1B Paper 6: Communications

Handout 1: Introduction, Signals, and Channels

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Course Information

- Seven lectures, recordings will be accessible after each lecture via the Panopto block on Moodle
- Lecture handouts (both filled and unfilled) will be posted on Moodle: `https://www.vle.cam.ac.uk`
- Feedback via email (`rv285@cam.ac.uk`) or using anonymous feedback facility

Topics

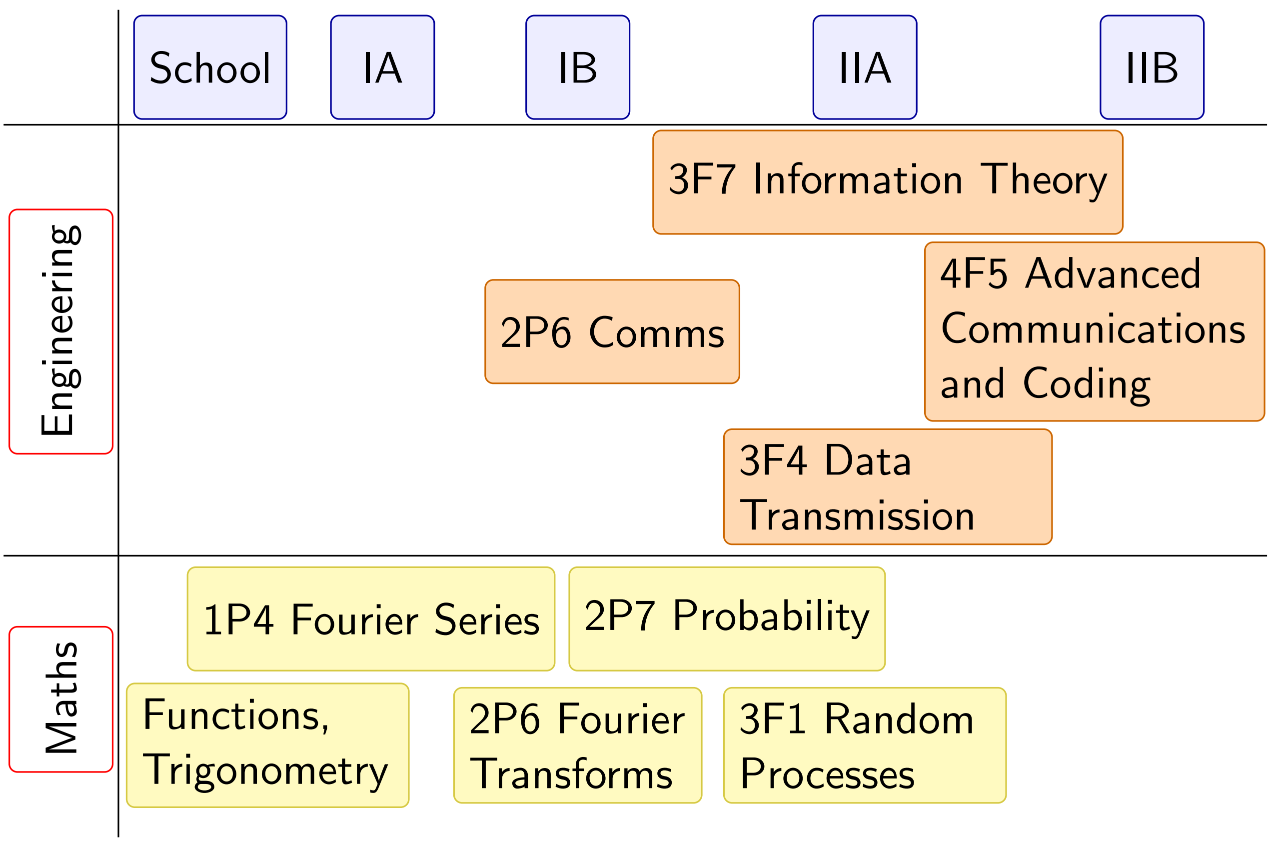
- Signals and Channels
- Analogue Modulation (AM, FM)
- Digitisation of Analogue Signals (sampling recap and quantisation)
- Digital Signals and Modulation
- A brief introduction to Channel Coding
- Multiple Access

References:

S. Haykin and M. Moher,
Introduction to Analog & Digital Communications 2nd Ed.,
John Wiley & Sons, 2007

R. G. Gallager, *Principles of Digital Communications*,
Cambridge University Press, 2008

"Communications" teaching



A Brief History

Analogue Communications

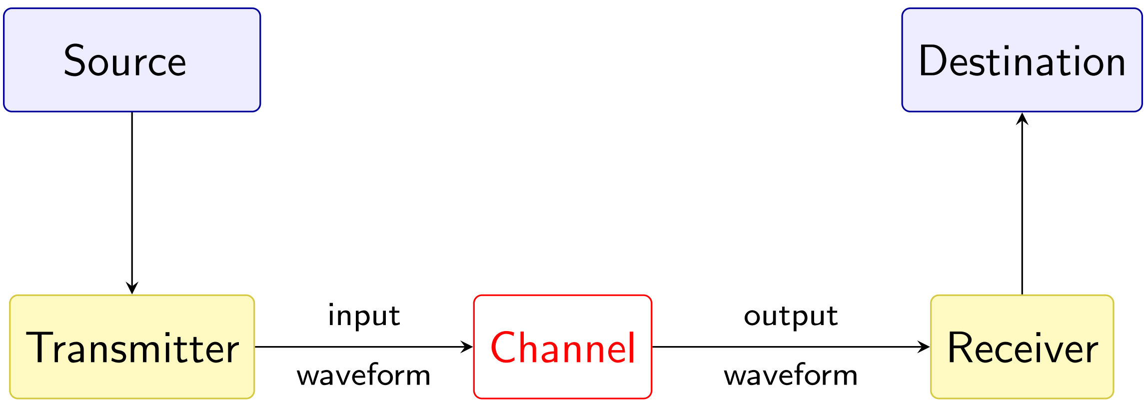
- Telephone: patented in 1876
- Radio: AM since early 1900s, FM patented in 1930s
- BBC broadcast analogue TV from 1936-2012

Digital Communications

- Telegraph: first optical/semaphore 1767, electrical 1816
- Mobile Communications: GSM (1991) → 3G → 4G LTE
- Wi-Fi, first deployed in 1997, Bluetooth in '98
- Asymmetric Digital Subscriber Line (ADSL), up to 4Mbit/s, appeared early 2000
- Digital Video Broadcasting (DVB), first broadcast ever in the UK, in 1998. Since 2012, all broadcast TV in the UK is digital

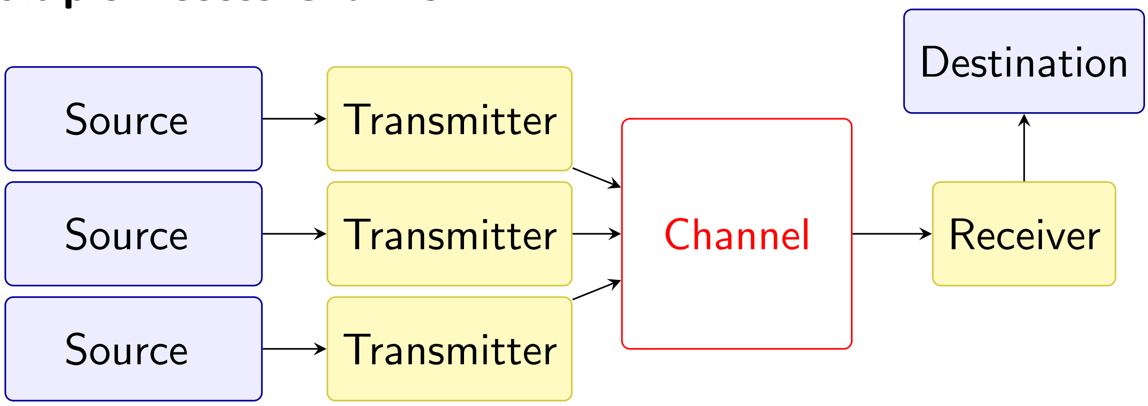
The Basic Idea

Communication: The process of delivering information from an information source to a destination through a communication channel.

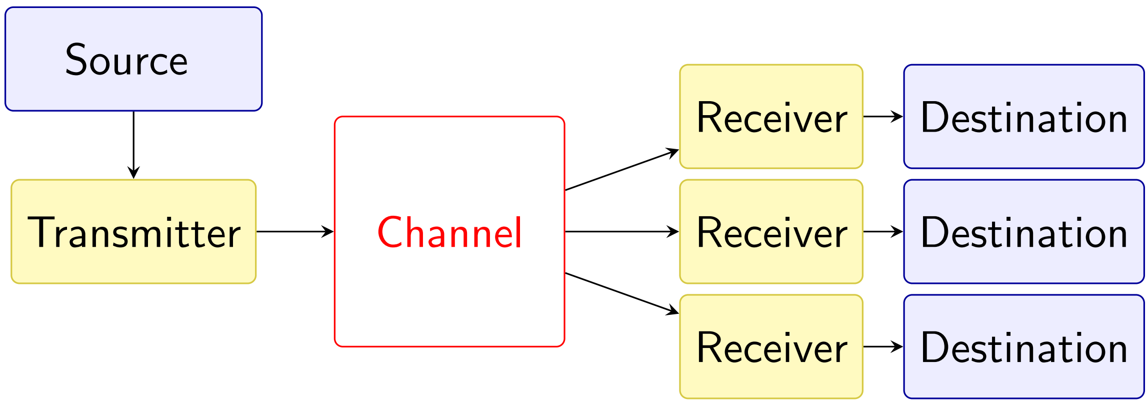


More generally, we could have multiple sources delivering information to multiple destinations through a common channel

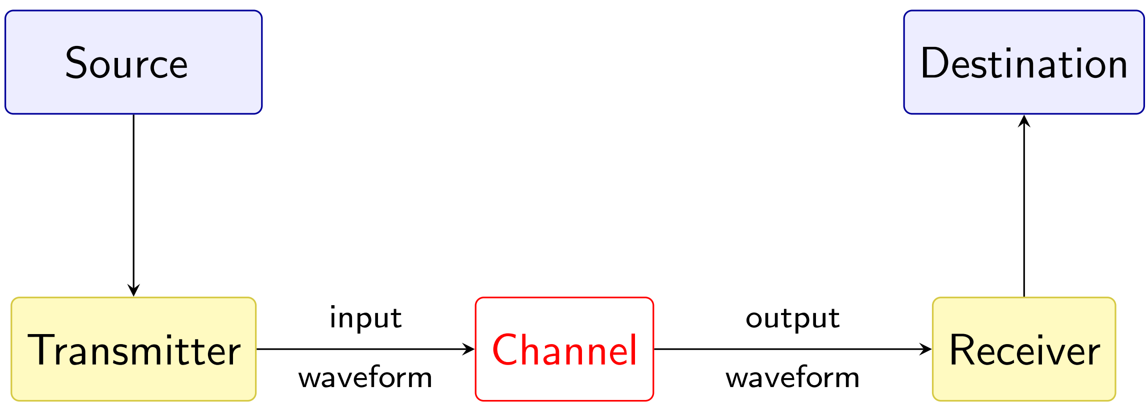
Multiple Access Channel:



Broadcast Channel:



For most of this course, we will focus on the point-to-point communication model:



Block Diagram Components

- Source of information: May be analogue (voice, music, video), or digital (e.g., e-mail, any file on your computer)
- Transmitter: translates the information into a signal suitable for transmission over the channel
- Channel: medium used to transmit the signal to the receiver
  - E.g., optical fibre, wireless channel, magnetic recording...
  - May distort transmitted signal, e.g., add noise or attenuate it
- Receiver: reconstructs the source of information from the received signal
- Destination: for whom the information is intended

Key Signal Properties

Two properties of signals that are important for communication:

1. Power
2. Bandwidth

Let us define these terms and understand why they are relevant.

Signal Energy

$$X(f) = \int_{-\infty}^{\infty} x(t) e^{-j2\pi f t} dt$$

$$x(t) = \int X(f) e^{j2\pi f t} df$$

The energy of a signal $x(t)$ is defined as

$$E_x = \int_{-\infty}^{\infty} |x(t)|^2 dt$$

If $X(\omega)$ is the Fourier transform of $x(t)$, recall Parseval's theorem:

$$E_x = \int_{-\infty}^{\infty} |x(t)|^2 dt = \frac{1}{2\pi} \int_{-\infty}^{\infty} |X(\omega)|^2 d\omega = \int_{-\infty}^{\infty} |X(f)|^2 df$$

- $\omega = 2\pi f$ is the frequency in radians, f is frequency in Hz
- $|X(f)|^2$ is the energy spectral density
  Can think of $|X(f)|^2 df$ as the energy of the signal in the frequency band $[f, f + df]$

Signal Power

For a signal $x(t)$ whose energy is infinite, the power is defined as

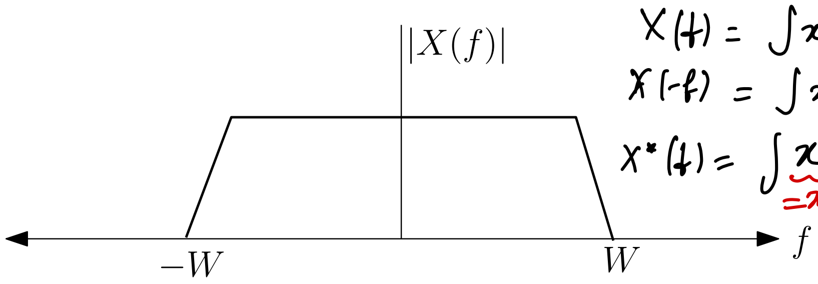
$$P_x = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} |x(t)|^2 dt$$

Why is signal power important?

- We are usually concerned about energy of the transmitted signal per unit time, i.e., *transmit power*
- Lower transmit power implies longer battery life for your phone
- But lower transmit power also makes signal harder to detect at the receiver in the presence of noise!
- Need clever Tx + Rx designs that make judicious use of available transmit power

Bandwidth

The bandwidth of a signal is roughly the range of frequencies over which its spectrum (Fourier transform) is non-zero.



$X(f) = \int x(t) e^{-j2\pi ft} dt$

$X(-f) = \int x(t) e^{j2\pi ft} dt.$

$X^*(f) = \int \underbrace{x^*(t)}_{= x(t) \text{ for } x(t) \text{ real}} e^{j2\pi ft} dt.$

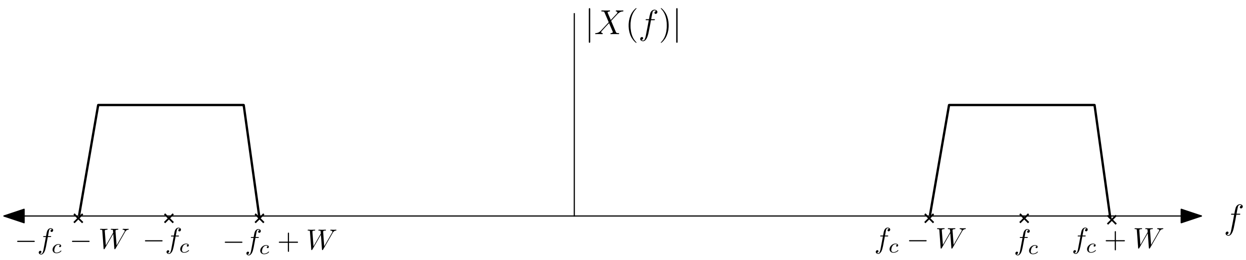
- For real signals, bandwidth measured as the range of **positive** frequencies as $|X(f)|$ is symmetric around 0 (as $X(-f) = X^*(f)$ for real $x(t)$) $\Rightarrow |X(-f)| = |X^*(f)| = |X(f)|$
- In communications, signal bandwidth typically specified in Hz

A signal is called *low-pass* or *baseband* if its spectral content is centred around $f = 0$.

- The bandwidth of the baseband signal above is W
- E.g., audio signals are baseband with bandwidth ≈ 20 kHz
  Voice signals in telephone systems have bandwidth ≈ 4 kHz

Passband signals

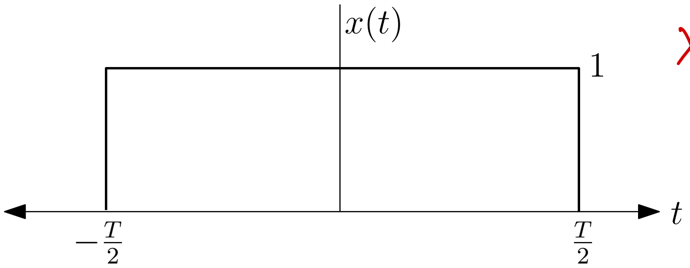
A signal is said to be *passband* if its spectral content is centred around $\pm f_c$, where $f_c \gg 0$



The bandwidth of this passband signal is $2W$

Examples of passband signals:

- AM (Amplitude-modulated) radio signals have bandwidth ≈ 10 kHz around $f_c \approx 1$ MHz
- Transmitted signals in a WiFi network have bandwidth ≈ 20 MHz around $f_c \approx 2.4$ GHz



$X(f) = T\, \mathrm{sinc}(\pi f T)$

$rect(t/T)$ is the rectangular pulse, which is 1 for $-\frac{T}{2} \le t \le \frac{T}{2}$, and 0 elsewhere. What is its bandwidth?

Bandwidth – A sensible definition?

Many real-world signals are time-limited

$\Rightarrow$ These *will not* be strictly limited in frequency

The absolute bandwidth of $rect(t/T)$ is ∞.

Other, more practical, definitions of bandwidth:

1. 90% bandwidth: The range of frequencies which contain 90% of the energy of the spectrum
2. 3-dB bandwidth: The range of frequencies which contain 50% of the energy of the spectrum
3. *Null-to-null* bandwidth: The width of the "main lobe" of the spectrum for the rect signal

- The "main-lobe" bandwidth of $rect(t/T)$ is $\frac{1}{T}$
- If we also include one side-lobe, bandwidth of $rect(t/T)$ is $\frac{2}{T}$

Thus, bandwidth is a measure of the *extent of significant spectral content* of the signal

Bandwidth is a scarce resource, especially in mobile (cellular) communication:

- Wireless bandwidth licensed and regulated by OFCOM
- A company has to buy a slice of spectrum, say few tens of MHz around $f_c \approx 2$ GHz, and restrict its transmitted signals to *within* the spectrum
- Passband 4G spectrum of few tens of MHz auctioned for hundreds of millions of £ to telecom companies!

Wired channels such as telephone lines and USB cables act like linear systems or *filters*:

- Their transfer function is roughly flat over a band of frequencies $[-W, W]$ around 0, and then attenuates to 0 for higher frequencies.
- Therefore, transmitted signals need to be bandlimited to W

In both wired and wireless communication, need good Tx + Rx designs that make optimal use of available bandwidth

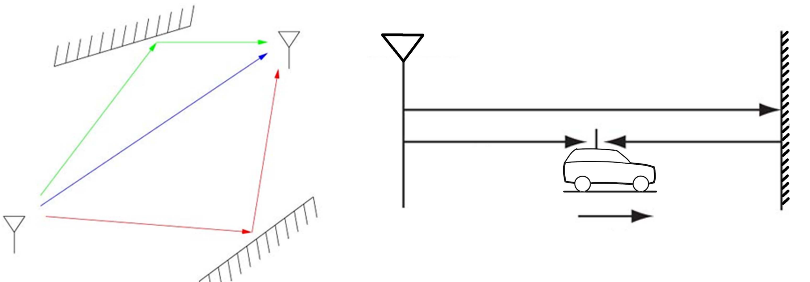
Communication Channels

What is a channel?

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

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

Some Real-world Channels



From "Fundamentals of Wireless Communication", Tse and Viswanath, CUP 2005

1. Mobile Wireless Channel:
   - There is distortion of the signal caused by multipath propagation and mobility
   - Exact type of distortion depends on the signal bandwidth
2. Optical Fibre Channel:
   - Very large BW, cheap production, low attenuation
   - Cons: dispersion of optical pulses, expensive regenerators reqd.
   - Used in the core of the internet, for long-distance communication networks
3. Electrical Wire Channel:
   - Twisted pair cables (e.g., Ethernet) have limited bandwidth, high attenuation; Cheap, used for short distances

Modelling a channel

KEY Q: How to model a channel ?

Channels are often modelled as *linear systems* with additive noise:

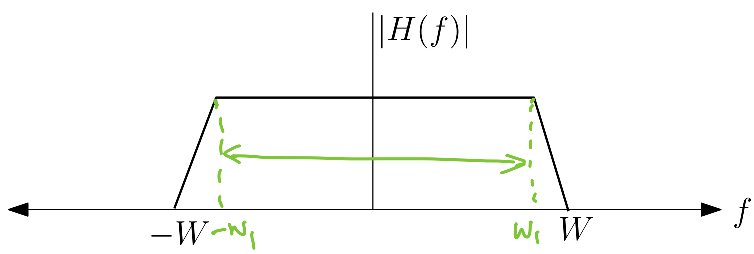
Channel output $y(t)$ generated from input $x(t)$ as

$$y(t) = h(t) \star x(t) + n(t)$$

In frequency domain:

$$Y(f) = H(f)X(f) + N(f)$$

For example, the frequency response of a telephone cable may look like:



Additive Noise Channel

If the input is restricted to the band where the channel $H(f)$ is flat, then the channel is

$$Y(f) = X(f) + N(f)$$

or

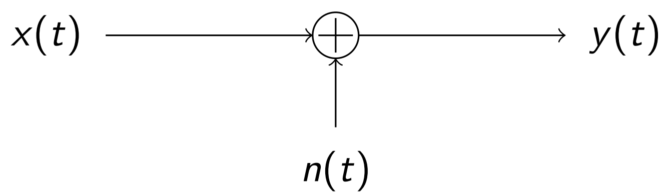
$$y(t) = x(t) + n(t)$$

This is a very popular and useful model. What about $n(t)$?

$n(t)$ is thermal noise at the Rx:

- Thermal noise is the noise generated by the thermal agitation of electrons inside an electrical conductor
- Happens regardless of the applied voltage
- All receivers (WiFi, mobile phone, AM, FM,...) generate thermal noise

Additive Gaussian Noise



Thermal noise $n(t)$ is modelled as a *Gaussian* random process:

- At each time t, $n(t)$ is a Gaussian random variable
- A rigorous description requires knowledge of random processes (in 3F1)

- The additive Gaussian noise channel is the workhorse of communication theory: good model for many real-world communication systems

- Channels whose frequency response $H(f)$ is not flat are important in practice, but outside the scope of this course

In the remainder of the course:

- we will learn how to design both analogue & digital communication schemes (Tx + Rx)
- keeping in mind power and bandwidth constraints
- we'll then study how noise affects the performance of these schemes