TM355: COMMUNICATIONS TECHNOLOGY
BLOCK 1

PART 3:
NOISE, INTERFERENCE AND COEXISTENCE

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OUTLINE

- Introduction
- Noise and interference
- Mobility and urban environments
- Noise and signal power
- Noise and data rate
- Noise and bit error rate
- Spectrum management

1. INTRODUCTION

- So far, this block has mostly considered communications links as isolated systems.
- However, this is an idealisation; the reality in practical communications systems is that **noise and interference are always present and can adversely affect performance**.
- <u>This final part of Block 1</u> focuses on the effects of noise and interference in real-world communications.

2. NOISE AND INTERFERENCE [1/4]

- **Examples of interference:**
  - Interference from unwanted stations on AM or FM radio.
  - Mobile phones interference with unrelated equipment radio transmitter.
  - Domestic appliances or power tools.
  - Natural sources of noise including electrical storms and the effects of the sun.
  - Noise generated within the receiver.

2. NOISE AND INTERFERENCE [2/4]

- The terms ‘noise’ and ‘interference’ are sometimes used interchangeably or lumped together
- However, a distinction can be made:
  - **Noise**: from natural sources, which tends to be unavoidable.
  - **Interference**: from unwanted transmissions.

2. NOISE AND INTERFERENCE [3/4]

- **How might mutual interference be avoided?**
  - Use two different frequencies
    - However, the amount of spectrum available is finite, so there is a practical limit to the number of transmitters that can transmit at the same time.
  - If the two transmitters are in separate places, then we may use the same frequency
  - Transmit at different times
  - Design of antennas
    - Different polarisations (horizontal and vertical).
    - Directional antennas could be used to beam the transmissions in different directions .

2. NOISE AND INTERFERENCE [4/4]

- To mitigate the causes and effects of interference, **electromagnetic compatibility (EMC) is a major factor in the design of electrical goods**.
- Standards must be complied with concerning two key areas:
  - **emissions** – the amount of power a device is allowed to radiate at different frequencies is limited.
  - **immunity** – the device must function normally in the presence of radio waves up to a certain power at different frequencies.

3. MOBILITY AND URBAN ENVIRONMENTS

- Noise and interference from sources outside the communications link are not the only factors that affect communications in the real world.
- **Urban environments present particular difficulties in radio propagation at VHF and above, <u>due to the large number of obstructions and reflecting surfaces.</u>**
- Two types of fading are commonly distinguished: **slow fading** and **fast fading**.

3.1 FADING [1/3]

- **The terms 'slow' and 'fast' here relate to how quickly the signal changes as the receiver or transmitter moves around.**
- **Fast fading**: the changes happen with only a small change in position.
- **Slow fading**: a larger movement is needed to have an effect.
- Both slow and fast fading are due to obstacles and reflections.

3.1 FADING [2/3]

- The variation in power in slow fading can be modelled by a log-normal distribution.
- Note: the variation due to slow fading is additional to any power variation due to the inverse fourth-power law.

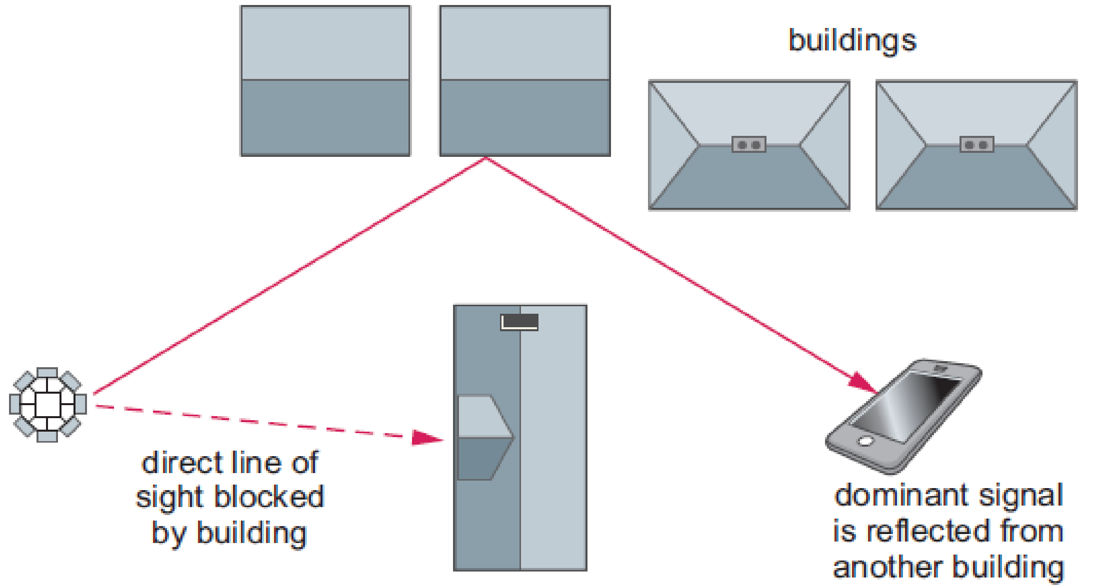

Figure 3.2 Slow fading

3.1 FADING [3/3]

- Fast fading: the mobile phone receives reflections from two different buildings.
- When two waves come together having travelled along paths of different lengths, **they may reinforce each other, or cancel out, or the effect could be somewhere in between.**
- When there is **no line of sight**, as with Figure 3.3, the **Rayleigh distribution** is a good approximation.
- When there is a **predominant line-of-sight signal**, the **Rician distribution** is used.

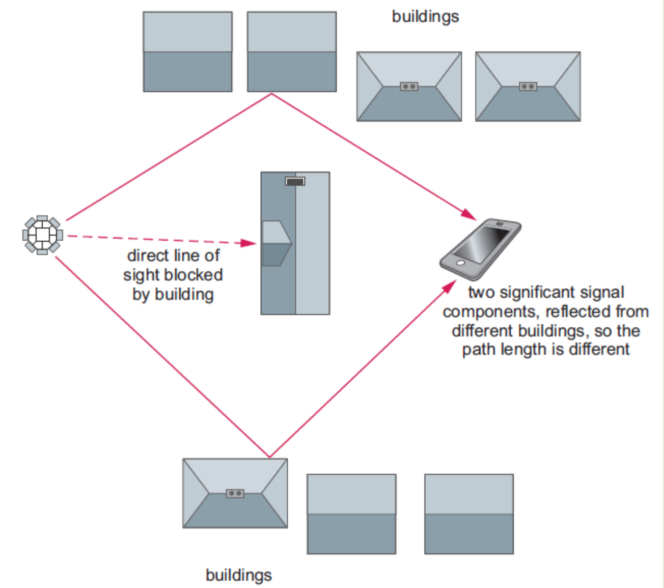

Figure 3.3 Fast fading

3.2 DOPPLER SHIFT

- **Doppler shift**: occurs when radio receivers in vehicles suffer from a problem **due to their speed** causing a **shifting of frequency** when a transmitter and receiver are moving relative to each other.
  - When they are **moving towards each other**, the received signal is **higher in frequency** than the signal transmitted, and when they are **moving apart, it is lower**.

$$\Rightarrow f_r = f_t\left(1 + \frac{v}{c}\right)$$

- Orthogonal frequency-division multiplexing (discussed in Block 3) uses a large number of narrow-band subcarriers, and Doppler shift places a practical limit on how closely they can be spaced.

3.3 FREQUENCY REUSE [1/2]

- Mobile communications networks illustrate how sometimes a restricted range of propagation – as characterised by the **inverse fourth-power law – can actually be a benefit, because frequencies can be reused.**
- Suppose the transmitting power of a base station is sufficient to serve mobile devices up to 1 km away with an adequate signal.
- If an **inverse square law** applied (as in free-space propagation) then **at 5 km** from the base station, the received power would be 1/25 as much as it was at 1 km.
- But with an **inverse fourth-power** law, the received power at **5 km** would be only 1/625 of the power at 1 km.

3.3 FREQUENCY REUSE [2/2]

- **Another aspect** of propagation that is exploited in mobile communications is the **use of directional antennas.**
  - **The area covered by a base station may be divided into sectors**, with a directional antenna covering each sector.
    - A mast can be placed at a point where three cells join up, with each antenna serving a different cell.

3.4 MULTIPLE ANTENNAS AND MIMO [1/4]

- **Question**: Can performance be improved by using more than one antenna?
- **Answer:** there are a number of benefits that can be obtained by using multiple antennas at the transmitter, at the receiver or at both, though at the cost of increased complexity.
- Arrays of antennas have long been used at the transmitter or receiver to increase gain and/or to achieve desired directional properties.

3.4 MULTIPLE ANTENNAS AND MIMO [2/4]

- **Because the signals received at multiple antennas are likely to differ in quality, it would make sense to select the best one**, so that if one signal suffers from fading then a better one is chosen to take over.
- **Another approach is to combine all the received signals in some way**, so that no contribution goes to waste.
  - Unfortunately, **it is not enough simply to add the signals together,** as the **amplitudes and phases would differ** and so the signals could destructively interfere with each other.
  - However, the signals **can be combined effectively by more sophisticated digital signal-processing techniques**.

3.4 MULTIPLE ANTENNAS AND MIMO [3/4]

- **Beam steering**: also called beamforming, is a technique that uses multiple transmitter antennas.
- It is **used when communicating with a single receiver**, and its purpose is to improve reception at this target device.
- In this technique, the **relative amplitudes and phases of the signals from each antenna are adjusted** so that when they arrive at the target receiver, they **add** together **constructively**.
- This **increases the strength** of the received signal and provides some **resistance to fading**.

3.4 MULTIPLE ANTENNAS AND MIMO [4/4]

- **Multiple Input Multiple Output (MIMO)**: uses **multiple antennas at both the transmitter and the receiver**, with a consequent increase in the number of paths available.
  - **Applications**: **LTE (4G)** for mobile telephony and **IEEE 802.11ac** and **802.11n (WiFi)** for wireless networking.

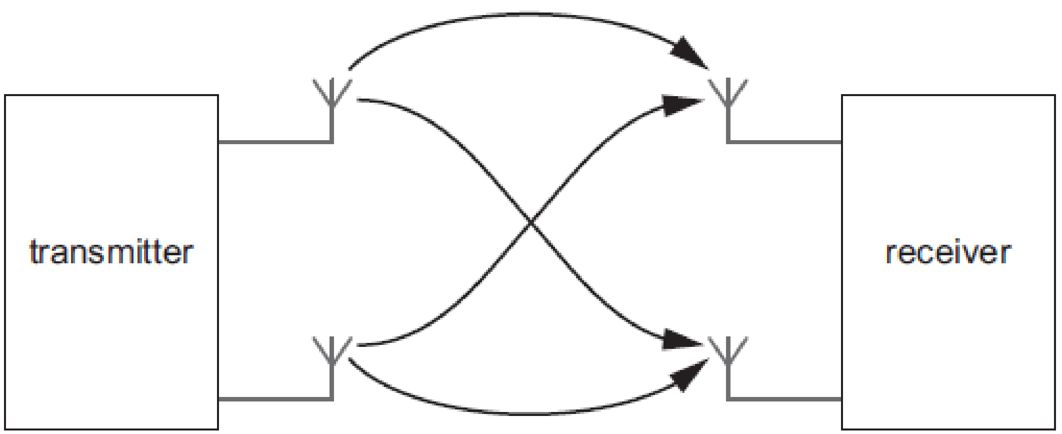

Figure 3.5 MIMO system with two antennas at the transmitter and two at the receiver

4. NOISE AND SIGNAL POWER
4.1 POWER CALCULATION [1/2]

- Most sources of noise and interference also have continuous spectra, though some have well-defined frequencies.
- The total amount of power in a signal can be measured in watts.
- Figure 3.6 shows an example in which a total transmitted power of 100 mW is spread evenly over a portion of spectrum.

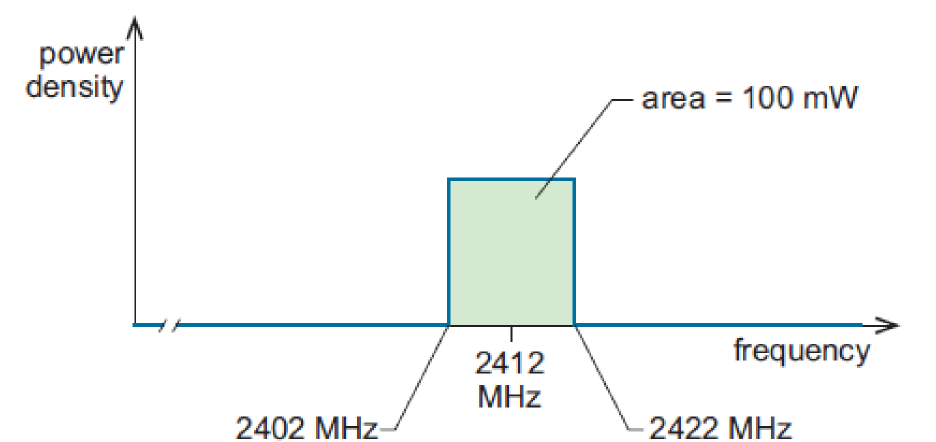

Figure 3.6 Simplified power distribution

4.1 POWER CALCULATION [2/2]

- In Figure 3.6 the vertical or y-axis is not power, but power density:

$$\boxed{\textbf{Power density=Power/Bandwidth}}$$

- The total power of 100 mW is represented by the area under the graph.
- Since the power is spread over a bandwidth of:

  2422 MHz – 2402 MHz = 20 MHz

➔ the power density = 5 mW/MHz.

4.2 SIGNAL-TO-NOISE RATIO [1/2]

- **The signal-to-noise ratio** (or S/N ratio, also abbreviated to SNR) is the signal power divided by the noise power.
- The higher the signal-to-noise ratio, the less the signal is affected by noise – and furthermore, as it turns out, the higher the data rate that can be obtained.
- Because it is a ratio of two powers, signal-to-noise ratio can be expressed either as a simple ratio or in decibels.

4.2 SIGNAL-TO-NOISE RATIO [2/2]

- Figure 3.8 shows a signal spectrum and a noise spectrum.
- Of the three receivers, **receiver B would be the best one to use.**
- Receiver A could lose data because it would not receive all the frequency components in the signal, and receiver C would allow through more noise than necessary.

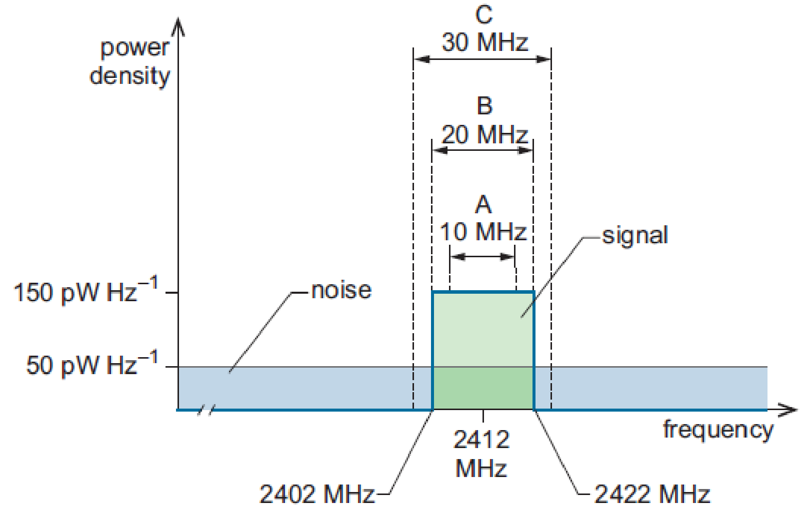

Figure 3.8 Power densities of a signal and noise, with passbands of three receivers

4.3 THE EFFECT OF NOISE ON DATA AND ERROR RATES

- Increased noise power would make errors more likely.
- If the set of symbols is large, then the chance of misinterpreting a symbol is also increased.
- By, increasing the signal power the chance of errors is reduced, as the symbols will be more different from each other and less likely to be misinterpreted.

5. NOISE AND DATA RATE
5.1 THE SAMPLING THEOREM [1/2]

- The sampling theorem is a fundamental result in communications theory.
- Assume that the spectrum of the signal to be sampled has frequency components ranging from zero to $\boldsymbol{f}$ Hz.
- **The sampling theorem states that** the signal can be exactly reconstructed from its samples (at least in principle) if the samples are taken at a rate exceeding $\mathbf{2}\boldsymbol{f}$ samples per second.

5.1 THE SAMPLING THEOREM [2/2]

- Figure 3.9(a) shows a sine wave sampled at **a rate less than $2f$.**
- Figure 3.9(b) shows the samples on their own.
- Figure 3.9(c) shows what could happen if an attempt at reconstruction **was made using Figure 3.9(b)**.
- It is clear that Figure 3.9(c) is entirely different from Figure 3.9(a).

➔ This effect is called aliasing.

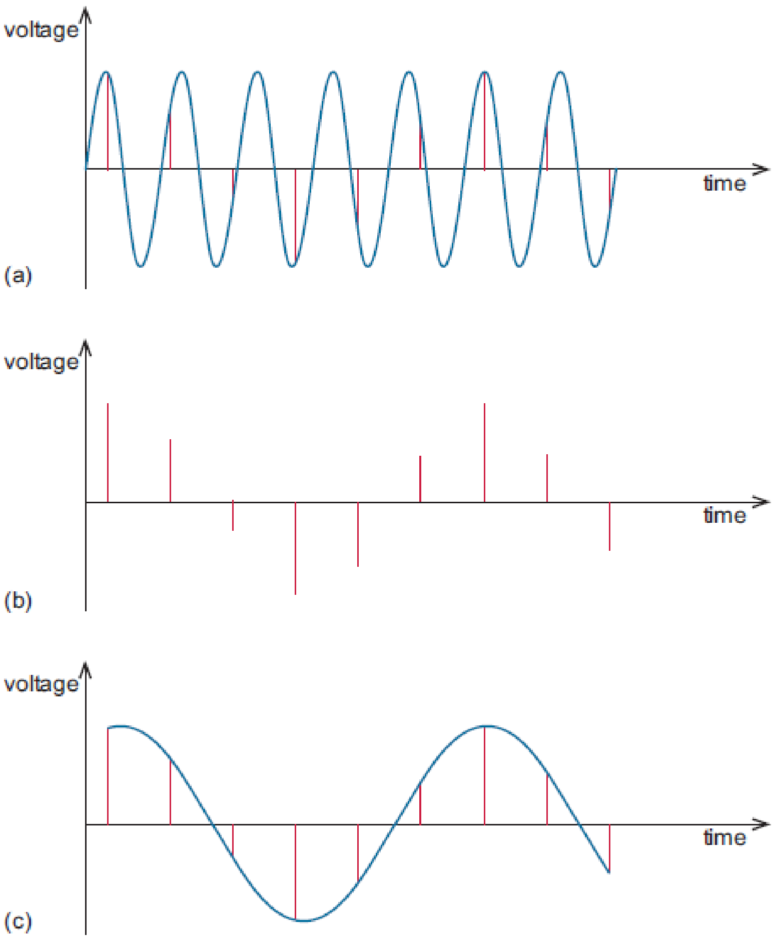

Figure 3.9 Aliasing: (a) sampled sine wave; (b) the samples; (c) reconstructed signal

5.2 DATA RATE IN A NOISE-FREE CHANNEL [1/3]

- The sampling theorem, or variants of it, was formulated independently by a number of people, notably Kotelnikov and Shannon.
- The figure of twice the bandwidth is often referred to as the '**Nyquist rate**'.
  - After Harry Nyquist (1889–1976), an electronics engineer who made significant contributions to early communications problems and information theory.

5.2 DATA RATE IN A NOISE-FREE CHANNEL [2/3]

- **Nyquist's key result can be stated as follows:**

  "The maximum rate at which symbols can be sent through a noise-free channel is $2B$ <u>symbols per second</u> (where B is the bandwidth of the channel in Hz)."

- The maximum data rate, D, in <u>bits per second</u> in a noise-free channel with bandwidth B and a set of M symbols is given by:

$$D = 2B\ log_2 M$$

➔ *To find the data rate in <u>bits per second</u>, the symbol rate is multiplied by the number of bits that can be represented by a single symbol.*

5.2 DATA RATE IN A NOISE-FREE CHANNEL [3/3]

- **Remember:** if number of bits per symbol, ***n***, given by a set of ***M*** different symbols then:

$$n = log_2 M$$

  - 16-QAM, which has $2^4 = 16$ different symbols, can send four bits as one symbol.
  - 64-QAM, with $2^6 = 64$ symbols, can send six bits.

- **Example:** if the bandwidth is 10 kHz then, 64-QAM can support a maximum data rate of:

2 × 10 000 Hz × 6 = 120 000 bits per second= 120 kbit/s

(Note: $log_2(64) = 6$ (or $2^6 = 64$)).

5.3 DATA RATE IN A NOISY CHANNEL

- It may appear from Nyquist's formula that the data rate could be increased indefinitely just by increasing the number of different symbols in the set.
- Remember, though, that this is for a noise-free channel.
- **As the number of symbols increases, the more difficult they are to distinguish, and the more susceptible they become to corruption by noise.**

5.3.1 SHANNON'S EQUATION [1/3]

- The incidence of errors can be reduced in various ways:
  - by using error-correcting coding,
  - or reducing the data rate,
  - or increasing the signal power.
- How low the data rate needs to be is given by a result discovered by Claude Shannon (1916 – 2001)
  - *A cryptographer and electronics engineer who made important contributions to the field of information theory.*
- He showed that there is a theoretical maximum rate at which data can be transmitted in a noisy communications channel at an arbitrarily low error rate.

5.3.1 SHANNON'S EQUATION [2/3]

- This is expressed mathematically as:

$$\boldsymbol{C = W\ log_2\ (1 + S/N)}$$

  - $\boldsymbol{C}$ is the theoretical maximum channel capacity, measured in bits per second.
  - $\boldsymbol{W}$ is the bandwidth of the channel, in hertz.
  - $\boldsymbol{S}$ is the signal power and $\boldsymbol{N}$ is the noise power, so that $\boldsymbol{S/N}$ is the signal-to-noise ratio.
- **Note:** $log_2(x) = \frac{log_{10}(x)}{0.301}$.
- **Note** also that while bandwidth is often denoted as B, W is the notation used by Shannon.

5.3.1 SHANNON'S EQUATION [3/3]

- An example of Shannon's equation in action is provided by space probes, which send data from millions or even billions of kilometres away from Earth.
- The transmitters are modest in power, typically around 20W.
- **As energy supplies are limited, several techniques are used to get the best possible *S/N* ratio:**
  - The antenna at the probe is designed to have a very high gain and is pointed at the Earth. Even so, the amount of power reaching any particular location on Earth is tiny.
  - The receiving antenna is a dish antenna with a large collecting area. Even so, the signal power collected may be only femtowatts (10^{-15} W) or less.
  - The noise generated at the receiver is kept to a minimum.

6. NOISE AND BIT ERROR RATE (BER)

- A noisy channel, perfectly error-free communication is not attainable in practice.
- At the most basic level, this means that noise and interference can cause a demodulated received bit to differ from the original transmitted bit.
- The BER is the number of bits received in error divided by the number of bits transmitted in total.

7. SPECTRUM MANAGEMENT [1/2]

- Because there are so many competing uses of the radio spectrum, there is a need for some planning.
- Users of the spectrum include not only broadcasters, and mobile phone networks, but also:
  - Radar and radio-navigation
  - Meteorological
  - Earth-exploration satellites
  - Radio astronomy
- As radio waves cross borders, the effect on neighbours must be taken into account.
  - A radio broadcaster may wish to operate a high-power transmitter to obtain good coverage all over the country, but it could interfere with services in neighbouring countries.

7. SPECTRUM MANAGEMENT [2/2]

- When allocating services to different parts of the spectrum, a number of technical issues should be considered:
  - **Line-of-sight**.
  - **Long-distance** terrestrial communication, using the surface wave or the sky wave, is **limited to the lower frequency bands**.
  - **It is not possible to accommodate wide bandwidths in low-frequency bands**.
  - Communication between a **satellite and the ground** requires a **window through the atmosphere where absorption is low** and the ionosphere is transparent.
  - **Transmitters and receivers** for the highest frequencies **present** significant engineering **challenges**.