Contents

[Lecture on 1.2]

1 Introduction

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1.1 Motivation and Introduction

1. Signals travel without wires

   (a) In this module, signals travel as radio waves
       (optical and acoustic systems ignored)

2. Applications are mostly in communications

   (a) Signals modulated to carry information

   (b) Many familiar applications such as radar, navigation, etc.

> Example: Modern smart phone has approximately 9 distinct wireless systems. Try identifying them?
>
> - NFC
> - Cellulars
>   - 2G
>   - 3G
>   - 4G
>   - 5G
> - GPS
> - Bluetooth
> - WiFi
> - UWB
> - Lidar

Advantages of Wireless

- Mobility
- Good for one-to-many transmissions
- Cheap

Increasingly used for high capacity point-to-point links (cheaper than wired) (e.g. to serve remote areas)

Advantages of Wired

- Very little leakage
- No interference
- Multiple systems can operate adjacently without issue

but considerably more overheads. Suitable for super high capacity lines (eg. fibre-optic transatlantic cables)

1.2 The Wireless Spectrum

The EM spectrum is a shared and limited resource.
Mostly regulated by government agencies.

Frequencies must be carefully given out, but can be reused at different locations as we will see.

Overview of a wireless system:

- Start with raw data
- Source coding (compression)
- Channel coding (error detection & error correction)
- Modulation
- TX
- RX
- Demodulation
- Channel decoding
- Source decoding

This module is mainly about modulation and TX/RX, the rest is information theory.

1.3 Assessment & Delivery

Component	**Timing**	**Weight**
Lab Assignments	Varied (3 labs)	25%
Online BS quizzes	?	25%
Final Exam		50%

- Lab 1: Receiver architectures
- Lab 2: Phase-Locked Loops
- Lab 3: Amplifiers

Open book final with emphasis on design and problem solving

1.4 Module Outline

- (1) Radio Link Design
  - Link budget?
  - How far? How much power?

- (2) Non-Linear System
- (3) Frequency Generation and Synthesis
- (4) Transmitter Design
  - Requirements and specifications
  - Transmitter architecture choices
- (5) Noise
  - Sources of noise
  - Noise analysis, low-noise design
- (6) Receiver Design
  - Requirements and specifications
  - Receiver architecture choices
- (7) Transceiver Design
  - Transmitter and receiver combined!
- (8) Antennas and Propagation
  - Review of antenna theory
  - Practical antennas and propagation of radio waves
- (9) System-Level Issues and Examples

1.5 Textbooks

Purely optional, module notes should be sufficient.

- "Microwave and RF Design of Wireless Systems"
  by David M. Pozar
- "Antennas"
  by John D. Kraus

[Lecture on 1.3]

1.6 Basics of Wireless Communication

Amplifier to increase signal power enough to drive the antenna

Multiple Access

- CSMA: Listen to the channel, send if it's clear
- FDMA: Frequency divided MA
- TDMA: Time divided MA

You require a 'guard band' between frequency bands where no data is sent to avoid interference

CDMA is a good way to overcome this waste, ODMA is an even better approach

1.6.1 Main components of a transmitter

- Signal is 'mixed' (modulated) with an oscillator at the frequency of the channel being used
  - The frequency has to be adjustable to allow for different channels
- A power amp is required to power an antenna

Amp goes first because high-frequency amplification is a fucking nightmare

1.6.2 Main components of a receiver

Signal arrives on an antenna (which collects EM waves in the vicinity, sometimes in a preferred direction, and puts them on a cable, waveguide, or circuit board track)

RX:

- Receive at very low power
- Select and amplify the desired signal
- Estimate the original signal

The signal is too weak to demodulate, so you need a high-frequency amplifier before the demodulator.

For most of this module, we will look at block-level circuits and not worry about precise circuit design.

Channel capacity (Shannon-Hartley): $C = B \times \log_2(1 + \frac{S}{N})$

- C is channel capacity (eg. bits per second)
- B is bandwidth (Hz)
- $\frac{S}{N}$ is the signal-to-noise ratio

Cellular:

- 2G operated at 800-900 MHz and 64 kHz channels
- 3G operated at 1-2 GHz and got 8 MHz channels

- 4G operates at up to 5 GHz and 50-100 MHz channels
- 5G has channels up to 10 GHz

The increase in speed is partially due to better MA schemes, but mainly due to the bigger bandwidth.

Other options to increase capacity:

- Increase SNR
  - Increase power (limited by regulations)
  - or reduce noise (choose a frequency with less background?)

2 Basic Antennae & Propagation

2.1 Basic Antennae

Radio link design

- What will be the power at the receiver (or SNR)?
- How far away can the antennae be?
- How much power is needed?

Answers culminate in a *link budget* calculation

Antennae

- Circuitry generates the signal and amplifies to high power
- High power signal goes along a 'feed track'
  - Very little losses here
- Then into the antenna
  - Can be directed, but not guided, so loses power quickly
  - Not all power is radiated, some is lost

[Lecture on 1.5]

Antenna Power

Ignoring free space losses

- Assume total power remains constant as it propagates
- but spreads over a larger area (inverse square law)
- Consider *power density* in W/m^2

With space losses

- Model with a 'propagation constant' $\gamma \geq 2$
- $\frac{\text{Power density at distance } r_2}{\text{Power density at distance } r_1} = \frac{r_1}{r_2}^\gamma$

Isotropic Reference Antenna

- Assume a point source
- Radiates in all directions uniformly
- 100% of input power is radiated

Not possible but useful for comparison purposes

Omni-directional Antenna

- Similar model but losses are allowable
- I npractice only possible in one plane

Antenna Gain

- Antennae are not amps - they don't actually have gain.
- However, a focused antenna delivers more power to the receiver than an isotropic tradiator, so there is a 'focusing gain'

$$\text{Gain in a particular direction} := \frac{\text{Power density observed in that direction}}{\text{Power density expected from an isotropic radiator}}$$

- Obviously normally measured in the direction of transmission

2.1.1 Receiver Antennae

- Collects electromagnetic waves
- May be directional - sensitive to waves from a certain direction
- Measure the aperture / collection area
  - Some antennae have an obvious physical aperture (eg. parabolic dish)
  - Others have an 'effective aperture' A, such that $P_{RX} = D_{RX}A$ where P_{RX} is the collected power and D_{RX} is the power density of the incoming wave
- Aperture efficiency

- Even those with a physical aperture have an 'effective aperture', which is lower due to losses on the dish
  Aperture efficiency $:= \frac{\text{Effective aperture } A}{\text{Physical aperture}} < 1$
- Always use 'effective aperture', which accounts for dish losses

Reciprocity

- Antennae can TX and RX
  - Same beam and shape each way
- RX gain is equal to TX gain
- One expression for gain based on the aperture is
  $G = \frac{4\pi A}{\lambda^2}$ where λ is wavelength.

[Lecture on 2.2]

2.2 Basic Propagation

- Speed of light in free space

Propagation on Earth

- Curvature of Earth comes into play
- Distance to horizon is given by $d = \sqrt{h(2R+h)} \sim \sqrt{2Rh}$
  where R is Earth's radius and h is the tower height
- For tower-to-tower, you have to consider the height of both towers, the maximum distance between them is the sum of their distances to horizon

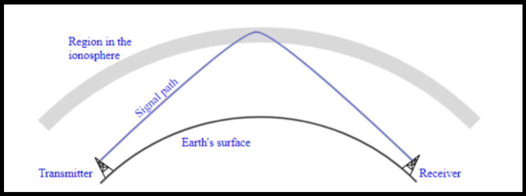
Atmospheric Effects at High Frequency

- Air is less dense higher up so refraction causes high frequency waves to 'bend' downward, which shortens transmission range
- Compensate by pointing TX upward, increasing total range!
- 'Effective' Earth radius R becomes $\frac{4}{3}R$

Atmospheric Effects at Low Frequency

- Between 3 and 30 MHz, strong refraction in ionosphere
- Waves can bend back and return to Earth
- But propagation changes with day/night and season

Cool fact: at 3 Mz, a vertically polarised wave will curve around Earth's surface perfectly (called ground wave propagation, example is the Rugby

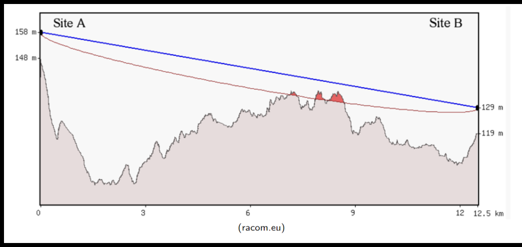


Atomic Clock system)

2.2.1 Free Space Links

Consider a line-of-sight scenario

- Typically ¿ 1 GHz
- Directional antennae on both ends
- No obstructions



This is not a suitable line-of-sight (LOS) path (blue), because the hills are *close* to the LOS, which will cause reflections

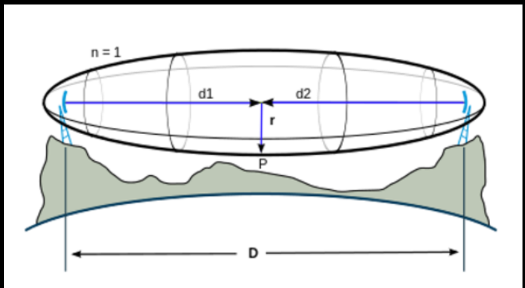
Consider two paths: direct path and reflected path. Calculate the length of each and therefore the phase difference on arrival - if they are 180 degrees out of phase, the signal will be completely destroyed! Reflection causes 180 degree phase switch Okay but isn't signal strength relevant here ? See slide 25 in this chapter

2.2.2 Fresnel Zones

The nth Fresnel zone is the ellipsoid space around transmitters where the length of any reflected path is between $(n-1)\frac{\lambda}{2}$ and $n\frac{\lambda}{2}$ longer than the LOS path.

Accordingly, an object inside the 1st Fresnel Zone would induce a phase difference between π and 2π.

The presence of obstructions in the Fresnel zone will result in *some* parts of the receiving area geting destructive interference



(Wikipedia)

Radius of the nth Fresnel zone at distance d_1 and d_2 is $r_n \sim \sqrt{\frac{n\lambda d_1 d_2}{d}}$

e.g. For a 10 km link at 10 GHz, radius is $\sim$9 m at the centre

An object right at the edge of the Fresnel Zone actually causes constructive interference. It gets more destructive the further it goes in

Okay this makes a lot of sense but I'm losing track of the Fresnel 'layers' - is the boundary of the 2nd zone constructive or destructive ? Need to get a pen and paper and just figuer that out

Assume the reflecting surface is parallel to the LOS (anything else isn't relevant ig?)

An object in the very centre of the Fresnel Zone (parallel to the LOS) will cause perfect destructive interference (because the reflection itself causes a phase flip, and the path length will be the same)

We normally allow objects to be up to 20% into the Fresnel zone

2.2.3 Non-Free Space Links

- In an indoor or urban landscape, there are way too many reflecting paths to use rely on Fresnel zones
- Variation may be rapid (e.g. high-speed trains in the way)
- LOS may not exist
- Different paths with different lengths

3 Link Budgets

Contents

3.1 Computing the RX Signal Power

EIRP: Effective Isotropic Radiated Power A measure of local signal strength that answer this question: If the transmitter were an isotropic radiator (in the same place the actual antenna is), how powerful would it need to be for us to be receiving at this strength? Measured as a power (Watts or dBW or similar)

[Lecture on 2.5]

3.2 Working with Decibels

Decibels (dB) define a *ratio* of powers, not a power value (though dB is sometimes used as shorthand for dBW, confusingly)

$G[\text{dB}] = 10 \times \log\frac{P_1}{P_2}$

- **dB**: Measure of power ratio, between two powers
- **dBW**: Measure of power value, with a reference denominator of 1 W
- **dBm**: Measure of power value, with a reference denominator of 1 mW

e.g.

- 10 dB corresponds to a tenfold increase in power
- 20 dB corresponds to a hundredfold increase in power

- 0 dBW = 1 W
- 10 dBW = 10 W
- 20 dBW = 100 W

Summing decibel values is equivalent to *multiplying* gain factors.

You should never sum dBW

You can sum dB with dBm or dBW to get another value in dBm or dBW, equivalent to applying a gain factor to an absolute power value.

3.2.1 Power Spectral Density

People get this wrong a lot.

- Has units W/Hz
- Continuous spectrum of values at different Frequencies
- Often converted to dBW/Hz or dBm/Hz

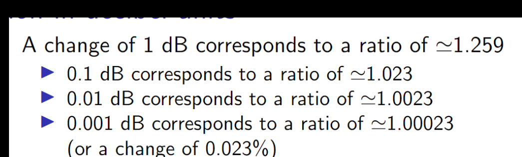
e.g. White noise has a flat PSD (by definition), often assumed to have value

$N_o = -174$ dBm/Hz

Therefore in a 100 Hz bandwidth, there is -154 dBm of noise

(not an intuitive calculation, you can't simply multiply because that's equivalent to summing a series of dBm values)

3.2.2 Precision in Decibel Units



Usually only use one (or two) decimal places in dB to avoid excessive precision

[Lecture on 3.2]

TODO go back through notes on modelling nonlinear systems and type up some notes

[Lecture on 3.3]

4 Nonlinear Systems

Nonlinearity of your amplifier can introduce harmonics to your signal (reflecting clipping in the time domain).

Superposition may not apply. If two frequencies are sent together through a nonlinear system, the result will not necessarily be the superposition of their individual results.

Extra frequencies get added - 'intermodulation products'. These are difficult to filter out as they may be very close to our desired frequencies.

Nonlinearity of amplifiers can be modelled by describing the amps behaviour using a polynomial with voltage input. The amp specs should give coefficients for this polynomial. For small v_{in}, the higher-order terms become negligible.

You can use trig to expand out $cos^2(\omega t)$ into $0.5+0.5cos(2\omega t)$. Repeating this for other terms gives a set of frequencies at harmonics of the fundamental.

$$
\begin{aligned}
v_{out} = & \overbrace{\sum_{\substack{n=0 \\ n \text{ even}}}^{N} b_n A^n \frac{1}{2^n} \binom{n}{\frac{n}{2}}}^{\text{DC term}} + \overbrace{\sum_{\substack{n=0 \\ n \text{ odd}}}^{N} b_n A^n \frac{1}{2^{n-1}} \binom{n}{\frac{n-1}{2}}}^{\text{Amplitude of Fundamental}} \cos(\omega t) + \\
& + \underbrace{\sum_{\substack{n=2 \\ n \text{ even}}}^{N} b_n A^n \frac{1}{2^{n-1}} \binom{n}{\frac{n}{2}-1}}_{\text{Amplitude of 2}^{\text{nd}}\text{ Harmonic}} \cos(2\omega t) + \underbrace{\sum_{\substack{n=3 \\ n \text{ odd}}}^{N} b_n A^n \frac{1}{2^{n-1}} \binom{n}{\frac{n-3}{2}}}_{\text{Amplitude of 3}^{\text{rd}}\text{ Harmonic}} \cos(3\omega t) \\
& + \ldots \text{terms up to N}^{\text{th}} \text{ harmonic} \ldots
\end{aligned}
$$

4.1 Narrowband Models

Characteristics for evaluating an amp:

- 1 dB Compression
- Multiple Input Signals
- 3rd Order Intercept Point (IP3)
- Higher order intermodulation products

Example Simple NL Amp

$$v_{out} = b_0 + b_1 v_{in} + b_2 v_{in}^2 + b_3 v_{in}^3$$

$$b_0 = 0$$
$$b_1 = 10$$
$$b_2 = 0$$
$$b_3 = -0.8$$
$$R_{in} = 50\Omega$$
$$R_{out} = 50\Omega$$

Typical amps, b1 and b3 have opposite sign to get an S-shape