

# Introduction to Communication Engineering

## SSY121, Lecture # 11

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# Information

Sign up for the exam no later than Oct 8!

The project points are invalid after the second re-exam in Aug 2024!

## Project Quiz **Voluntary!**

- First part of the last lecture (Wed Oct 11, 10:00–10:20) in room ED.
- 10 multiple choice questions (answered individually) to evaluate the understanding of the scientific base of the project (no re-quiz).

## Computer Lab (room 5225, EDIT)

- Booked for you all weekdays until Thu Oct 12 at 17-21 (unsupervised).
- You can always also use other Computer rooms, e.g., ES61, ES62, and ES63, to test and debug your solution.

## Ericsson workshop on Wed Oct 18, 13:15–17:00 **Voluntary!**

- There will be a sign up list in Canvas.

# Outline

- 1 The linear channel model
- 2 Guided Channels
- 3 Wireless Channels
- 4 Transmission Impairments
- 5 Multiple Access Techniques
- 6 Advanced topics in Communications

# Part I

## Communication Channels

## The linear channel

- The channel is represented using a linear filter
- The impulse response of the channel  $h(t)$  determines the channel's characteristics
- Noise is added at the receiver, but not by the channel
- The output of the channel is

$$r(t) = s(t) * h(t) = \int_{-\infty}^{\infty} s(\tau)h(t - \tau)d\tau,$$

or in the frequency domain  $R(f) = S(f) \cdot H(f)$ .

## Different types of channels

- Ideal channel

- The impulse response is  $h(t) = \delta(t)$
- The received signal is

$$y(t) = s(t) + n(t)$$

- Multipath channel

- The impulse response is

$$h(t) = k_0\delta(t) + k_1\delta(t - \tau_1) + k_2\delta(t - \tau_2) + \dots$$

- The received signal is

$$y(t) = k_0s(t) + k_1s(t - \tau_1) + k_2s(t - \tau_2) + \dots + n(t),$$

i.e., a weighted sum of delayed versions of the original signal

- It is caused by signals arriving through different *paths*

## Different types of channels

- Fading channel
  - The impulse response is

$$h(t) = \beta(t),$$

where  $\beta(t)$  varies over time

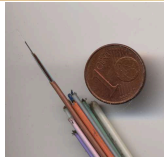
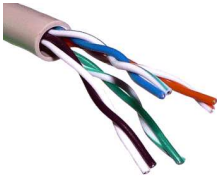
- The received signal is

$$y(t) = \beta(t) * s(t) + n(t)$$

- Usually caused by movement of the Tx, Rx, or both (or the channel)
- Very relevant in mobile wireless communications
- A *fade* is observed when we enter a “shadowed” area
- It could also be caused by multipath components with different phase that interfere destructively
- The remedy?
  - Channel estimation  $\hat{\beta}(t)$
  - Use of “diversity” (multiple antennas, multiple frequencies, multiple timeslots)

## Guided channels

- A transmission channel protected from the “outside world”
- Examples
  - wire pair (also called twisted pair)
  - wave guides
  - coaxial cable
  - optical fibers
- They distort the signal but do not add noise

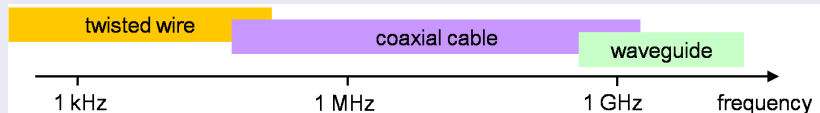




## Wires and Cables

- Pros
  - Cheap
  - Little noise
  - Installed “everywhere”
- Cons
  - Short range (max  $\approx 30$  km)
  - Low BW

## Types

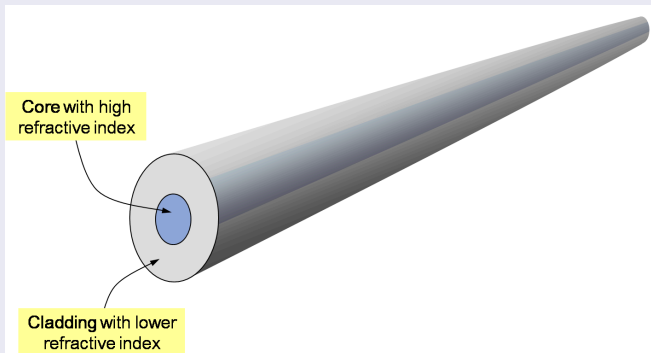


## Optical fibers

- Pros
  - Huge capacity (in the infrared band, 100.000 GHz)
  - Little interference/noise
  - Low attenuation (0.2 dB/km, i.e., 3 dB/15 km)
- Cons
  - Expensive hardware
  - Not “everywhere” (or not yet)
- New technology
  - 2% of transoceanic communication in 1988, 80% in 2000
  - Nowadays taking over wireless backbone (microwave links), and access network (fiber-to-the-home)

## How optical fibers work

- A lightwave is injected in the core
- The surface between the core and cladding looks like a mirror from the inside



## Wireless Links

- Pros
  - Mobility
  - Installation at endpoints only
- Cons
  - Limited spectrum
  - Expensive spectrum
  - Serious transmission impairments (noise, multipath, interference)

## Link Budget

- Let  $P_T$  [W] be the transmitted power by an isotropic antenna (which radiates in all directions)
- The receiver's antenna is at distance  $d$  [m]
- The wavelength  $\lambda = \frac{3 \cdot 10^8}{f_c}$  [m]; carrier frequency  $f_c$  [Hz]
- The received power  $P_R$  [W]

$$P_R = P_T \left( \frac{\lambda}{4\pi d} \right)^2$$

- For directional antennas with gains  $G_T$  and  $G_R$

$$P_R = P_T G_T G_R \left( \frac{\lambda}{4\pi d} \right)^2$$

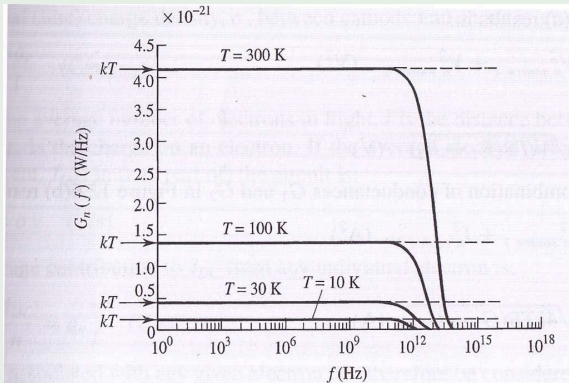
- For parabolic dish antennas with area  $A$  [m<sup>2</sup>] the gain is

$$G_{\text{Par}} = \frac{4\pi A}{\lambda^2}$$

## Part II

# Transmission Impairments

## Example (How the AWGN of $L_7$ is)



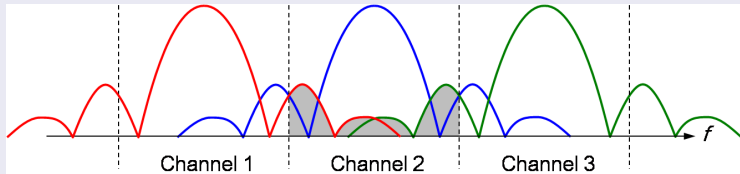
*Power spectral densities of thermal noise at four temperatures.*

## Co-channel interference (CCI)

- Cause: crosstalk from two different radio transmitters using the same channel
- Remedy: controlled by various radio resource management schemes

## Adjacent channel interference (ACI)

- Cause: the spectrum is wider than the allocated frequency band
- Remedy: sharper filter or larger channel separation



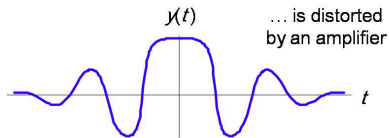
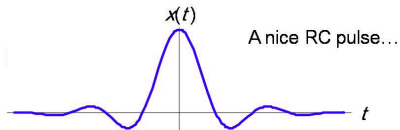
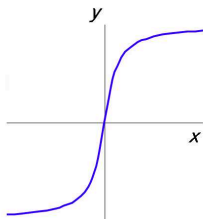
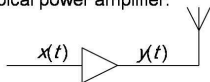


## Intersymbol interference (ISI)

- See the SRx and MFRx ( $L_2$  and  $L_4$ )
- Orthogonal/Nyquist pulses
- Cause: Non-orthogonal pulses, non-nyquist pulses, wrong sampling instants, ...
- Remedy: Symbol synchronization, correct pulse selection, decrease of the symbol rate, ...

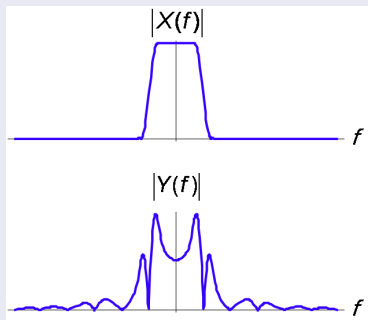
## A PA with clipping

A typical power amplifier:



## A PA with clipping

- Problem: Distorted spectrum  $\rightarrow$  orthogonality is lost (still Nyquist though), and broad spectrum  $\rightarrow$  unhappy neighbors



- Cause: Nonlinear channels, nonlinear PA
- Remedy: Linear amplifier (costs power), constant-envelope modulation ( $L_6$ ).

## Part III

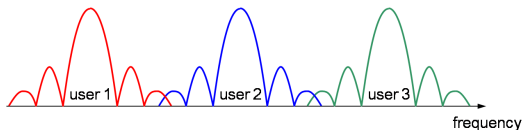
# Multiple Access and Advanced Topics

## Multiple Access (MA) Techniques

- Several users share the same physical channel
- Users will disturb each other unless some “rules” are imposed
- How can we avoid disturbances? Communicate using different...
  - frequencies: frequency-division multiple access (FDMA)
  - time instants: time-division multiple access (TDMA)
  - codes: code-division multiple access (CDMA)

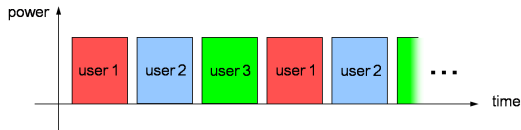
## FDMA

- Different users use different frequencies
- ACI can occur



## TDMA

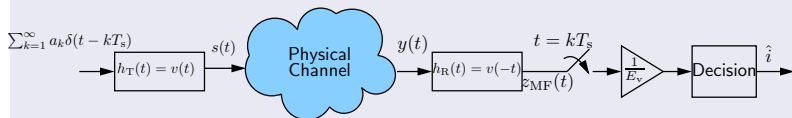
- Different users use different time slots
- Users must be synchronized. This is hard when they are at different locations. *Why?*
- TDMA is used in GSM (2G: second generation)



## The MFRx for a sequence of $M$ -ary pulses ( $L_4$ )

The transmitted signal is

$$s(t) = \sum_{k=0}^{\infty} a_k v(t - kT_s) = a_0 v(t) + a_1 v(t - T_s) + a_2 v(t - 2T_s) + \dots$$



## The output of the MF

If  $y(t) = s(t)$ , the output of the MF at  $t = 0, T_s, 2T_s, \dots$  is

$$z_{MF}(kT_s) = E_v a_k$$

## And if there is an interfering pulse?

Suppose that the received signal is now

$$s(t) = \sum_{k=0}^{\infty} a_k v(t - kT_s) + \sum_{k=0}^{\infty} b_k v'(t - kT_s),$$

where the second sum is a train of pulses from **other user** who uses the pulse  $v'(t)$  (and the same frequency).

If  $v'(t)$  and  $v(t)$  are orthogonal and  $T_s$ -orthogonal?

$$\int_{-\infty}^{\infty} v(t)v'(t - kT_s) dt = 0, \quad \text{for all } k = 0, \pm 1, \pm 2$$

The output of the MF is still the same (no interference)

$$z_{\text{MF}}(kT_s) = E_v a_k$$

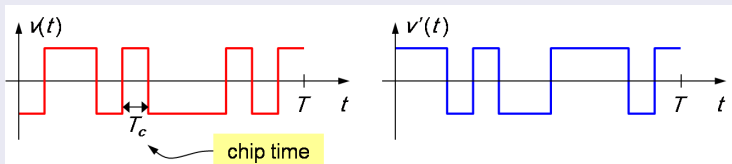
and for the MFR matched to  $v'(t)$

$$z'_{\text{MF}}(kT_s) = E_{v'} b_k$$



## CDMA

- In CDMA, all the users transmit continuously over the entire available spectrum
- Each user has different pulses  $v(t)$ ,  $v'(t)$ ,  $v''(t)$ , ... They are usually binary, pseudorandom sequences



- The BW is large, proportional to  $1/T_c$
- $v(t)$ ,  $v'(t)$ ,  $v''(t)$  are called spreading sequences and CDMA is a spread-spectrum technique
- Spreading sequences must be (almost) orthogonal
- The spreading sequences allow receivers to separate the users
- CDMA is used in WCDMA (3G)

## Remember the “common” set of basis functions $\mathcal{P}$ ?

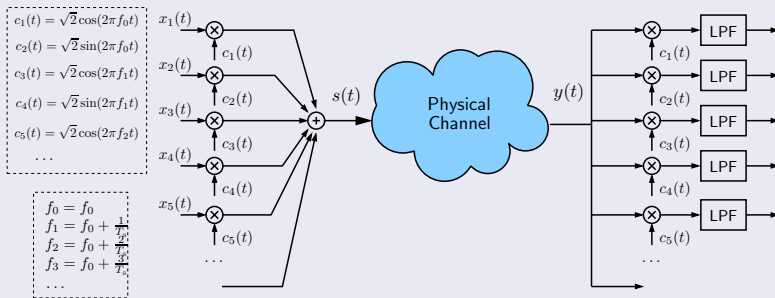
- A very common  $\mathcal{P} = \{\phi_1(t), \phi_2(t)\}$  is

$$\phi_1(t) = \sqrt{2}v(t) \cos(w_c t)$$

$$\phi_2(t) = \sqrt{2}v(t) \sin(w_c t)$$

- $f_c = \frac{w_c}{2\pi}$  is the carrier frequency
- $v(t)$  is a unit-energy baseband pulse
- $v(t)$  is  $T_s$ -orthogonal  $\rightarrow \phi_1(t)$  and  $\phi_2(t)$  form an orthonormal basis (both have unit energy and have correlation zero) and also  $T_s$ -orthogonal.
- The previous condition means we can detect  $a_k$  and  $b_k$  without ISI...

## Orthogonal frequency-division multiplexing (OFDM) Tx and Rx



### OFDM Details

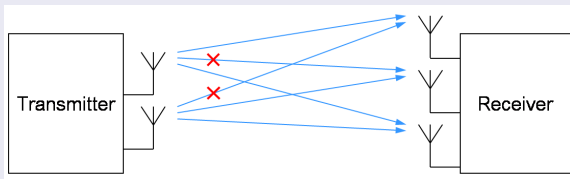
- $x_i(t)$  with  $i = 1, 2, \dots$  are PAM signals with rectangular pulse shape and the same symbol separation  $T_s$
- All the signals used for Tx are orthogonal with this pair of Tx/Rx
- $T_s$  is usually large (small frequency separation) so the symbol rate per carrier is low. However, the number of carriers is usually large (512, 1024, ...), and therefore, high transmission rates are achieved

## OFDM

- The PAM pulses for each frequency may have different  $M$ , power, or modulation.
- The previous condition results in flexible spectrum: OFDM can adapt to channel conditions
- Since  $T_s$  is large, OFDM is less sensitive to ISI (because of the channel dispersion)
- One of the main problems with OFDM is that the transmit signal amplitude varies a lot  $\rightarrow$  sensitive to nonlinearities in the PA
- OFDM can easily be implemented using IFFT in TX and FFT in RX
- OFDM is used in broadband internet (DSL), terrestrial digital TV (DVB-T), some WLANs (IEEE 802.11a/g/n), WiMax, long term evolution (LTE), ...

## Multiple-input Multiple-output (MIMO)

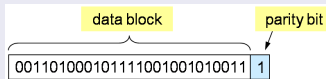
- Send the same data over several paths
- Some path are good, some are bad
- The receiver combines the signals from all antennas



## More about MIMO

- MIMO requires good channel estimates
- Higher bitrates are possible at a given SNR than without MIMO
- Used in 802.11n, WiMax, and LTE

## A very simple example



- If  $K$  is the number of ones in the data block, then the parity bit is 1 if  $K$  is odd and 0 if  $K$  is even
- If one bit is in error, the receiver...
  - will know that an error has occurred
  - cannot know where the error is
  - might request retransmission
- If two bits are in error, the receiver... **cannot detect any error**

## Error control coding (Channel coding)

- The objective of error control coding (or channel coding) is to detect and/or correct transmission errors by adding *redundancy*
- With more than one parity bit per data block, the receiver...
  - can detect more than one error
  - can identify the location of these errors and hence correct them

## Coded modulation schemes: Basic concepts

- Uncoded BPSK gives a maximum transmission rate of 1 bit per  $T_s$  [s]
- We could add a channel encoder that makes the transmission more robust (decrease the *effective* transmission rate in information bits per second)
- If the channel is really really good, there is a maximum of 1 bit per  $T_s$  [s], and therefore, we are *wasting* resources
- The solution is to use high order modulations (more than one bit per symbol), however, by doing this the probability of making mistakes increases...
- The “complete” solution is to combine channel coding and high order modulations. These systems are called coded modulation schemes
- Examples: trellis coded modulation (TCM), multilevel coding (MLC), bit-interleaved coded modulation (BICM), etc.

## Data compression

- The objective of data compression (or source coding) is to represent a signal with as few bits as possible
- The receiver should be able to reconstruct the original signal
- Algorithms are application-specific, not channel-specific
- For example, for DVB, MPEG-2 is used for data compression of audio and video signals.

## Classification and general ideas

- Source coding can be classified into:
  - Lossless source coding: Exact reconstruction (Example: zip file)
  - Lossy source coding: Approximate reconstruction (Example: MPEG or speech coders)
- The general ideas are:
  - Common (rare) patterns should be given few (many) bits
  - Perceptually unimportant features of the signal may be ignored (lossy source coding only)



## Do you want to learn more?

- SSY125 – Digital Communications (Q2)
- SSY135 – Wireless Communications (Q3)
- SSY145 – Wireless Networks (Q4)
- Advanced Topics in Communications:
  - SSY196 – Error Control Coding (Q3-2024 even years)
  - SSY210 – Information Theory (Q4-2025 odd years)
- Even more? PhD courses...

## The Evolution of WiFi

- The next lecture is a bit different than the other lectures. I will talk about the evolution of WiFi 802.11, which is part of the course as an example of a modern communication system.
- I will describe the main blocks and the technologies used in WiFi to show how 802.11n from 2009 can support rates of up to 600 Mbps compared to 54 Mbps in 802.11a from 1999.
- I then continue to describe the latest standards 802.11ac (from 2013) and 802.11ax (from 2020) and how they can support data rates of almost 7 and 10 Gbps, respectively.
- The lecture is tutorial like and based on my experience working at Quantenna Communications.
- **Homework before the lecture:** Check the speed of your fixed Internet connection at home and check also what your WiFi router supports (802.11b/a/g/n/ac/ax, 2.4 and/or 5 GHz, maximum bitrate, multiple streams, etc?)