Communications

IB Paper 6

Handout 1: Introduction, Signals and Channels

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Lent Term

Acknowledgements

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Outline

1. Background
    - Course Organisation
    - Basic Concepts
    - History of Communications
2. Analogue Signals
    - Signal Energy
    - Signal Power
    - Decibel Representation
    - Bandwidth
3. Communications Channels
    - Attenuation
    - Noise
    - Typical Real Channels

Course Organisation

Organisation

- All lectures in LT0
- 7 lectures, Wednesdays 11-12, Fridays 10-11
- 2 examples papers (8 and 9) and 2 examples classes (Friday 1&8 March, 11-12am, LR5)
- All questions and feedback highly appreciated via email (js851), orally, or any other means

Course Organisation

Topics

- Signals and Channels
- Analogue Modulation (AM, FM)
- Digitisation of Analogue Signals (sampling recap and quantisation)
- Digital Signals and Modulation
- Multiple Access

Basic Concepts

Definition

Definition: Communication

The process of delivering information from an information source to a destination through a communications channel.

Basic Concepts

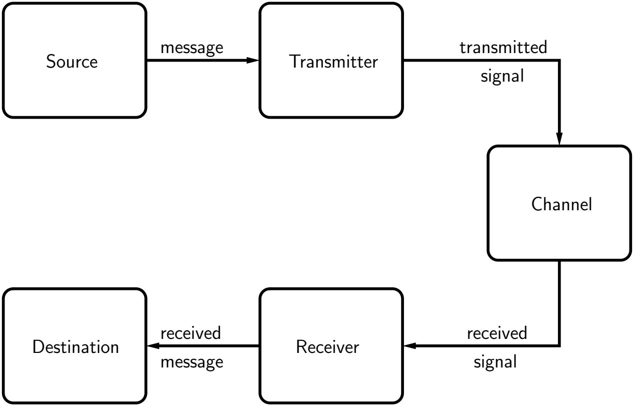
Definition

Definition: Communication

The process of delivering information from an information source to a destination through a communications channel.

or: from one or many sources to one or many destinations.

Basic Block Diagram



Basic Block Diagram

Component Description

- Source: voice, music, video (analogue), e-mail, file transfer (digital). Has an information message to transmit
- Transmitter: translates the information message into a signal suitable for transmission over the channel
- Channel: medium used to transmit the signal to the receiver: optical fibre, mobile wireless radio channel, magnetic recording... Might add noise or interference.
- Receiver: reconstructs the message from the signal (inverse operation)
- Destination: to whom the message is intended

Basic Concepts

Fundamental Problem

Claude E. Shannon (1948)

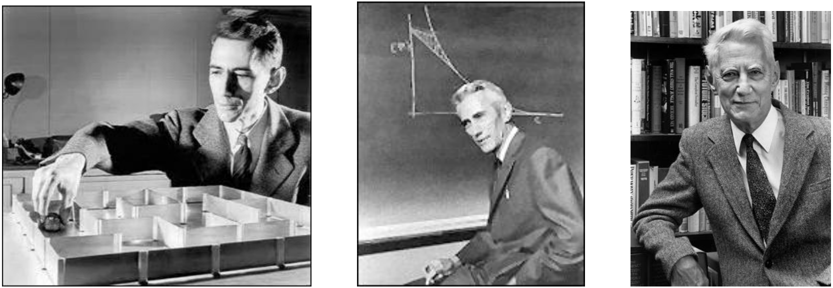
"The fundamental problem of communication is that of reproducing at one point exactly or approximately a message selected at another point."

John L. Kelly

"A channel is that part of a communication system that one is wither unwilling or unable to change."

A Brief History...

Claude E. Shannon (1916-2001)



Inventor of the information bit and Father of the *Information Age* (type "Claude Shannon" on YouTube for an interesting video)

A Brief History...

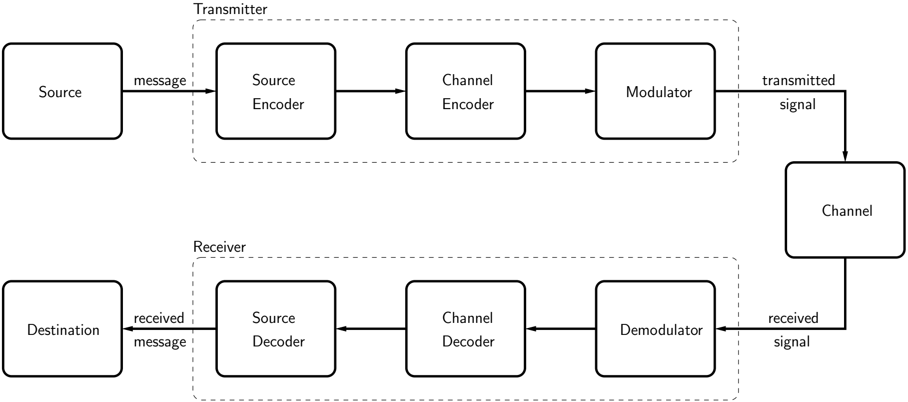
Claude E. Shannon (1916-2001)

Claude E. Shannon's contributions

- Mathematical foundations of digital communications
  - ultimate data rate (in bits / second) for reliable communication: channel capacity
- Mathematical foundations of data compression
  - ultimate compression rate (in bits / source symbol) for source reconstruction: entropy
- Unfortunately, he did not tell us how to achieve these limits
  - since 1993 we can approach Shannon's limits with practical codes: turbo and LDPC codes.

Basic Block Diagram

...with some more detail (digital communications)

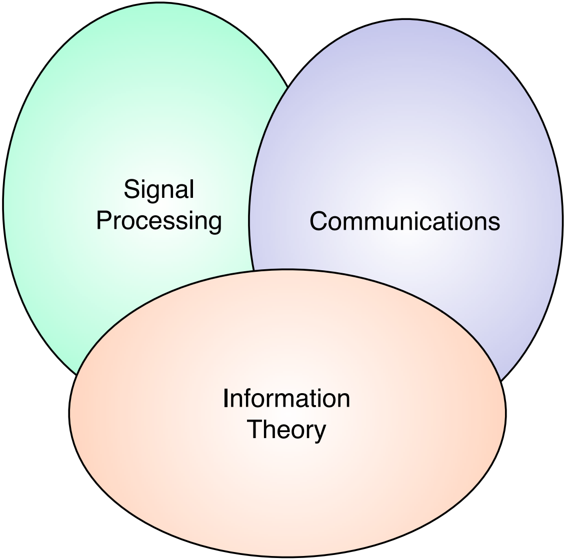


Basic Block Diagram

Definition

- Source Encoder: compresses the source message such that redundancy is removed
  - MP3, JPEG, MPEG are compression standards.
- Channel Encoder: introduces *smart* redundancy suited to the channel characteristics (noise, interference...)
- Modulator: maps output of channel encoder to signal waveforms (electrical/optical signal), matched to the channel characteristics

Disciplines Involved



A Brief History...

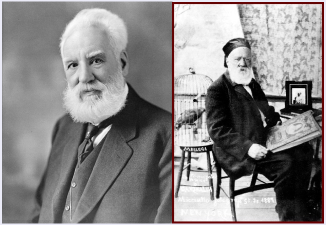
Early Days

Telegraph

- Invented by Weber and Gauss in 1833, patented by Morse in 1849
- Revolutionary means of real-time long-distance communications

Telephone

- Patented by Bell in 1876, possibly invented and realised by Meucci a few years before
- Real-time transmission of speech



A Brief History...

Radio

- Maxwell formulated electromagnetic theory in 1864
- Hertz confirmed the existence of radio waves in 1887
- Lodge demonstrated short distance wireless communication in 1894
- Marconi received first transatlantic radio signal in 1901

$$\begin{aligned}\nabla \cdot D &= \rho \\ \nabla \cdot B &= 0 \\ \nabla \times E &= -\frac{\partial B}{\partial t} \\ \nabla \times H &= J + \frac{\partial D}{\partial t}\end{aligned}$$

A Brief History...

Early Days

Television

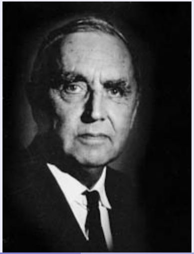
- Farnsworth (1928) and Zworykin (1929) demonstrated the first all-electronic televisions
- BBC TV starts commercial broadcasting in 1936

A Brief History...

Early Days

Digital Communications

- Nyquist published a classic paper of signal transmission in telegraphy in 1928
- Reeves invented pulse-code modulation (PCM) for digital encoding of speech in 1937
- Shannon publishes "The Mathematical Theory of Communication" in 1948

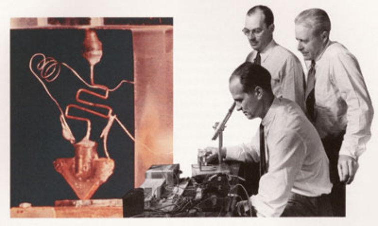


A Brief History...

Early Days

Electronics

- Brattain, Bardeen and Shockley invented the transistor in 1947
- Noyce produced the first integrated circuit in 1958



which lead to...

- development of very-large scale integrated (VLSI) circuits
- single-chip microprocessors
- technology is now mature for practical implementations of Shannon's challenge: mobile phones, WiFi, DVB...

A Brief History...

Today

Modern Digital Communications

- Groupe Spécial Mobile (GSM/2G), specifications 1990 (2G), Universal Mobile Telecommunications System (UMTS/3G) in 1999, Long Term Evolution (LTE/4G) in 2009.
- Asymmetric Digital Subscriber Line (ADSL), up to 2Mbit/s, appeared early 2000.
- Wi-Fi, up to 2Mbit/s, created in 1991
- Bluetooth, first developed in 1998
- Digital Audio Broadcasting (DAB), specification in 1993
- Digital Video Broadcasting (DVB), first broadcast ever in the UK, in 1998

Analogue Sources

Analogue Signals

Produce continuous outputs

- Speech
- Music
- (Moving/Static) images
- And also: temperature, speed, time...

using a device that converts the real signal to voltage.

Signal Energy

Energy

The energy of a signal $x(t)$ is defined as (recall Parseval's theorem)

$$E_x = \int |x(t)|^2 dt = \frac{1}{2\pi} \int |X(\omega)|^2 d\omega \quad \text{Joules (J)}$$

- $X(\omega)$ is the Fourier transform of $x(t)$
- $\omega = 2\pi f$ is the frequency in radians
- f is the frequency in Hertz (Hz)
- $|X(\omega)|^2$ is the energy spectral density

Signal Power

Power

The power of a signal $x(t)$ (whose energy is not finite) is

$$P_x = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} |x(t)|^2 dt \quad \text{Watts (W)}$$

Defining now

$$x_T(t) = \begin{cases} x(t), & -\frac{T}{2} < t < \frac{T}{2} \\ 0, & \text{elsewhere} \end{cases}$$

we have that

$$P_x = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} |x_T(t)|^2 dt = \lim_{T\to\infty} \frac{1}{2\pi T} \int_{-T/2}^{T/2} |X_T(\omega)|^2 d\omega$$

Hence, the power spectral density is given by

$$\lim_{T\to\infty} \frac{1}{2\pi T} |X_T(\omega)|^2$$

where $X_T(\omega)$ is the Fourier transform of $x_T(t)$.

Decibel Representation

Decibel Representation

The decibel representation (dB) is a logarithmic measure of a power (or energy) ratio.

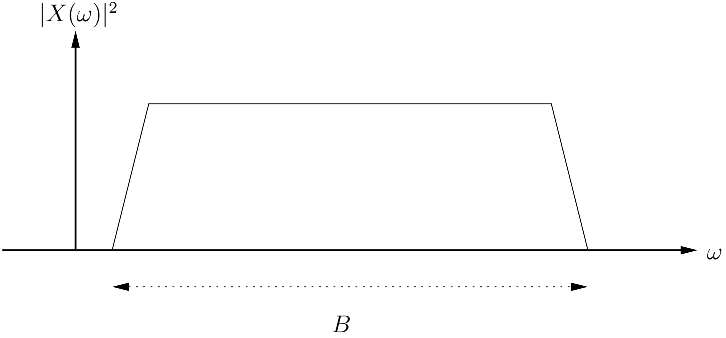
$$\begin{aligned}\overline{P}(\text{dB}) &= 10\log_{10}\frac{P_1}{P_2}\\ &= 10\log_{10}P_1 - 10\log_{10}P_2\\ &= \overline{P}_1(\text{dB}) - \overline{P}_2(\text{dB})\end{aligned}$$

where $\overline{P}_1, \overline{P}_2$ are the dB representations of the ratios $P_1/1\text{W}$ and $P_2/1\text{W}$, respectively.

Bandwidth

The Main Idea

The range of frequencies over which a signal has significant power (or energy).



Bandwidth

Possible Definitons

- Absolute bandwidth: support of the power spectral density
- 3dB bandwidth: frequency interval at which the power spectral density drops 3dB (in linear, it halves).
- Fractional power-containment bandwidth: frequency interval which contains a given percentage of the total signal power.

But...

These definitions depend on the actual signal employed.

Example

What is the absolute bandwidth of a rectangular pulse of duration T? (a) $\frac{1}{T}$, (b) ∞, (c) no clue.

Communications Channels

Definition and Properties

The medium used to transmit the signal from transmitter to receiver.

- Introduces attenuation and noise so that the received signal is a faded and noisy version of what the transmitter sent
- Noise and attenuation can cause errors at the receiver

Channel Input

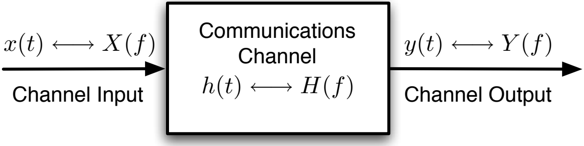
Communications Channel

Channel Output

Linear Time-Invariant Channels

Linear Time-Invariant Channels

- Input-output relationship does not change with time and can be characterised by a linear operator
- We view channels as linear systems and the input-output operator is therefore convolution integral
- The channel impulse response is *h*(*t*)



$x(t) \longleftrightarrow X(f)$

Channel Input

Communications Channel

$h(t) \longleftrightarrow H(f)$

$y(t) \longleftrightarrow Y(f)$

Channel Output

$$y(t) = h(t) * x(t) \longleftrightarrow Y(f) = H(f)X(f)$$

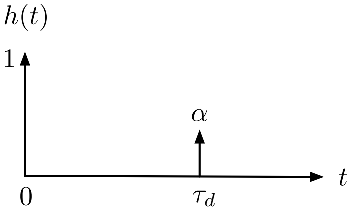
Linear Time-Invariant Channels

Example: Echo or Multipath Channel

Consider a channel with the following impulse response

$$h(t) = \delta(t) + \alpha\delta(t - \tau_d)$$

- The signal is received perfectly with no delay
- A copy of the transmitted signal is also received with delay τ_d and attenuation α (echo or multipath)
- Multipath causes interference (see the examples paper)

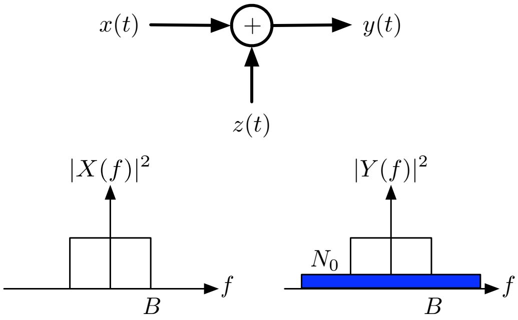


The Additive Gaussian Noise Channel

Thermal Noise

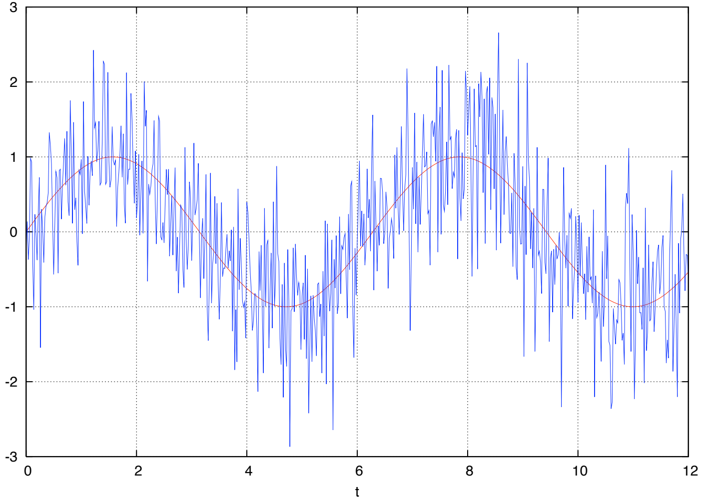
- Noise (thermal noise, to be precise) is the noise generated by the thermal agitation of electrons inside an electrical conductor
- Happens regardless of the applied voltage
- Thermal noise has a flat power spectral density, with approximately a Gaussian distribution (of occurrence)
- All receivers (GSM, WiFi, AM, FM,...) generate thermal noise, which causes errors

The Additive Gaussian Noise Channel



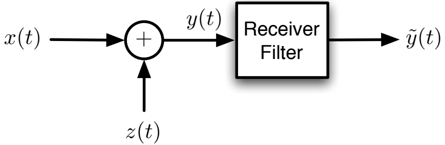
- $x(t)$, transmitted signal of power P and bandwidth B
- $y(t)$ received signal
- $z(t)$ Gaussian noise with flat power spectral density N_0

The Additive Gaussian Noise Channel

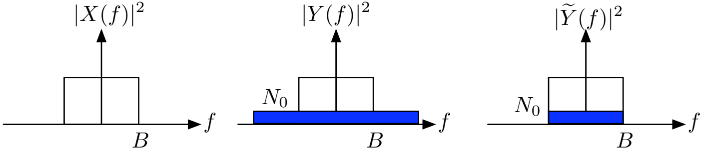


The Additive Gaussian Noise Channel

How can we effectively reduce the amount of noise?



Receiver Filter



Mobile Radio Channels

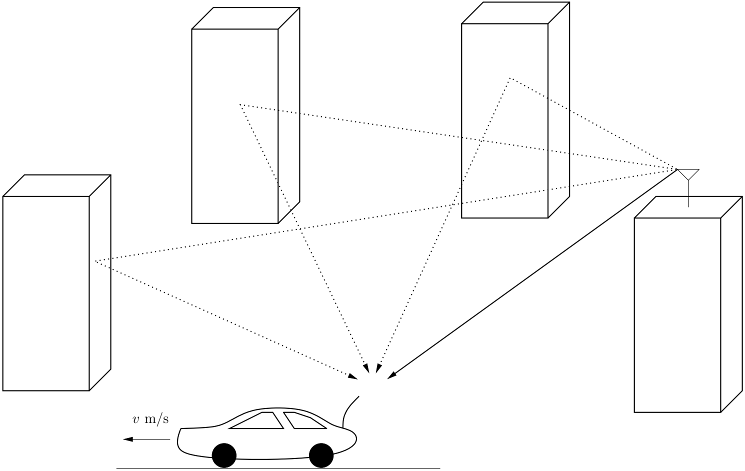
Properties

The main characteristic of mobile radio channels are (apart from thermal noise) fluctuations on the received signal strength called fading due to

- mobility
- multiple path propagation, i.e., signal multiple delays with reflection, refraction and scattering (constructive and destructive interference of signals)

which are usually modeled as random. Fading degrades performance, but its exact impact on data transmission largely depends on the signal bandwidth.

Mobile Radio Channels

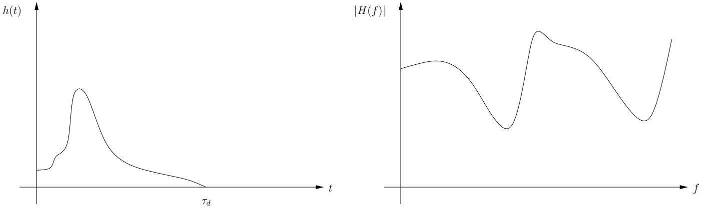


Mobile Radio Channels

Fading: Multipath Propagation

Definitions

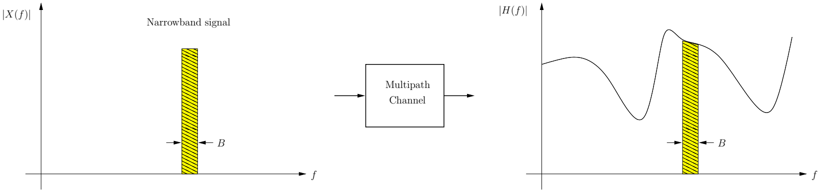
- Multiple paths arrive with different attenuations, phases and delays $\alpha_i, \theta_i, \tau_i$, i.e., $h(t) = \sum_i \alpha_i e^{j\theta_i} \delta(t - \tau_i)$
- The delay spread is the largest delay, $\tau_d = \max_{i,j} |\tau_i - \tau_j|$
- The coherence bandwidth is the inverse of the delay spread, $B_c = \frac{1}{\tau_d}$



Mobile Radio Channels

Fading: Multipath Propagation

Narrowband transmission $B \ll B_c$, flat frequency response across signal bandwidth.

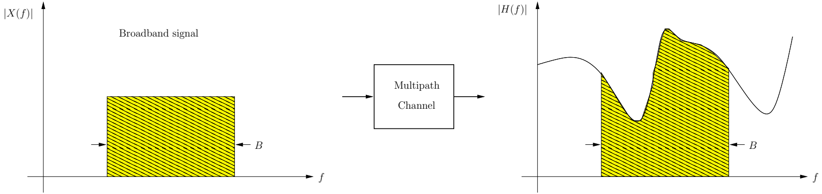


The channel is said to be frequency flat.

Mobile Radio Channels

Fading: Multipath Propagation

Broadband transmission $B \gtrapprox B_c$, the channel introduces severe distortion to the transmitted signal. More formally, the channel is said to be frequency selective (introduces severe distortion).



We need to equalise the channel. GSM channels are frequency selective $\tau_d = 20\mu$s, $B_c = 50$ kHz, $B = 200$ kHz (per user), and *hop* frequencies to avoid getting stuck in a deep fade (diversity). WiFi does it in a more sophisticated way, but we will get there!

Mobile Radio Channels

Fading: Mobility

Doppler frequency spread

- If transmitter and receiver in relative motion (with speed v), the received signal (assuming transmission of a tone at f) is subject to a constant frequency shift (Doppler shift)

$$\Delta f_D = f\frac{v}{c}$$

- For a given signal we will have an increased bandwidth due to mobility since every frequency component of our signal will have a different Doppler shift

Mobile Radio Channels

Fading: Mobility

Doppler frequency spread

- The Doppler spread is the largest of the frequency shifts
- The coherence time T_c is the inverse of the Doppler spread
- If the signal duration $T \ll T_c$, we have slow fading (not time-selective). Typical of low mobility scenarios like WiFi.
- Otherwise, we have fast fading (time-selective)

Mobile Radio Channels

Summarising...

- Fading is caused by multipath propagation and mobility
- Fading causes signal distortion
- The exact type of distortion depends on the transmitted signal bandwidth
- Due to the key role of wireless systems in modern times, a deep understanding of the fading process and how to design efficient communications systems under fading is crucial to success...
- More on this in the coming years!

Other Important Channels

Electrical Wires

Introduce attenuation and the corresponding receivers introduce thermal noise

- low frequency (100 MHz) coaxial cables introduce 88.6 dB/Km attenuation
- high frequency (10 GHz) coaxial cables introduce 1.37 dB/m attenuation
- twisted pair cables (Ethernet) introduce up to 215 dB/Km attenuation (100 MHz)

Other Important Channels

Optical Fibres

Introduce attenuation and quantum noise (different properties than thermal noise)

- Pros: very large bandwidth, cheap production, low attenuation (0.2 dB/Km)
- Cons: all-optical processing difficult, connecting fibres induces large attenuation, cost of deployment