Introduction to Telecommunications

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Goals

To present the basics concepts of telecommunication systems with focus on digital and wireless.

Basic Concepts

- Signal Analog, Digital,
 Random
 Sampling
 Bandwidth
 Spectrum
- Noise

- Interference
- Channel Capacity
- •BER
- Modulation
- Multiplexing
- Duplexing

Telecommunication Signals

Telecommunication signals are variation over *time* of voltages, currents or light levels that carry information.

For analog signals, these variations are directly proportional to some physical variable like sound, light, temperature, wind speed, etc.

The information can also be transmitted by digital signals, that will have only two values, a digital **one** and a digital **zero**.





Telecommunication Signals

- Any analog signal can be converted into a digital signal by appropriately *sampling* it.
- The sampling frequency must be at least *twice* the maximum frequency present in the signal in order to carry *all* the information contained in it.
- Random signals are the ones that are unpredictable and can be described only by statistical means.
- **Noise** is a typical random signal, described by its mean power and frequency distribution.



Sinusoidal Signal

$$\mathbf{v}(t) = \mathbf{A} \cos(\omega_{o} t - \Theta)$$

$$\mathbf{A} = \text{Amplitude, volts}$$

- $\omega_o = 2\pi f_o$, angular frequency in radians
- $f_o = frequency in Hz$
- T = period in seconds, T= $1/f_o$
- $\Theta_{\frac{7}{7}}$ Phase

Signal Power

The power of a signal is the product of the current times voltage (VI). It can also be calculated as V^2/R , where R is the resistance in ohms over which the voltage is applied, or I²R, where I is the current. For a time varying signal, the *average* power can therefore be calculated as:

P= limit
$$_{T-\infty} 1/T \int_{-T/2}^{T/2} (t)/R dt$$

for a periodic signal, the integration can be carried out over its period T_o .

Example: v(t)=Asin(
$$\omega$$
t - Θ), P= 1/T $\int_{-T_o/2}^{T_o/2} [A^2 / R] sin^2 (\omega t)dt = A^2/[2R]$

The power of a sinusoidal signal is proportional to the square of its amplitude, irrelevant of its frequency or phase.

Waveforms and Spectra



Spectral analysis and filters



Filter Types



- Bandpass
- -Lowpass
- High Pass
- Bandstop

Signals and spectra

Given the time domain description of a signal, we can obtain its spectrum by performing the mathematical operation known as Fourier Transform.

The Fourier transform it is very often calculated digitally, and a well known algorithm to expedite this calculation is the Fast Fourier Transform, FFT.

The signal can be obtained from its spectrum by means of the Inverse Fourier Transform.

Orthogonality



Orthogonality



Mixers are key components for Frequency Conversion Can be used for either Up or Down Conversion



Sampling



The minimum sampling frequency f_s that allows to recover all the information contained in the signal corresponds to twice the highest frequency f_h present in it and it is called the Nyquist frequency, and the sampling theorem is known as the Nyquist-Shannon theorem.

Sampling

Sampling implies multiplication of the signal by a train of equally spaced impulses every 1/f_s seconds.

The original signal can be recovered from its samples by a low pass filter with a cutoff frequency f_h . This is called an interpolation filter since it fills the gaps between adjacent sampling points.

The sampled signal can be quantized and coded to convert it to a digital signal.

This is normally done with an ADC (Analog to Digital Converter), and the reverse operation with a DAC (Digital to Analog Converter)

Sampling of an image

Normal, 72pixels/inch

Sampled Image, 10 pixels/inch





Sampling, Quantization and Coding



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Why Digital?

- Noise does not accumulate when you have a chain of devices like it happens in an analog system.
- The same goes for the storing of the information: CD versus Vinyl, DVD versus VHS.
- Detection of a digital signal is easier than an analog signal, so digital signal can have greater range.
- Digital signals can use less bandwidth, as exemplified by the "digital dividend" currently being harnessed in many countries.
- Digital signals can be encoded in ways that allow the recover from transmission errors, albeit at the expense of throughput.

Communication System





Electrical Noise

•Noise poses the ultimate limit to the range of a communications system

- •Every component of the system introduces noise
- •There are also external sources of noise, like atmospheric noise and man made noise

•Thermal noise power (always present) is frequency independent and is given (in watts) by k*T*B, where:

k is Boltzmann constant, 1.38x10-23 J/K

T is absolute temperature in kelvins (K), B is bandwidth in Hz At 26 °C (T= 273.4+26) the noise power in dBm in 1 MHz is: - $174 + 10*\log_{10}(B) = -144 \text{ dBm}$

Signal Delay

The delay between the transmission and reception of a signal is called latency, and it is an important parameter for many applications.



Attenuation



Noise in an analog Signal



Bandwidth Limitation



Interference

Any signal different from the one that our system is designed to receive that is captured by the receiver impairs the communication and is called interference.

Co-channel interference originates in the same channel as our signal.

Adjacent-channel interference is due to the imperfection of the filters that will let in signals from adjacent channels.

Information Measurement

 $I = \log_2 (1/Pe)$

The information carried by a signal is expressed in bits and is proportional to the binary logarithm of the inverse of the probability of the occurrence of a given event. The more unlikely an event is to happen, the more information it will carry.

Transmitting a message corresponding to an event that is already known to the receiver carries no information. The amount of information transmitted in one second is the *capacity* of the channel, expressed in bit/s.

Redundancy

- Sending twice the same information is a waste of the system capacity that reduces the *throughput*.
- Nevertheless, if an error occurs, the redundancy can be used to overcome the error.
- Every *error correcting code* must use some sort of redundancy.
- The Cyclic Redundancy Check (CRC) is an example of error detecting code

Forward Error Correcting (FEC)

Forward error correcting codes are used in many modern communication systems and are specified in terms of the ratio of information bearing bits divided by the total number bits (including redundancy) transmitted. They are used in combination with different types of modulation to provide the optimum combination of *modulation and coding schemes* (**mcs**) for a particular condition of the channel.

Some systems are adaptive, and changes mcs on the fly to dynamically adapt to the amount of noise and interference in the channel.

Channel Capacity



This formula was formulated by Claude Shannon, the father of information theory in a breakthrough paper published in 1948

Symbol rate

- The symbol rate is defined as the number of symbols per second that a system can transmit.
- The unit for symbol rate is the baud.
- A baud can pack several bits per second, depending on the type of modulation.

The baud can also be calculated as the inverse of shortest duration of the transmitted signal

Detection of a noisy signal

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time, s





time, s



Detection of a noisy signal

- Detection of a simple binary signal is performed by sampling the received signal, measuring the energy in it and comparing with a detection threshold.
- The value of the threshold is determined by the noise and interference present.
- The key parameter is then Eb/No, the ratio between the energy per bit and the noise spectral density.
- A higher data rate requires a greater Eb/No to achieve the same bit error rate (BER).

Detection of a noisy signal

An analogy with voice communication helps to understand the detection process.

- The stronger the noise in a room, the louder a person must speak to be understood.
- When listening to a foreign language one always think they are speaking too fast, because the "modulation of the signal" is unfamiliar and more processing is required to detect the meaning.
- The faster a person speaks, the louder must speak to be understood.

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MoDem



Comparison of modulation techniques



Digital Sequence

ASK modulation

FSK modulation

PSK modulation

QAM modulation, changes both amplitude and phase

Digital Modulation

Polar Display: Magnitude & Phase Represented Together



- Magnitude is an absolute value
- Phase is relative to a reference signal

Digital Modulation Polar vs. I/Q representation



Digital Modulation Signal Changes or Modifications



Digital Modulation Binary Phase Shift Keying (BPSK) I/Q Diagram



Digital Modulation Quadrature Phase Shift Keying (QPSK) IQ Diagram



Digital Modulation: QPSK Effect of the noise in the received Signal This kind of diagram is called a constellation because of the fuzziness of the points



Digital Modulation power

- The power in phase and frequency modulated signals is indepent of the modulation index, that is the envelope is constant.
- In amplitude modulated signals the power changes with the modulation index, so the peak to average power ratio (PAR) is a figure used to compare different modulation systems.
- Expensive linear amplifiers are required for amplitude modulated signals.

Relationship between BER and E_b/N_o

- BPSK and QPSK are noise tolerant but can transmit only 1b/s per symbol.
- 16 PSK transmits 4 bits per symbol, but requires a much higher E_b/N_o to achieve the same BER



from: https://https://en.wikipedia.org/wiki/Eb/No

BER versus E_b/N_o in dB for QAM

A 10 $^{-5}$ BER requires an E_b/N_o of 10 dB for 4QAM, 13.5 dB for 16QAM, 18 dB for 64 QAM and 23 dB for 256QAM. The latter transmits 8 bits per symbol.

> https://cdn.rohdeschwarz.com/pws/dl_downloads/dl_applicat ion/application_notes/7bm03/7BM03_4E.pd



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Orthogonality



Modulation and E_b/N_o

Mod. Type	bits/Symbol	Required E_{b}/N_{o}
16 PSK	4	18 dB
16 QAM	4	15 dB
8 PSK	3	14.5 dB
4 PSK	2	10.1 dB
4 QAM	2	10.1 dB
BFSK	1	13.5 dB
BPSK	1	10.5 dB

Medium sharing techniques



Example:

U.S. Television Channels Allocation

Signal Power



Medium sharing techniques: OFDMA

In FDMA a guard band must be let vacant between adjacent channels to allow for the separation of the channels with non-ideal filters. This is a waste of spectrum, so by taking advantage of orthogonality the guard band can be eliminated provided that the frequencies of the sub-carriers meet certain restrictions and that a cyclic prefix code is added to the signal to facilitate decoding.



Time Division Multiplexing



CDMA analogy

Two messages superposed, one in yellow and one in blue

A blue filter reveals what is written in yellow

A yellow filter reveals what is written in blue

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MIMO: Multiple Input, Multiple Output

- Deploying two or more transmitter chains and two or more received chains in the same system to enhance the performance.
- Leverages the differences in trajectories from the different transmitting antennas to the receiving antennas to increase either the throughput or the range of the system.
- Is a sort of "space diversity" that takes advantage of reflections and refractions from objects between the transmitter and the receivers to differentiate among the trajectories.

MIMO: Multiple Input, Multiple Output

- Requires that the different trajectories have little correlation, which means that the antennas must be at least half wavelength apart, or use orthogonal polarizations.
- Exploits space as a domain to increase the data rate or share the resources among several users.
- Widely used in most modern systems.

2 X 2 MIMO



2 X 2 MIMO



The two "data pipes" created by the four streams are in general of different sizes, in relation with the amount of correlation among the streams

2 X 2 MIMO

- Uses two transmitters and two receivers, thus creating up to four independent channels.
- If the receiver can use the differences in trajectories to distinguish between streams, it can demodulate two independent data streams at the same frequency and at the same time.
- Similar to solving a system of two equations with two variables, the requirement is that the two equations must be independent (the streams must be uncorrelated, they must have some difference).

Beamforming

- Multiple antennas transmit the same radio signal, but their phases are manipulated to concentrate all the beams in the direction of the intended recipient.
- The beams are steered on the fly by adjusting the phases of the antennas, so they can serve another user at a subsequent time.
- It can be used in FDD systems as well, provided that the information about the RF channel is available.
- The nulls of the radiation pattern can be positioned to reject interfering signals.
- It can be used in combination of MIMO to extend the benefits of high throughput at longer distances.

Modulation and coding schemes (MCS)

MCS for IEEE 802.11n standard.

Spatial streams is the number of data flows sent simultaneously using different antennas with MIMO. GI is the minimum guard interval between adjacent frames.

1000	0.01	Data rate					e (Mbit/s)		
MCS Spatial index streams	Spatial	al Modulation	Coding	20 MHz channel 40 MHz channel					
	type	rate	800 ns GI	400 ns GI	800 ns GI	400 ns GI			
0	1	BPSK	1/2	6.50	7.20	13.50	15.00		
1	1	QPSK	1/2	13.00	14.40	27.00	30.00		
2	1	QPSK	3/4	19.50	21.70	40.50	45.00		
3	1	16-QAM	1/2	26.00	28.90	54.00	60.00		
4	1	16-QAM	3/4	39.00	43.30	81.00	90.00		
5	1	64-QAM	2/3	52.00	57.80	108.00	120.00		
6	1	64-QAM	3/4	58.50	65.00	121.50	135.00		
7	1	64-QAM	5/6	65.00	72.20	135.00	150.00		
8	2	BPSK	1/2	13.00	14.40	27.00	30.00		
9	2	QPSK	1/2	26.00	28.90	54.00	60.00		
10	2	QPSK	3/4	39.00	43.30	81.00	90.00		
11	2	16-QAM	1/2	52.00	57.80	108.00	120.00		
12	2	16-QAM	3/4	78.00	86.70	162.00	180.00		
13	2	64-QAM	2/3	104.00	115.60	216.00	240.00		
14	2	64-QAM	3/4	117.00	130.00	243.00	270.00		
15	2	64-QAM	5/6	130.00	144.40	270.00	300.00		
16	3	BPSK	1/2	19.50	21.70	40.50	45.00		
17	3	QPSK	1/2	39.00	43.30	81.00	90.00		
18	3	QPSK	3/4	58.50	65.00	121.50	135.00		
19	3	16-QAM	1/2	78.00	86.70	162.00	180.00		
20	3	16-QAM	3/4	117.00	130.00	243.00	270.00		
21	3	64-QAM	2/3	156.00	173.30	324.00	360.00		
22	3	64-QAM	3/4	175.50	195.00	364.50	405.00		
23	3	64-QAM	5/6	195.00	216.70	405.00	450.00		
24	4	BPSK	1/2	26.00	28.80	54.00	60.00		
25	4	QPSK	1/2	52.00	57.60	108.00	120.00		
26	4	QPSK	3/4	78.00	86.80	162.00	180.00		
27	4	16-QAM	1/2	104.00	115.60	216.00	240.00		
28	4	16-QAM	3/4	156.00	173.20	324.00	360.00		
29	4	64-QAM	2/3	208.00	231.20	432.00	480.00		
30	4	64-QAM	3/4	234.00	260.00	486.00	540.00		
31	4	64-QAM	5/6	260.00	288.80	540.00	600.00		

https://en.wikipedia. org/wiki/IEEE_802. 11n-2009

from:

Duplexing

Simplex:

One way only, example: TV Broadcasting **Half-duplex:**

The corresponding stations have to take turns to access the medium, example: walkie-talkie. Requires hand-shaking to coordinate access.

This technique is called **TDD** (Time Division Duplexing) **Full-duplex:**

The two corresponding stations can transmit simultaneously, employing different frequencies. This technique is called **FDD** (Frequency Division Duplexing). A guard band must be allowed between the two frequencies in use.

Conclusions

The communication system must overcome the noise and interference to deliver a suitable replica of the signal to the receiver.

The capacity of the communication channel is proportional to the bandwidth and to the logarithm of the S/N ratio. Modulation is used to adapt the signal to the channel and to allow several signals to share the same channel. Higher order modulation schemes permit higher transmission rates, but require higher S/N ratio. The channel can be shared by several uses that occupy different frequencies, different time slots or different ⁶²codes