

In 1990, the **ITU Radiocommunications sector** (formerly CCIR) published measurements for signal attenuation in different atmospheric conditions.

The figure plots the attenuation for different wavelengths in dB/km.

Note the heavy peaks caused by H_2O and O_2 which are due to resonance effects.



Attenuation due to gaseous constituents and precipiation for transmission through the atmosphere

Pressure:	Sea level: 1 atm (1013.6 mbar)	A: Rain
Temperature:	20°C	B: Fog
Water vapor:	7.5 g / m³	C: Gaseous

Attenuation due to rain, gases and fog.

3.2. Modulation Schemes

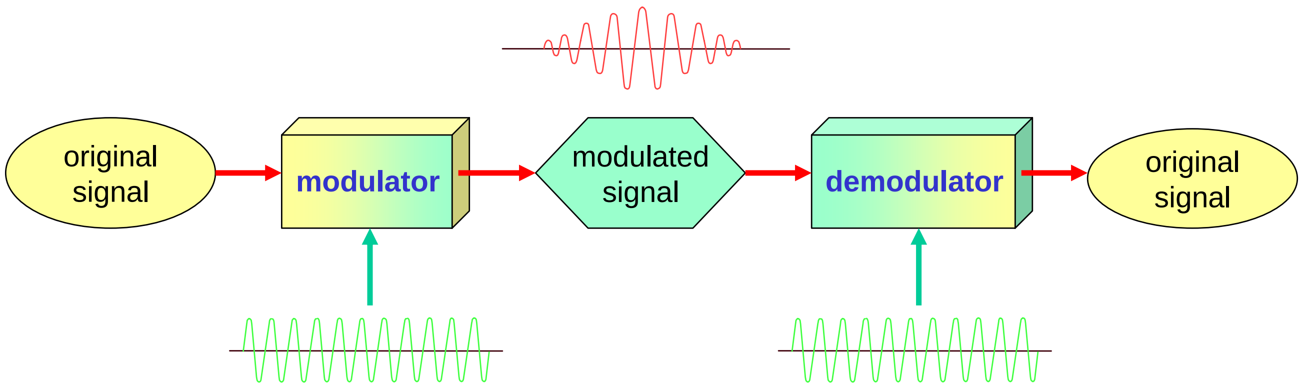
For the transmission of **information** using electromagnetic waves, the actual information is encoded by **modulation of a carrier-frequency** by
- varying the **amplitude**
- varying the **frequency** or
- varying the **phase shift** of the carrier-signal
- or a combination of these factors.

Reminder (WS): 3.2.8. … Modulation and Demodulation

Modulation is
the **variation of a signal parameter** (or: more parameters) **of a "carrier signal"** by a modulating signal.

In most cases: Variations of characteristics of an oscillation.

Demodulation is
the **recovery of the original signal** from the modulated signal.



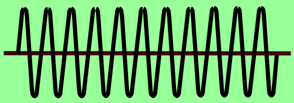
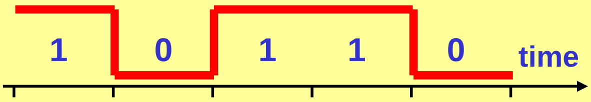
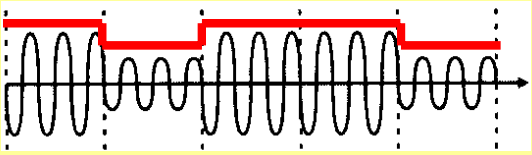
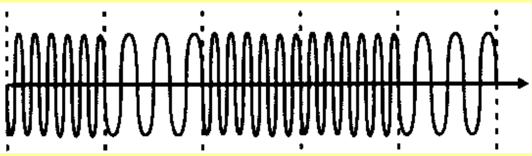
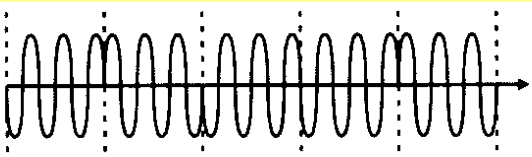
Reminder (WS): 3.2.8. Analog Transmission of Digital Data

The most familiar case is transmitting digital data through the conventional analog telephone network. The **analog telephone network** was designed to receive, switch, and transmit analog signals in the voice-frequency range of about **300 Hz to 3,400 Hz**.

There are **three basic encoding or modulation techniques** for transforming digital data into analog signals:

- **Amplitude-shift keying (ASK)**
- **Frequency-shift keying (FSK)**
- **Phase-shift keying (PSK and QPSK)**

Reminder (WS): Modulation Techniques

carrier signal	original digital signal	
		
Modulation of the signal parameter "amplitude"	 time	"0" and "1" are represented by different signal levels (e.g. voltage level).
Modulation of the signal parameter "frequency"	 time	"0" and "1" are represented by different frequencies.
Modulation of the signal parameter "phase"	 time	"0" and "1" are represented by different phasing.

Wireless Modulation Schemes (also see WS ch. 3.2.8)

In modern wireless communication systems, these modulation schemes are enhanced to achieve higher data rates:

Quadrature-PSK (QPSK):
Four discrete phase shifts are used instead of two. This allows for an encoding of 2 bits.

Note: This approach may be generalised to more levels and also other modulation schemes.

Quadrature Amplitude Modulation (QAM):
QAM is a combination of ASK and PSK. In a common approach four discrete amplitude levels and four discrete phase shifts are used to form 16-QAM. This allows for a transmission of 4 bits simultaneously. More complex version are also in use, e.g. 64-QAM.

Note: The more complex these modulation schemes get, the more **error-prone** the transmission gets and thus, better filters are required to decode the signal.

3.3. Multiple Access Schemes

Goal: parallel wireless communication of several devices in spatial proximity.

Required: controlled separation of the communication

Time Division Multiple Access (TDMA):
- all communication on the same frequency
- separation by allocating time slots for communication

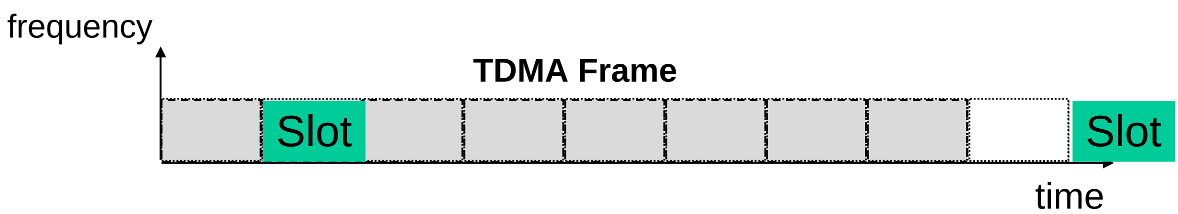
Frequency Division Multiple Access (FDMA):
- all communication at the same time
- separation by allocating different frequencies for communication

Code Division Multiple Access (CDMA):
- all communication at the same time on the same frequency
- separation by allocating different communication codes

Space Division Multiple Access (SDMA):
- all communication at the same time on the same frequency
- separation by allowing separating the communication based on the users' location

Time Division Multiple Access

Time Division Multiple Access (TDMA):
- each channel is split up into time slots
- time slots repeat periodically (also called TDMA frames)
- each sender is assigned a fixed subset of slots per frame

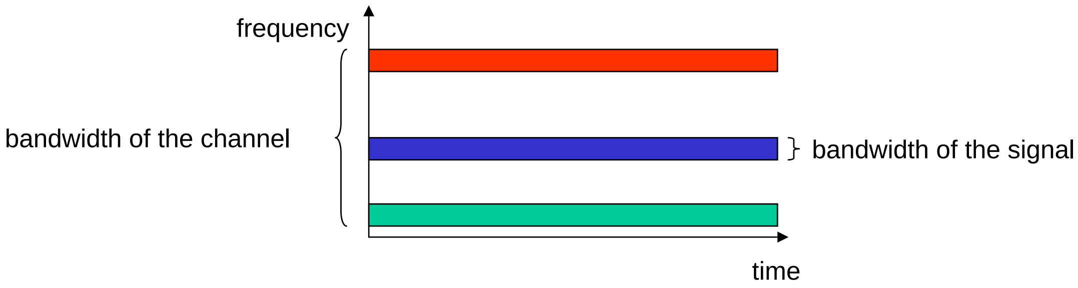


Properties:
- different users transmit/receive in different time slots
- requires exact synchronization of the devices
- devices may be turned off during idle slots to save power

Challenge:
- mobile devices are placed at different distances to each other (different round trip times)
- mobile devices change their location (round trip times change)
- a scheduling policy is required

Frequency Division Multiple Access

Frequency Division Multiple Access (FDMA):
- each channel is split up into narrower frequency bands, so-called **sub-carriers**
- each frequency is used exclusively by one user

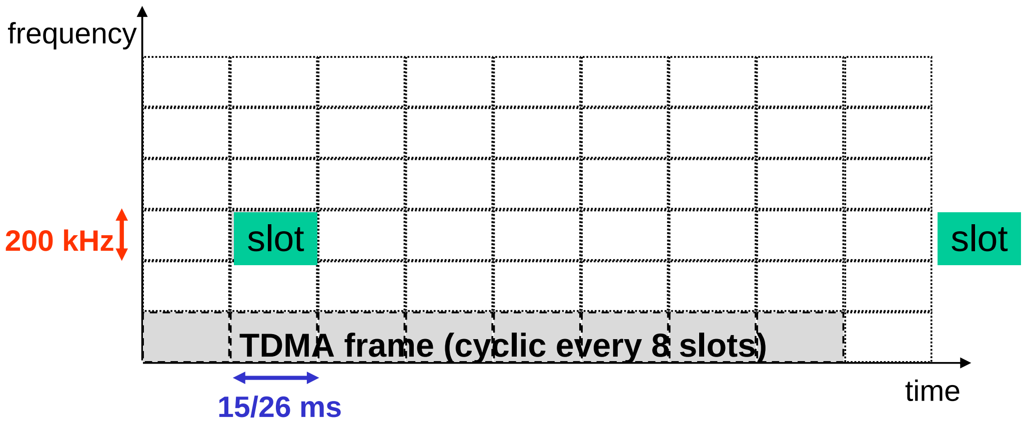


Note: Perfect separation of sub-carriers is impossible due to imperfect filters!
=> **Guard-Bands** between neighbouring frequencies
- this limits the max. achievable data rate of a channel

Typical usage: FDD (Frequency Division Duplex)
Base station and mobile use two different frequencies to achieve a full duplex communication.

Example: GSM uses FDMA and TDMA

GSM uses
- FDD to separate uplink and downlink traffic by 45MHz.
- FDMA to separate different channels in each direction by 200kHz.
  (The overall bandwidth per direction is 25MHz.)
- TDMA to separate 8 sub-channels on each channel (i.e. frequency).

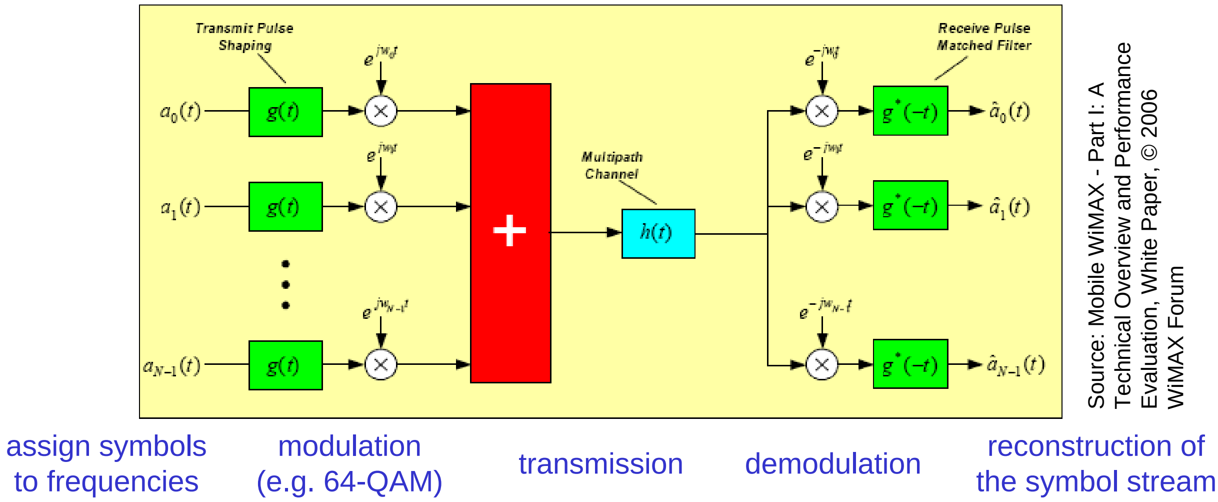


Result:
- GSM supports 125 channels in 25 MHz with 8 time slots each, i.e. a total of **1000 physical channels** (frequency band D around 900 MHz)
- Each channel supports a gross data rate of 33,875 kbit/s.

Orthogonal Frequency Division Multiplex (OFDM)

A specialisation of FDMA can be used to efficiently transmit data in multipath environments.

Orthogonal Frequency Division Multiplex (OFDM)
Idea: Transmit several symbols simultaneously on different frequencies.
Benefit: The symbol duration may be increased for higher robustness.



Source: Mobile WiMAX - Part I: A Technical Overview and Performance Evaluation, White Paper, © 2006 WiMAX Forum

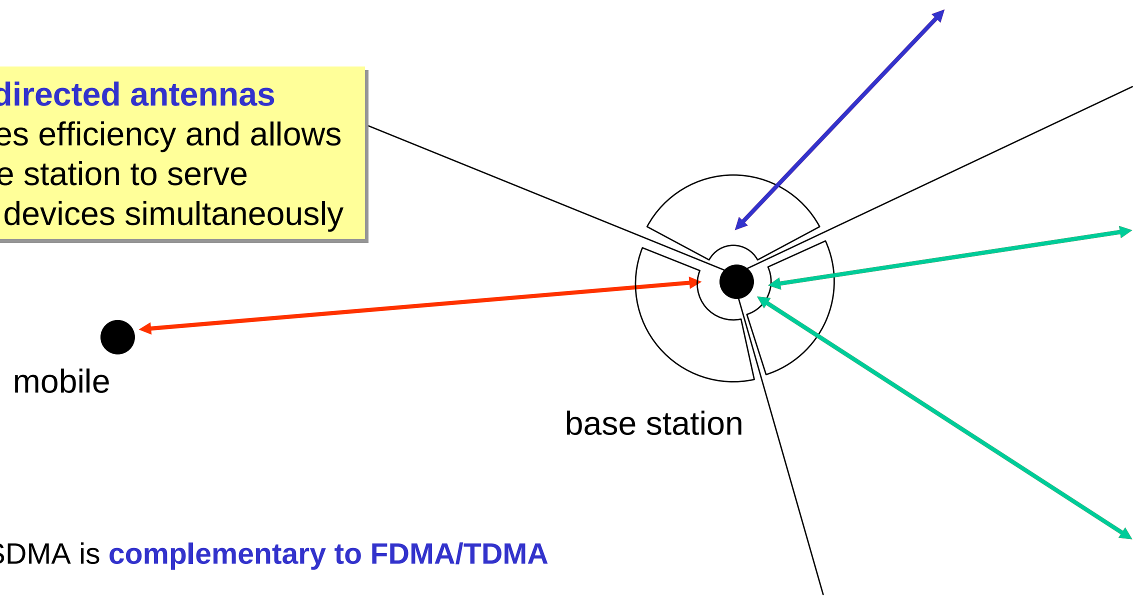
Note: Each frequency represents a flat channel which makes it robust against time dispersion (i.e. no inter-symbol interference).

Space Division Multiple Access (SDMA)

Properties of a base station:
- stand-alone installation
- little obstruction in close proximity

=> Uplink is usually received with small dispersion
(with an angle of only few degrees)

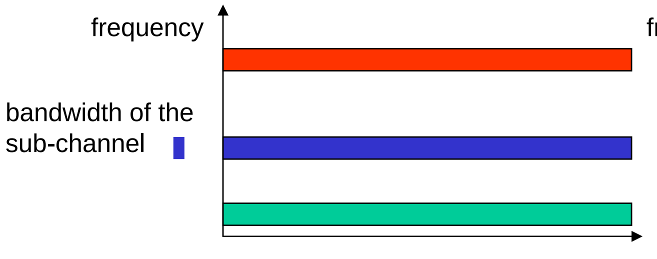
Use of **directed antennas** increases efficiency and allows the base station to serve several devices simultaneously



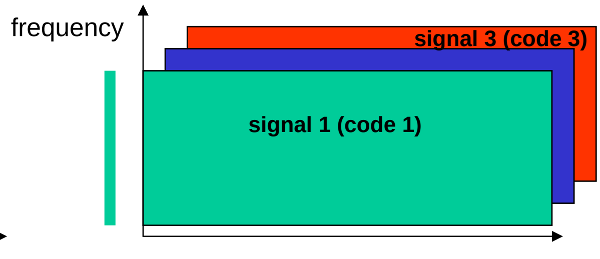
Note: SDMA is **complementary to FDMA/TDMA**

Code Division Multiple Access (CDMA)

Idea of CDMA:
- all users use the whole frequency band for the whole time
- separate sub-channels by using different "**codes**" for modulation
- **narrowband signal** (user data) is spread into a **wideband signal**
- wideband signals of several sub-channels are superimposed



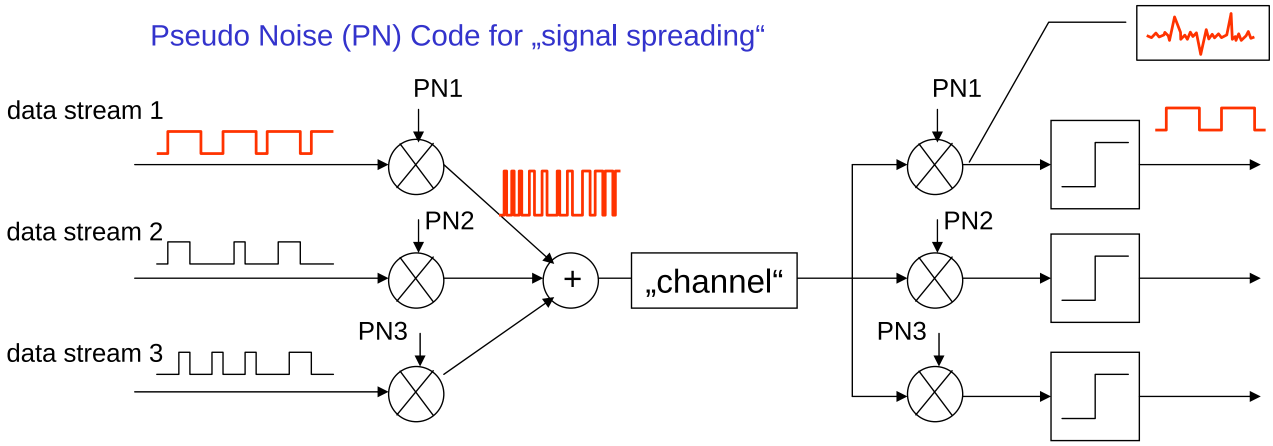
Three sub-channels using **FDMA**



Three sub-channels using **CDMA**

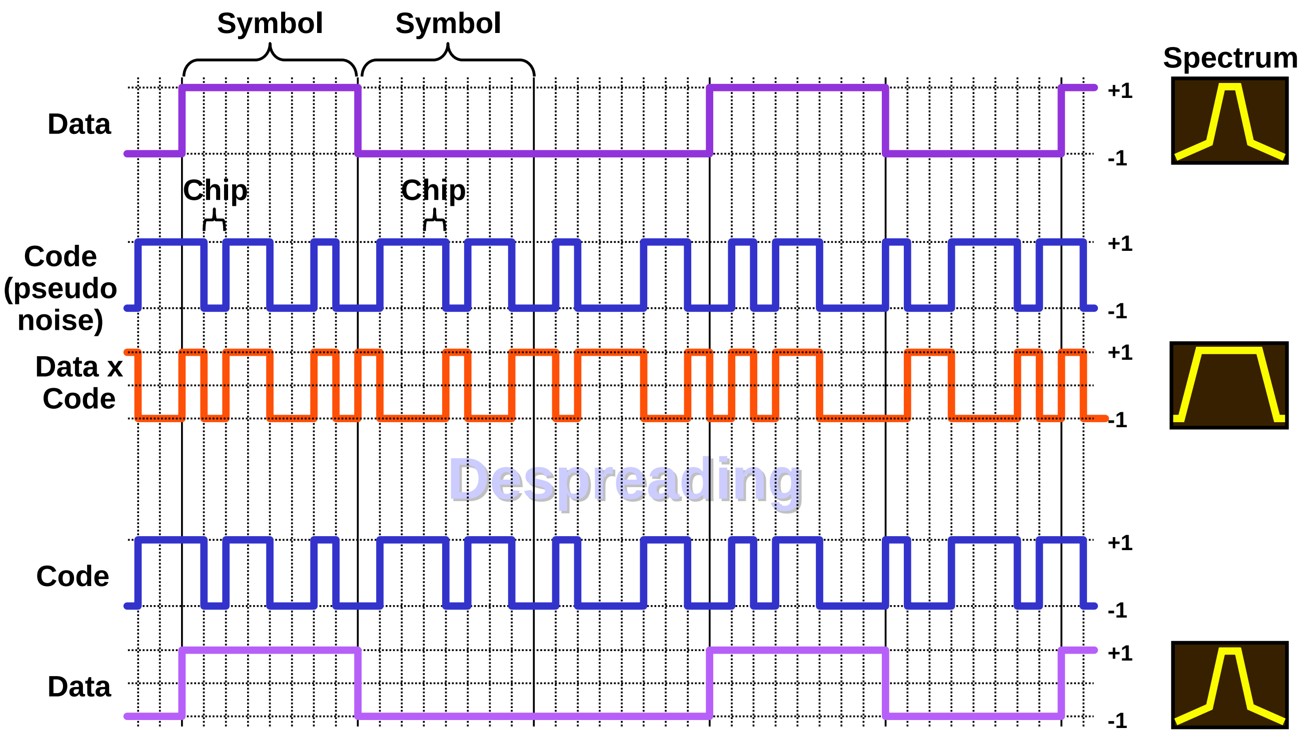
How does it work?
- spreading of the signal achieved by modulation with a high-frequency spreading code
- receiver filters out the relevant signal by applying the same spreading code to the received signal
- The spreading code frequency is given by the **chip-rate** as opposed to the **bit-rate** of the user data.

Encoding und Decoding using CDMA



narrowband data streams	„spreading“ with respective code sequence (multiplication) spreading of the bandwidth	superposition of the wideband signals in the „air“-medium attenuation fading effects	repeat the multiplication with PN-code sequence (filter)	„Decider“ recognises digital signal stream

Spreading and Despreading with CDMA



Source: Nokia Guest Lecture, SS 2002

Properties of CDMA

- CDMA is **robust against interference** due to its wideband properties (cf. Slide 15)
- "Challenge": **Code sequences** (pseudo random) **must be orthogonal**,
  - i.e. a unique channel separation must be possible
  - otherwise random statistic disturbance by other signals possible
- CDMA is known as **W-CDMA** (Wideband CDMA) in UMTS.

CDMA and Wireless LAN IEEE 802.11

- In IEEE 802.11, the physical layer is modelled using the spreading scheme described above. This is called **Direct Sequence Spread Spectrum (DSSS).**
- Opposed to W-CDMA in UMTS, DSSS is not used to manage multiple access in IEEE 802.11.
- Instead, only **a single code** is used for all transmissions from any user.
- IEEE 802.11's intention of using DSSS is its **robustness against interference**.

3.4. Wireless Links

As in wired communication, a transmission in wireless systems is between neighbouring stations on the same **physical link.** However, a link in wireless systems behaves **completely different** than in wired systems.

Wired	Wireless
low bit error rate	high bit error rate (10^{-1} to 10^{-2})
constant propagation characteristics	(rapidly) changing propagation characteristics
constant quality of the link	short periods with no communication (deep fades)
clear separation of links by cables	unclear boundaries of a link

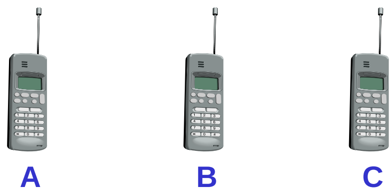
=> While a link in a wired channel is deterministic, **a link in wireless communications is a probabilistic property**.

Note: This has **consequences** on the networking mechanisms:

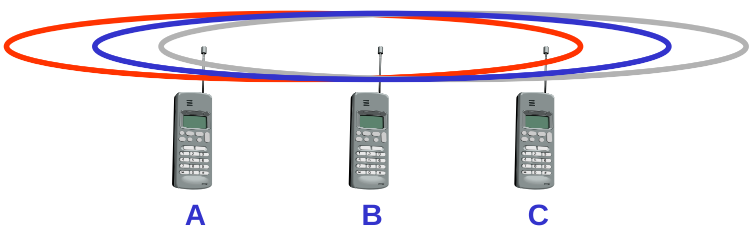
- further **protection and error recovery** mechanisms have to be introduced

Wireless Links (II)

Opposed to wired communication, links have no clear separation in wireless communication. Whether stations A, B, and C are on the same link depends on the communication ranges of the stations.

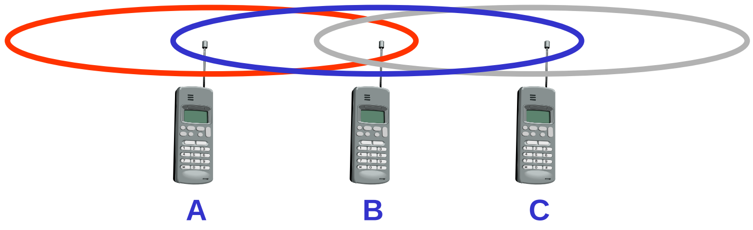


For sufficient transmission ranges, all three devices form **a single link**.



Wireless Links (II)

For smaller transmission ranges, the devices form **different links**, one containing stations A and B, the other containing stations B and C.



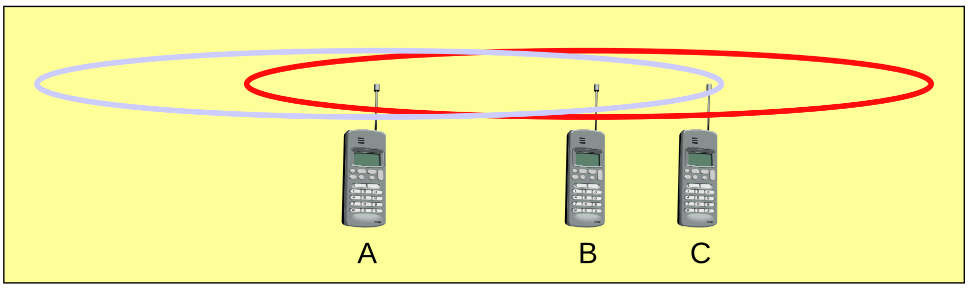
This means:

- C might **not even be aware** of A's presence (A is hidden to C)
- A might **interfere** on BC's link (which is impossible in wired communication)
- The **available bandwidth on a link** does not only depend on the load on that link, but also on the load on different links. Ultimately, the available bandwidth on a link cannot be known from information from that link alone.

Near and far terminals *JS*

Terminals A and B send, C receives

- signal **strength decreases** according to the specific path loss
- the **signal** of terminal B therefore **drowns out** A's signal
- **C cannot receive** A



If C for example was an arbiter for sending rights, terminal B would drown out terminal A already on the physical layer.

Therefore, many wireless systems provide means for **power control.**

Conclusions

Compared to a wired medium, **wireless communication offers a range of additional challenges**.

- **Signal strength** at the receiver depends on many factors
  (distance between sender and receiver is among these)

- **Multipath propagation** of the signal in medium “air”

- **Mobility of a wireless device** imposes further challenges

- **Mobility of other “obstacles”** has further influence

- We do not have a **“link property”** as in wired systems
  (here, either the link is available or broken)