A-Level Electronics ELEC5 Notes

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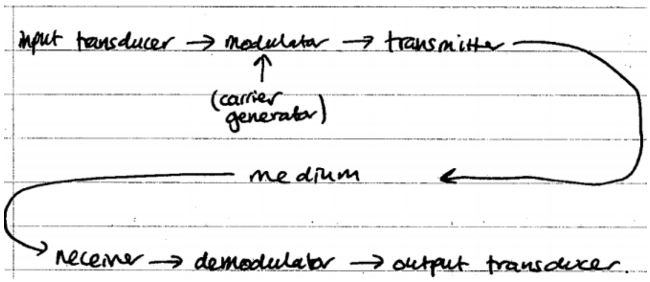
1 General principles



Generalised Telecommunications System

1.0.1 Transmission media

- electrical signals along cables (metallic path)
- electromagnetic radiation in the form of light through optical fibres
- electromagnetic radiation in the form of radio waves through free space

1.0.2 Cables

- Factors affecting choice of cable:
  - Impedance — opposition to the flow of alternating current, consisting of both reactive and resistive parts
    - will also depend upon capacitance between conductors; inductance of the wires and frequency
    - need to match the impedances of the transmitter, cable and receiver to minimise energy loss
  - Inductive linkage with adjacent cables — the flux linkage between two cables carrying alternating currents can lead to an effect called crosstalk: a form of noise where unwanted signals are transferred to other circuits

The signals passed along a twisted pair are differential — this means that the magnetic & electric fields produced by one conductor are cancelled out by those resulting from the other, minimising any radiated signal and so reducing crosstalk (this is also the aim of the twisting together of the conductors). The receiver is only sensitive to the differences between the two wires' signals — noise or interference is induced equally in both wires and so is cancelled out.

As the frequency of the a.c. through a conductor increases, the current begins to pass more through the outer of the conductor and less through the centre. This 'skin' effect leads to the increasing of impedance with frequency. To counter this effect we can use coaxial cable.

Coaxial cable consists of an inner conductor and an outer braid, separated by a dielectric. It performs better at high frequencies than twisted pair, but can be bulky when designed for higher frequencies. The ability of coaxial cable to confine a signal is dependent on the quality of the braid — cheaper cables tend to be lossier, with the effect more noticeable at higher frequencies.

1.1 Multiplexing

Multiplexing is a way of sending multiple signals along a medium so as to maximise the available bandwidth of the medium.

Frequency division multiplexing In frequency division multiplexing we transmit signals on different carrier frequencies, then use filters at the receiver to isolate the wanted signal.

Time division multiplexing Multiple signals are sent along the same medium on the same frequency (where applicable) by dividing them in the time domain. Each signal is sampled periodically and is transmitted in its own specific time slot. The receiver then combines the data and decodes it to obtain the original signal

1.2 Distortion and noise

Distortion Distortion is the alteration of a signal waveform as a result of signal processing. 'Clipping' is seen where an amplifier is overloaded and saturates. Where the shape of a square wave becomes rounded, this is a sign of poor high frequency response.

Distortion has the effect of introducing frequencies to the signal spectrum which were not in the original, and makes the signal bandwidth greater which can lead to interference with adjacent signals in a frequency multiplexed system.

Noise Noise is the addition of unwanted (often random) electrical energy to a system.

- Channel noise is added as a signal passes through a medium
  - crosstalk
  - cosmic noise
  - fluctuation noise from natural sources such as electrical storms or man-made sources such as electric motors and spark plugs
- thermal, or Johnson noise is produced by resistors and increases with temperature
- Active devices produce shot noise when electrons pass through semiconductor junctions
- Some media are immune to certain types of noise e.g. optical fibres do not suffer from crosstalk as there is no induced magnetic field thanks to the lack of a conductor

$$\text{signal to noise ratio in dB} = 10 \log \frac{P_{\text{signal}}}{P_{\text{noise}}}$$

1.3 Optical fibres

An optical fibre consists of a core, which provides a medium through which light rays can travel, surrounded by a cladding which is of lower refractive index. The cladding helps ensure that total internal reflection (TIR) occurs, and also protects the core from scratches which would allow light to radiate out of the fibre.

Light rays in an optical fibre as totally internally reflected in the fibre so long as the angle of incidence is greater than the critical angle — it is for this reason that fibre optic cables have a minimum bend radius: if a bend is too sharp, light may be incident at less than θ_C and so refract out of the fibre.

1.3.1 Attenuation

Attenuation is the reduction in amplitude of a signal as it passes through a medium. There are several causes of this effect in optical fibres:

- Absorption occurs due to the presence of impurities in the glass
- Scattering — the amorphous (non-crystalline) structure of glass leads to Rayleigh scattering, which is more pronounced at short wavelengths
- Radiation takes place where there are sharp bends in the fibre or joints are misaligned

1.3.2 Dispersion

Dispersion leads to the broadening of the signal pulses and loss of definition of their shape.

- Material dispersion: different frequencies of light travel at different speeds through the fibre. Fixed by using monochromatic light.
- Modal dispersion: light can take multiple paths through a fibre and so takes different lengths of time to travel the length of the fibre. It is fixed by using monomode fibre, which has a very narrow core of the same order of magnitude as the wavelength of the light such that there is only one path. Could also use graded index fibre instead.

1.3.3 Transmitters and detectors

For optical communications there are two possible light sources: the light emitting diode (LED) and the semiconductor laser.

- Semiconductor lasers are better transmitters as:
  - greater intensity than LED
  - can be switched on and off more quickly
  - much closer to monochromatic
  - smaller beam width making it easier to focus
- Lasers are more expensive than LEDs but must be used in high bit rate systems or where monomode fibres are employed.

Photodiodes are commonly used as detectors: the principal one being the PIN (positive intrinsic negative) avalanche photodiode.

- Photodiodes have optimum wavelengths of light to which they respond
  - the thickness of the p-type layer is determined by the wavelength to be detected
- The capacitance of the p—n junction depends on the thickness of the variable depletion region. Increasing the bias voltage increases the depth of the depletion region and lowers capacitance.
  - capacitance of the junction helps determine the maximum rate of pulses that can be detected: for a high speed system the capacitance needs to be low
- When photodiodes are used in forward bias the slow diffusion of the electrons and holes gives rise times of the order of 0.5 μs. In reverse bias 2 ns is possible
  - PIN diode has a very high reverse bias voltage giving very low junction capacitance and a corresponding fast rise time

1.3.4 Advantages of optical fibres over wire systems

- much higher capacity: 10 Gb s^{-1}
- for given capacity, cable smaller, weighs less & cheaper to produce and install
- regenerators can be placed further apart than with metallic path systems
- virtually immune to electromagnetic interference, negligible crosstalk
- good security — difficult to intercept information passing along an optical fibre
- provides electrical isolation

2 Digital communication

Digital signals have only two values, whereas analogue signals vary continuously with time between certain limits.

- Advantages of digital:
  - can be transmitted over longer/noisier channels as it can be <u>regenerated</u> — noise is removed as original pulses are identified and reproduced
  - digital signals are used by many data processing systems so very convenient
  - multiplexing is simpler
  - compression & encryption possible
- Disadvantages:
  - need greater bandwidth
  - more difficult to process than analogue

2.1 Pulse code modulation

- Analogue information is sampled at a rate at least twice the highest information frequency — 'sample and hold' circuit used.
- Output from sampler is is pulse amplitude modulated (PAM) signal
- PAM signal is than quantised using an ADC
- Quantised signal goes through a PISO shift register ('digitiser') to give a serial stream of bits
- The difference between the analogue signal and its digital representation is the quantisation error
  - Quantisation error can be reduced and signal resolution improved by increasing the number of bits in the ADC and DAC processes

There are two other types of modulation:

Pulse width modulation In PWM, the pulses representing the sampled signal are all the same amplitude but vary in duration according to the amplitude of the information signal.

Pulse position modulation In PPM, the pulses representing the sampled signal are all of the same amplitude and duration but are delayed by intervals which are proportional to the size of the signal sample. PPM signals can be derived from PWM signals.

PWM and PPM are both relatively immune to noise but do require greater bandwidth than PAM.

2.2 Half and full-duplex communication

In a half-duplex system, information can travel in both directions along the communications link, but not simultaneously. Only one device transmits information at a time, the other device 'listening'. When the transmitting device has sent its information it then becomes a receiver and listens to the information sent.

This method has the advantage that only one transmission medium/communications channel is needed linking the two devices, but has the disadvantage that the transmitting device must finish before the other device can transmit, which can slow down the sending of data over a noisy link where it is necessary for the receiving device to request multiple re-transmissions of the data.

In a full-duplex system, both devices are able to receive and transmit simultaneously. Data can be transmitted much more quickly in a noisy environment as requests for re-transmission can be sent with a shorter delay. The main disadvantage is that usually two completely separate transmission channels are needed.

2.3 Serial vs parallel

Most digital information is now transmitted serially: one bit followed by another, but when all the data to be sent is present before transmission begins it could be sent more quickly if it were distributed to multiple transmitters which all transmit different parts of the information simultaneously i.e. in parallel.

When the channel bandwidth for serial communication is very small, the data rate can be increased by using many small channels in parallel.

Serial and parallel data can be transmitted either synchronously or asynchronously.

Synchronous transmission requires the transmitter and receiver to be exactly in phase and the data to be transmitted at a fixed rate. Synchronising the transmitter is fairly simple over optical fibre or cable, but more challenging over a radio link as the phase relationship can vary.

Asynchronous transmission is slower than synchronous but it is technically easier to implement as it only requires the transmitter and receiver to be able to exchange data at approximately the same rate. A technique called 'handshaking' is employed: along with the transmission channel used for sending data, there are two other links needed — one for the transmitter to warn the receiver of an incoming byte, and another for the receiver to tell the transmitter that the byte has been received and that it is ready for the next byte to be sent.

To minimise the time the transmitter and receiver need to remain in approximate phase, data is sent as individual bytes with the addition of 'start' and 'stop' bits to mark the beginning and end of each byte.

A further bit is often added to provide a simple 'parity' form of error detection. The parity bit is added to make the total number of 1s in the transmitted byte either odd or even (depending on whether odd or even parity is employed).

Bit and baud rate are terms which only apply to serial transmission (parallel transmission is measured by bytes or words (4 bytes) per second). Baud rate is a measure of the number of bits in total which are sent per second along a medium, whereas the bit rate is the rate of actual data transfer — so bit rate is always less than baud.

2.4 Switching

2.4.1 Circuit switching

In circuit switching a dedicated communications channel is reserved for the communications session which is of a preset bandwidth and is unavailable for any other user during the session. The GSM phone network is an example of this: such systems are characterised by time-based billing e.g. per minute of call.

Circuit switched systems are technically easier to implement but are wasteful of network resources and can provide weaker performance than the alternative.

2.4.2 Packet switching

In packet switching all data to be transmitted is broken up into suitably sized blocks known as 'packets'. As well as the payload data, packets also contain information such ash the source of the packet, the size of the packet, destination address, packet number and a checksum which allows for error detection. Padding is often added to packets to keep the size of the packets constant.

Often there is more than one path for a packet through a network, so packets can arrive at the destination out of order and are then reassembled by the receiver.

- Advantages:
  - more efficient use of the network as there are no reserved channels
  - greater throughput, as more than one channel can be used to send the information

An example of a packet-switched network is the GPRS mobile Internet system — packet switched systems have data-based billing rather than time.

Regeneration A Schmitt trigger can be used to regenerate digital signals thanks to its two separate switching levels. A comparator could produce multiple pulses at its switching point due to noise on the signal, whereas with a Schmitt trigger the signal must pass above the upper switching level when going from negative to positive and below the lower switching level when going from positive to negative.

3 Mobile telephones

Mobile phones are connected to the Public Switched Telephone Network (PSTN) through a radio link to a nearby base station.

Each base station effectively runs as a regenerator for the information where it not only amplifies the signal to make up for energy lost through attenuation, but also restores the original form of the signal by removing noise, distortion and interference.

Conversely, a repeater would merely amplify the signal and make no attempt to restore the original form: meaning they also amplify any noise on the signal.

The handset transmits data in digital form (for GSM it is both frequency and time division multiplexed) to the base station on an uplink channel.

The base station sends data to the handset via a downlink channel which is of a lower frequency than the uplink. The uplink and downlink channels are allocated separate frequencies to allow full-duplex communication to take place — if they were on the same frequency they would interfere, and the close transmitter next to a receiver on the same frequency would result in densensitising such that the base station or handset's signal couldn't be heard.

In practice, one of the possible channels from a given frequency band will be left unused as a 'guard' against causing interference to other licensees, or will be used as the control channel. With the 25 MHz allocated for uplink, and 200 kHz needed per channel, 125 channels are possible, -1 for guard so 124. Through TDMA, each channel in GSM is then split into 8 time slots.

The control channel handles things such as call set-up, channel/time-slot allocation to handsets and handover between base stations as a handset moves out of one coverage area and into another.

Base stations' coverage areas are known as 'cells'. Within each cell only certain allocated frequencies are used. The area of each cell is limited by the use of low power transmitters, as well as directional antennae and 'beamforming' technology.

Thanks to the low power limiting transmitters' ranges, other base stations some distance away can reuse the same frequencies — frequency reuse. This allows for much more efficient use of the finite radio spectrum. The smaller the areas of the cells, the greater the number of simultaneous conversations that can be supported in a certain area, and the more frequent the frequency reuse.

4 Audio systems

- Capacitors can pass alternating current but block direct current.
- The opposition of a capacitor to a.c. is capacitive reactance:

$$X_C = \frac{1}{2\pi f C}, \ (\Omega)$$

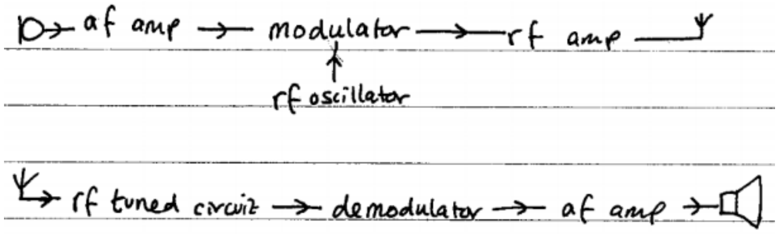
- Breakpoint frequency is the frequency at which the power gain of the filter is at half its maximum (or voltage gain $\frac{1}{\sqrt{2}}$ max). Occurs when $X_C = R$

$$f_0 = \frac{1}{2\pi RC}$$

- For a passive filter, transfer function cannot exceed 1 as there is no amplification.
- In active filters using op-amps the breakpoint frequency depends on the resistor which C is associated with. Note that if the feedback loop is broken by the insertion of a capacitor there will be no d.c. path for the small offset currents at the op-amp inputs to discharge, resulting in the system working for a short while and then saturating at one of the supply voltages. This can be solved by placing a very high value resistor in parallel with the capacitor, which does then limit the maximum voltage gain to $-\frac{R_\text{f}}{R_\text{in}}$
- Low pass filters
  - Passive filter: resistor on top and capacitor low.
  - A treble cut filter is made by putting a capacitor in parallel with the feedback resistor
  - A bass boost filter is made by putting the capacitor in place of the feedback resistor — but remember high value parallel resistor needed to prevent the op-amp just saturating.
- High pass filters
  - Passive filter: resistor on bottom and capacitor high.
  - A bass cut filter has a capacitor in series with the input resistor
  - A treble boost filter is made with a capacitor in parallel with the input resistor

4.1 Audio power amplifier ICs

- LM386 — 300-500 mW, b/w up to 300 kHz, G_V from 20 to 200
- LM380 — 2 W, 100 kHz, G_V 50
- TBA820 — for low voltage applications, 2 W, 22 kHz. G_V adjusted up to 50 through R connected to pin 2; capacitor used to control frequency response.
- Amplifier ICs can become unstable if the output is not kept well away from the input
- A resistor and appropriate capacitor from the output to 0 V can be used to reduce high frequency response / stop oscillation by shunting high frequencies to 0 V
- The bandwidth of an amplifier is the range of frequencies over which the power gain does not fall below half its maximum value.



5 Radio communication

5.1 Amplitude modulation

In amplitude modulation the frequency of the carrier wave is kept constant, but its amplitude is varied in sympathy with the amplitude of the information signal. The frequency of the information signal is represented by how often these variations in amplitude of the carrier occur.

$$\text{modulation depth} = \frac{\text{information signal amplitude}}{\text{carrier wave amplitude}} \times 100\%$$

If modulation depth exceeds 100% the signal is overmodulated — the information is distorted and the bandwidth of the signal will be increased as a result of the carrier actually disappearing. If modulation depth is too small the signal will be poor quality because signal-to-noise radio will be reduced. Target: 80%

When two frequencies are combined we get side frequencies at the sum and difference of these frequencies. For AM, efficiency can be increased by suppressing the carrier and one of the sidebands — giving 'single sideband' modulation.

$$\text{AM bandwidth} = 2 \times \text{max info frequency}$$

AM circuitry is simpler and thus cheaper than FM, but AM is more susceptible to noise and distortion e.g. lightning will create 'pops' on AM radio. AM also suffers from fading, which is the result in differences in phase between waves travelling paths of different lengths. Selective fading, dependent on frequency, can result in severe distortion.

5.2 Frequency modulation

With frequency modulation the amplitude of the carrier wave is kept constant, but its frequency is varied in sympathy with the amplitude of the information signal (increases as the information signal goes more positive, and decreases as the information signal goes more negative). The frequency of the information signal is encoded in how often the deviations in transmitted frequency occur. FM also produces sidebands.

$$\text{FM bandwidth} = 2 \times (\text{information frequency} + \text{deviation})$$

FM is much less susceptible to impulsive noise — such noise produces momentary variations in the amplitude of the signal which are suppressed in an FM receiver by a limiter: an amplifier which is in saturation so the output cannot rise as a result of impulsive noise.

5.3 Radio frequency classifications

- LF (longwave): 30 to 300 kHz
- MF (medium wave): 300 to 3000 kHz
- HF (short wave): 3 to 30 MHz
- VHF: 30 to 300 MHz
- UHF: 300 to 3000 MHz
  - 1 GHz+ is often considered 'microwave'
- SHF: 3 to 30 GHz

AM broadcast stations are spaced at 9 kHz in LF and MF. On HF they are spaced at 5 kHz. VHF FM broadcast stations have 200 kHz spacing (88 to 108 MHz)

5.4 DAB

DAB radio is used in the 217.5 to 230 MHz band. Stations are transmitted in multiplexes ('ensembles') which are on different frequencies, and are themselves further multiplexed.

The quality of a station depends on the bandwidth it can transmit, and so different stations transmit at different bit rates: for example BB3 R3 transmits classical music with a very high dynamic range and so has a higher bit rate than the pop on R1, while R4/R5L have much smaller bit rates as they transmit only voice.

- To send speech, a bandwidth of just 300 to 3500 kHz or so is needed.

5.5 Radio receivers

In the simple crystal radio receiver an LC network allows for tuning, a germanium diode acts as a demodulator, a capacitor filters out RF and a pair of headphones is the output transducer.

Pre-amplification of the RF signal can improve sensitivity by ensuring the tuned circuit is not shunted by low resistance.

To maximise efficiency, the impedance of an antenna, its feeder and the transmitter should all be matched. An impedance mismatch can result in power being reflected back and the formation of stationary waves which leads to a loss of signal strength and could damage the power amplifier.

Tuned circuits consist of an inductor (L) and capacitor (C) (in parallel for this spec) and provide selectivity — allowing the receiver to listen to one station and reject nearby strong signals.

$$X_L = 2\pi f L$$

At the resonant frequency impedance, Z, of the tuned circuit becomes entirely resistive and equals R_T. Tuned circuits with a greater R_T have a sharper resonance peak i.e. are more selective. At resonance $X_C = X_L$ so the magnitude of these currents is equal and they are in antiphase and so cancel.

Q-factor is a measure of selectivity — greater Q = more selective.

$$Q = \frac{f_0}{f_B}$$

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

5.5.1 Superheterodyne receiver

The superheterodyne (superhet) receiver allows multiple tuned circuits and specific amplifiers to be used in a chain, because they only have to deal with one frequency. It uses the 'sum and difference' concept to change the frequency of the desired station to an intermediate frequency.

The local oscillator is adjusted so that it oscillates at a frequency one IF above or below the station frequency. The LO output and initial tuning stage output are then mixed together, so there is always a difference product at the IF.

LW & MW radios use an intermediate frequency of 455 kHz, while VHF FM uses 10.7 MHz.

The IF amplifier contains many tuned circuits, all adjusted to the IF and thus has a well defined bandwidth and provides the extra selectivity needed to eliminate stations on adjacent frequencies. All of the signals from the mixer will be rejected except for those at the intermediate frequency.

Automatic gain control (AGC) automatically adjusts the gain of the IF amplifier to account for changes in received signal strength and minimise the effects of fading.

- Advantages of superhet:
  - improved selectivity
  - improved sensitivity
- Disadvantage:
  - the local oscillator can drift at high frequencies, though this can be reduced/eliminated with modern designs
  - image response interference

Image response or second channel interference occurs where there is another station transmitting one IF away from the local oscillator frequency which is not the desired station. This results in the unwanted station entering the IF amp as its signal also forms a different product at the IF. To eliminate this issue a high-Q tuned circuit is needed before the mixer, and this is also the reason for the higher IF used at VHF FM.