Introduction to Communication Engineering
SSY121, Lecture # 11

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Sign up for the exam no later than Thu Oct 10!

The project points are invalid after the second re-exam in Aug 2020!

Project Quiz Voluntary!

- In the beginning of the last lecture (Wed Oct 16, 10:00–10:20) in room MC.
- 10 multiple choice questions (answered individually) to evaluate the understanding of the scientific base of the project (no re-quiz).

Mid-course meeting today Wed Oct 2!

- Elia Saquand (ERASMUS) saquand@student.chalmers.se
- Yuling Zhang (MPCOM) yulingz@student.chalmers.se
- Isac Olofsson (MPSYS) isaco@student.chalmers.se

Selected Articles

One or two selected articles in advanced modern topics in communications will be uploaded in pingpong (part of course material).

The Evolution of WiFi 802.11

- In the next lecture (Wed Oct 9 at 10:00–11:45), I will talk about the evolution of WiFi 802.11. This is part of the course as an example of a modern communication system.
- I will show how 802.11n from 2009 can support rates of up to 600 Mbps compared to 54 Mbps in 802.11a from 1999. I also describe the latest standards 802.11ac and 802.11ax 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, CA.
- 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, 2.4 and/or 5 GHz, multiple streams, etc?)

Outline

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

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

  - The received signal is

$$y(t) = k_0 s(t) + k_1 s(t-\tau_1) + k_2 s(t-\tau_2) + \ldots + n(t),$$

    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

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

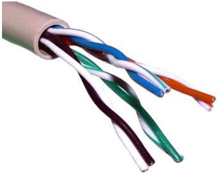
      where $\beta(t)$ varies over time
    - The received signal is

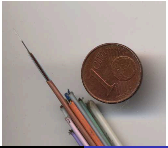
      $$y(t) = \beta(t) * s(t) + n(t)$$

    - 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

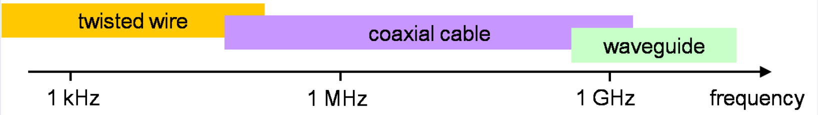


Wires and Cables

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

Types

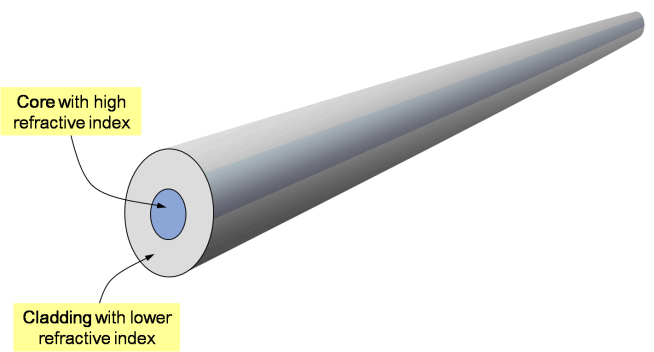


Optical fibers

- 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]

$$P_{\mathrm{R}} = P_{\mathrm{T}} \left(\frac{\lambda}{4\pi d} \right)^2$$

- For directional antennas with gains G_{T} and G_{R}

$$P_{\mathrm{R}} = P_{\mathrm{T}} G_{\mathrm{T}} G_{\mathrm{R}} \left(\frac{\lambda}{4\pi d} \right)^2$$

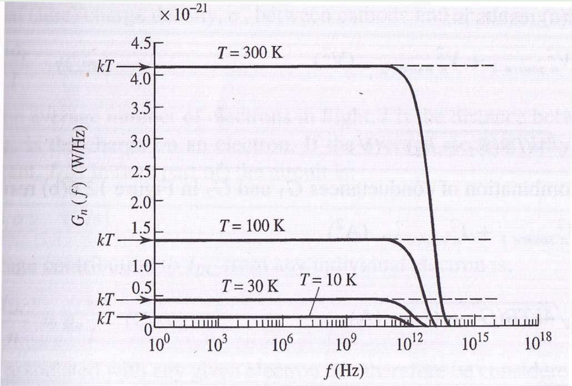
- For parabolic dish antennas with area A [m^2] the gain is

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

Part II

Transmission Impairments

Example (How the AWGN of L_7 is)



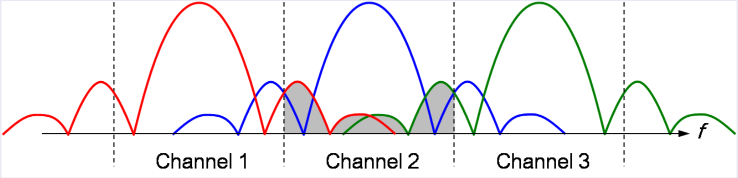
Power spectral densities of thermal noise at four temperatures.

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)

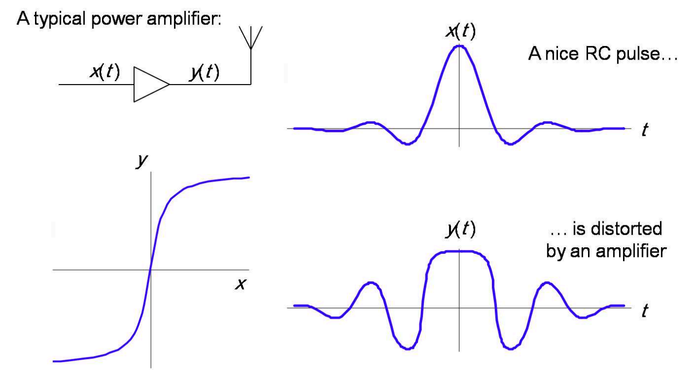
- Cause: the spectrum is wider than the allocated frequency band
- Remedy: sharper filter or larger channel separation



Intersymbol interference (ISI)

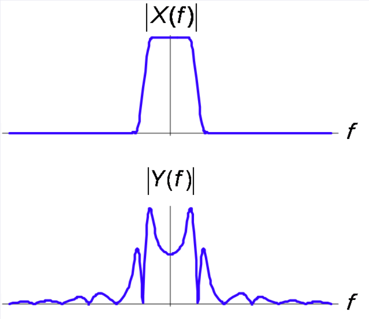
- See the SRx and MFRx (L_2 and L_4)
- Orthogonal/Nyquist pulses
- Cause: Non-orthogonal pulses, non-nyquist pulses, wrong sampling instants, ...
- Remedy: Symbol synchronization, correct pulse selection, decrease of the symbol rate, ...

A PA with clipping



A PA with clipping

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



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

Part III

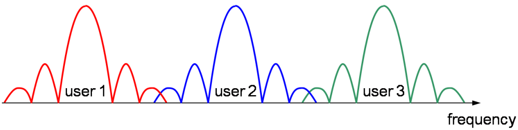
Multiple Access and Advanced Topics

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)

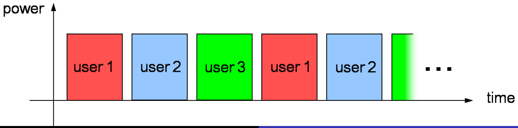
FDMA

- Different users use different frequencies
- ACI can occur



TDMA

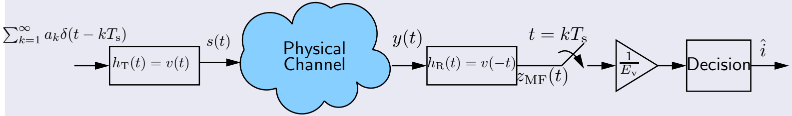
- Different users use different time slots
- Users must be synchronized. This is hard when they are at different locations. Why?
- TDMA is used in GSM (2G: second generation)



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

The transmitted signal is

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



The output of the MF

If $y(t) = s(t)$, the output of the MF at $t = 0, T_\mathrm{s}, 2T_\mathrm{s}, \dots$ is

$$z_\mathrm{MF}(kT_\mathrm{s}) = E_\mathrm{v} a_k$$

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)

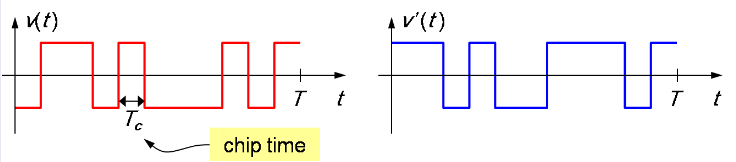
$$z_{\mathrm{MF}}(kT_s) = E_v a_k$$

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

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

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 $1/T_\mathrm{c}$
- $v(t)$, $v'(t)$, $v''(t)$ 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)

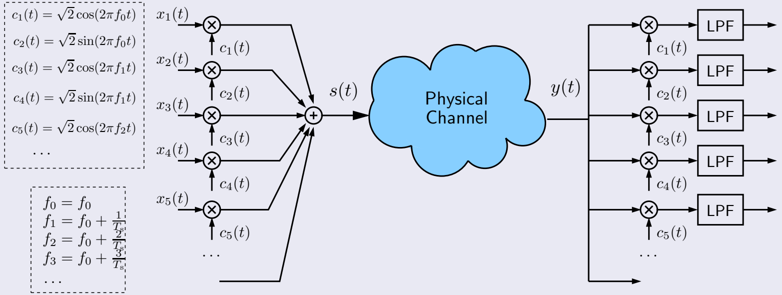
Remember the "common" set of basis functions $\mathcal{P}$?

- 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

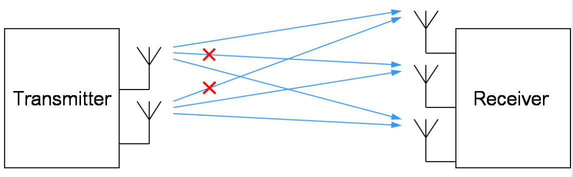
- $x_i(t)$ with $i = 1, 2, \dots$ are PAM signals with rectangular pulse shape and the same symbol separation T_s
- All the signals used for Tx are orthogonal with this pair of Tx/Rx
- T_s is usually large (small frequency separation) so the symbol rate per carrier is low. However, the number of carriers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

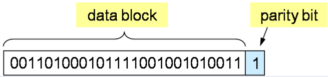
- Send the same data over several paths
- Some path are good, some are bad
- The receiver combines the signals from all antennas



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 (Q3-2020)
  - SSY210 – Information Theory (Q4-2021)
- Even more? PhD courses...