Chapter 11
ELECTROMAGNETIC WAVES and RADIO TRANSMISSION

Wave fundamentals

Everyone who has dropped a stone into a calm pond and observed the ripples spreading outward on the surface will be familiar with the idea of a wave. A wave is basically a disturbance or fluctuation in some material or *medium*, and moves or *propagates* through the medium at some (usually relatively constant) velocity. The medium itself does not, on the average, move in the direction of the wave, but energy is carried along by the wave.

Sound is an example of a wave where the air molecules wobble backwards and forwards in the same direction as the wave travels; this is referred to as a *longitudinal* wave. A wave on the surface of water (for example, waves arriving at Bondi beach) is an example of a *transverse* wave. Here the water locally bobs up and down, but the wave travels horizontally. These are both examples of "mechanical" waves, which involve the movement of matter, and the wave velocity depends on the density and "stiffness" of the medium. Sound waves in air travel at about 340 metres per second, while the velocity of surface waves on water is considerably slower, but depends on the water depth.

It is also possible to have a wave in which the fluctuations consist of changing electric and magnetic fields. This is referred to as an *electromagnetic (EM) wave*. The electric and magnetic fields are coupled together, and are always at right angles to each other and to the direction of wave travel. EM waves are thus transverse waves.

**** Aside:** What is the medium through which EM waves propagate?*

This worried people for a long time. Many attempts were made to find this medium (called the *aether* or *ether*), without success. The correct but apparently weird answer is that there doesn't appear to be any need for one. The electric and magnetic fields of an EM wave can exist and propagate without the presence of a medium. Electromagnetic waves will travel quite happily through a vacuum.

Notice that wave propagation is often referred to as *radiation* (for example, the terms "EM radiation", or saying that sound is "radiated" from a loudspeaker). Don't confuse this with some forms of nuclear radiation, which involve sub-atomic particles being emitted, although there are nuclear processes which generate EM radiation (such as *X-rays* and *gamma rays*, which are harmful to humans in large doses).

Wave velocity, frequency and wavelength

Let's consider a wave of a single frequency. If you were to look at this wave on the surface of water, its shape (taking a cut in the direction the wave is travelling) would look like a sine wave. Now if you stay at the same point and let the wave travel past (for example sitting on a dock and watching the waves roll in..), the number of crests which pass per second is the *frequency* of the wave, and is expressed in Hz in the usual way.

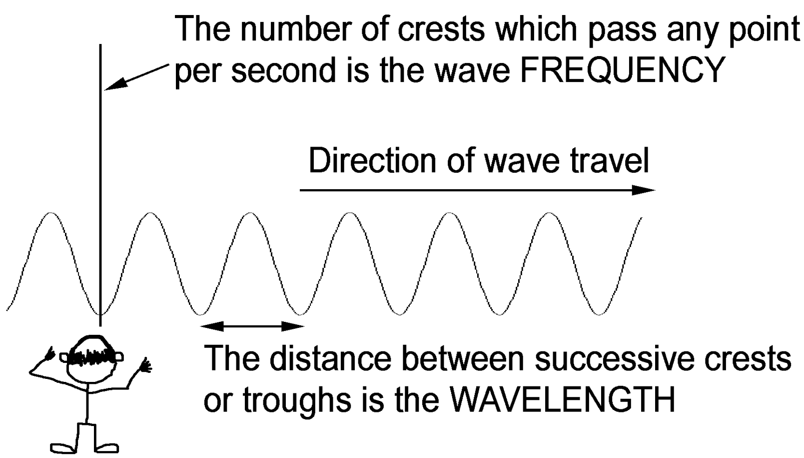

Figure 11.1 Frequency and wavelength.

On the other hand, if you travel along with the wave, the distance between successive crests is called the *wavelength*. These two quantities are related by a third, the wave *velocity*, as follows:

$v = f\,\lambda$, where v = velocity, f = frequency and λ = wavelength.

Note that this equation holds for **all** waves, be they sound, water, EM waves or whatever. In the case of EM waves, the wave velocity is the velocity of light. In a **vacuum**, this velocity is usually denoted by c and is equal to 3.00×10^8 m/s, while in **air** it is only slightly less, but still extremely close to this value. Don't confuse the velocity of EM waves with that of **sound** waves in air, which are about one million times slower[1] (sound is **not** an EM wave!).

Example 11.1: What is the wavelength λ of

(a) the radio waves broadcast by ABC-FM at 92.9 MHz, and
(b) the microwaves used in a microwave oven (f = 2.45 GHz)?

Answer: Rearranging $v = f\lambda$, we have

$\lambda = v / f$, where $v = c = 3.00 \times 10^8$ m/s, so that

(a) $\lambda = 3.00 \times 10^8 / (92.9 \times 10^6) = 3.23$ metres

(b) $\lambda = 3.00 \times 10^8 / (2.45 \times 10^9) = 0.122$ metres

Example 11.2: At a frequency of 900 MHz (the approximate frequency used by mobile phones) what is the wavelength (a) in air, and (b) in a cable with a velocity factor of 0.66?

Answer: As before, we use $\lambda = v / f$, but here the velocity is different for each case, so that

(a) $\lambda = 3.00 \times 10^8 / (900 \times 10^6) = 0.33$ metres

(b) Here $v \neq c$. Instead we have

$v = 3.00 \times 10^8 \times 0.66 = 1.98 \times 10^8$ m/s

so $\lambda = v / f = 1.98 \times 10^8 / (900 \times 10^6) = 0.22$ metres

Notice that, for the same frequency, the wavelength is **shorter** if the wave travels more slowly.

Types of electromagnetic waves

For convenience, various types of EM radiation are classified according to their wavelength –or, equivalently, their frequency. Although the underlying mechanism of all EM wave types is exactly the same, the techniques for generating, transmitting and detecting them do depend on the wavelength (as do their biological effects). The term *electromagnetic*

[1] A useful rule of thumb is that in air sound takes about 3 ms to travel one metre, while EM waves take about 3 ns to travel the same distance.

spectrum is used collectively to describe EM waves of all frequencies. The table below lists most of the common names used for EM waves in order of increasing frequency, with approximate frequency and wavelength limits. Radio, microwaves and infrared waves are commonly used for communications.

Common name	Approx wavelength (in vacuum or air)	Approx frequency	Notes
Radio waves:	30km - 30cm	10kHz - 1GHz	very broad range, including four examples shown
• (AM[1] radio band)	600m - 200m	0.5 - 1.6 MHz	
• (FM[2] radio band)	3m	88 - 108 MHz	
• (VHF[3] TV band)	6.7m - 1.4m	45 - 220 MHz	
• (UHF[4] TV band)	0.57m - 0.37m	530 - 820 MHz	
Microwaves	30cm - 1mm	1GHz - 300GHz	
Infrared (IR)	1mm - 700nm		includes "heat" radiation
Visible light	~700nm - 300nm		short wavelengths are "blue", long "red"
Ultraviolet (UV)	300nm - 100pm		
X-rays	1nm - 100fm		overlaps both UV and gamma rays
Gamma rays	< 100pm		

Terminology:
1: AM = amplitude modulation
2: FM = frequency modulation
3: VHF = "very high frequency" (30 - 300 MHz)
4: UHF = "ultra high frequency" (300 - 3000 MHz)

Table 11.1 The classification of some types of electromagnetic radiation.

Example 11.3: What would we commonly call EM radiation having

(a) a frequency of 5×10^{14} Hz? (visible light)
(b) a frequency of 10^6 Hz? (radio waves)
(c) a wavelength of 10μm? (infrared radiation)
(d) a wavelength of 1cm? (microwaves)

WAVE PROPAGATION

There are many aspects to wave propagation. To give an inkling of the issues involved, we might ask questions such as:

- Why do engineers need to build large antennas to detect faint radio signals?
- Why does last week's pizza get hot in the microwave oven?
- Why could you live near a large TV transmitter without getting totally fried too?

Hopefully, by the time we've finished, you should have a fairly good idea of some answers!
We're going to look at some of the things that happen as waves propagate. Although we will be talking about radio waves in particular, it's worth remembering that most of the general principles involved here apply to all sorts of EM (and non-EM) waves, although the mechanisms will vary. For example, we could apply many of the same principles to, say, the way sound waves behave in an auditorium.

The inverse square law

Suppose we have a very small energy source, radiating a total power P watts outward equally as waves in all directions ("*omnidirectionally*") in space. (Note that the term "space" or *free space* is not used here in the "outer space" sense –it could be, for example, in the atmosphere. It just implies that the radiation is not confined in any way, or absorbed or deflected by something along the way.) At some distance R away, the power received per area (called the *intensity*, I of the wave) is given by the *inverse square law*:

$$I = \frac{P}{4\pi R^2}$$

That is, the intensity is proportional to $1/R^2$. So if you double the distance from a source, the intensity falls by a factor of 4 (that is, 6 dB); if you increase the distance by a factor of 10, the intensity falls by a factor of 100 (or 20 dB), and so on. Notice that this falloff is not peculiar to any particular type of wave; it is a natural consequence of the geometry of three-dimensional space.

Although the inverse square law is strictly correct only in free-space conditions, it is a reasonable approximation in many real situations where there are no large reflections present. In addition, the $1/R^2$ part of the equation does not actually depend on the source radiating equally in all directions, as long as the radiation travels "in straight lines" away from the source.

Example 11.4: The intensity of the microwave signal received from a satellite at an earth station is about $2\mu W/m^2$. The satellite is in a geostationary orbit at a distance of 36,000 km. What would you expect the received intensity to be if instead the satellite were at the distance of the moon (390,000 km)?

Answer: In this case, we can safely assume that the inverse square law applies! The distance increases by a factor of 390000 / 36000 = 10.8. The received intensity will therefore be smaller by the factor $1 / (10.8)^2 = 0.0085$. Hence the intensity at 390,000 km will be $2 \mu W/m^2 \times 0.0085 = 0.017 \mu W/m^2$, or 17 nW/m^2.

Example 11.5: You have a mobile phone, but being a careful type you don't like operating it next to your head, so you hold it about a metre away and shout loudly when using it (you have permanent hearing damage anyway from being a drummer in a rock band so it doesn't matter that you can't hear the person at the other end). The phone transmitter has an output power of 3 watts. Meanwhile, your radio amateur neighbour has a rather powerful 1000 watt transmitter, with his roof-mounted antenna located about 50 metres from your bedroom. If we make the rather simplistic assumptions that both antennas are omnidirectional, and that the inverse square law applies, which radiation source will produce the greatest intensity at your head?

Answer: Using the inverse square law, for the amateur radio transmitter:

Intensity = $1000 / (4\pi \times 50^{2)} = 0.032$ W/m², while for the mobile phone:

Intensity = $3 / (4\pi \times 1^2) = 0.24$ W/m², which is about 8 times higher than the intensity produced by the high-power transmitter.

Absorption of EM waves

The drop in intensity of a wave in any situation where it is not in a confined space is just a natural consequence of the wave energy spreading out over a larger area, and is expressed as the inverse square law. However, it is also possible for energy to be **absorbed by the medium** through which the wave is travelling. In this case the energy is usually ultimately converted to heat (the final fate of all forms of energy in the universe).

A nice mechanical wave example of this occurs when you flick one end of a garden hose which is lying on the ground. You can usually manage to get a bump to propagate along the hose for some distance, but it rapidly gets smaller as it travels because of various frictional losses. This energy goes into heating the hose, ground and air by some miniscule amount.

In the case of EM waves, losses can occur in the medium through which it's travelling due to various mechanisms, some of which depend on the exact frequency. For example, if the medium is slightly electrically conductive, then the EM wave causes small currents to flow, and, just as in a resistor, electrical energy is converted to heat. The heating which occurs in a microwave oven is due to something similar, and relies on the presence of moisture in the food. At 2.45 GHz (the standard microwave oven frequency) the waves penetrate the surface of food to provide some heating from the inside. Because the waves lose energy to the food, they also get weaker in intensity as they travel inwards.

This loss in intensity, or *attenuation* of a wave as it travels through a lossy medium increases with distance exactly the same way as in a cable: that is, the loss **expressed in dB** is proportional to distance. So if the intensity of a wave drops by 5 dB in travelling 1 metre through a medium, it will drop by 10 dB in travelling 2 metres, and so on[2].

Example 11.6: The signal received over a 10 km long microwave link suffers an additional attenuation of about 6 dB on a foggy morning, due the presence of water vapour in the air. What would you expect the additional attenuation due to the water vapour under the same weather conditions to be for a link 25 km long? (Ignore attenuation due to the inverse square law, which –although different for both links –does not change with the weather. That was a separate problem for the designers of the link.)

Answer: The attenuation in dB due to water vapour is proportional to distance, so the attenuation per km is 6 dB / 10 km = 0.6 dB / km. Hence the additional attenuation for a 25 km link is just $0.6 \times 25 = 15$ dB.

This example highlights the fact that the atmosphere can play a big role in microwave communications. Microwaves above a frequency of several GHz can be severely affected by weather conditions; certainly a severe rain storm can effectively obliterate satellite reception.

Absorption of EM waves in the human body

Are mobile phones a health hazard? This is certainly a controversial issue of late, and one which isn't going to disappear overnight. While it's certainly true that no immediate or medium-term effects are obvious, I think the jury is still out on this one. It might be worth listing a few relevant points for consideration:

- Like any tissue, the human body absorbs energy from electromagnetic waves, and example 11.5 should convince you that mobile phones are the greatest source of such radiation when they are transmitting.

[2] Remember that when doing decibel calculations here, you are dealing with **power**, since intensity is power per area, so the form ***10*** $\boldsymbol{\log_{10}(\ldots)}$ must be used.

- It is unlikely that the use of a mobile phone "shield" will significantly change your exposure, as the antenna must still be uncovered to radiate properly!
- The current Australian standard for exposure to EM fields is an **average** (over time) of 200μW/cm^2, or a **peak** value of 1 watt/cm^2.
- Traditionally, safety limits for exposure to EM fields are determined purely by considering the **heating** effects. However, other, more subtle effects at the cell level have been observed for quite small intensities (but these are difficult to translate at present into health risks).
- Many of the nasty effects being suggested, such as cancers, may take a long time to show up (for example, 10 to 20 years). We really haven't had mobile phones around long enough to gather sufficient long-term data.
- The biological effects of EM radiation may be quite frequency dependent, so studies at quite different wavelengths may yield different results.
- The mobile phone industry is worth a huge amount of money. Many large and influential players are involved.

It's probably prudent to keep an open mind on the issue, and, for those who are interested, some web sites listed at the end of this chapter provide somewhat differing points of view:

Diffraction of Waves

Waves do not travel in nice, sharp straight lines like little bullets. *Diffraction* is the term used to describe the natural spreading that occurs when a wave propagates. This can show up in two ways:

- A wave cannot be exactly confined to a parallel "beam" of fixed width. To some degree, the beam always diverges with distance.

- When a wave encounters an obstacle or edge, some of the wave "leaks" or bends around it, so that the wave does not cast a sharp "shadow".

An example of the second case is illustrated in the diagram below, where water waves approaching a beach encounter a breakwater. Although the breakwater creates an essentially "calm zone" behind it, some waves do make it to this part of the beach as well, having been diffracted around the edge of the breakwater.

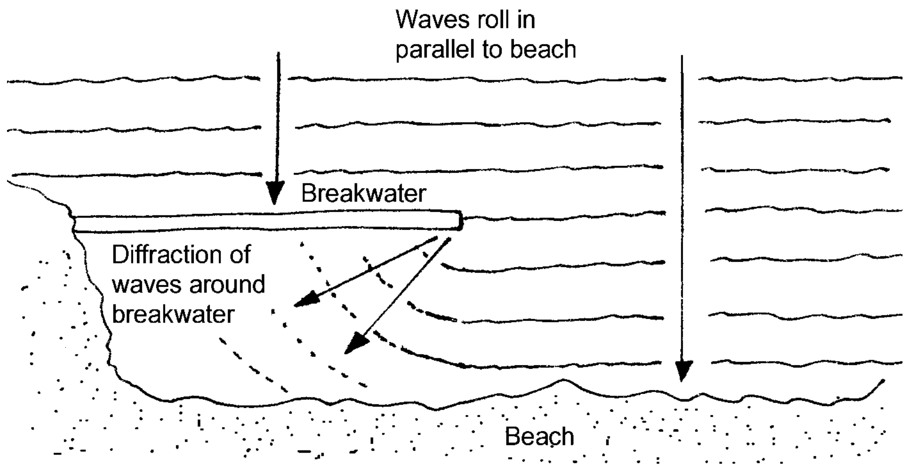

Figure 11.2 Diffraction of water waves around a breakwater.

How obvious the effects are depends on the wavelength, being more noticeable at longer wavelengths. When waves of different wavelengths encounter an object, the “shadow“ region behind the object is more extensive for shorter wavelengths (higher frequencies). It depends primarily on the **size of the obstacle compared to the wavelength of the waves**. So for, say, AM radio waves, where the wavelength is hundreds of metres, reception is not blocked by local hills and valleys. On the other hand, TV reception (particularly at UHF, where the wavelength is only half a metre or so) is very locality dependent, and reception may be very poor at some locations in valleys or behind hills, as seen from the transmitter. In these cases, very high antennas might be needed, or even *repeaters*, which receive the TV signal at a more favourable location (for example, on top of a hill) and re-radiate it at a different frequency to the local community.

For this reason, we refer to radio communications at UHF and above (that is, above about 300 MHz) as “*line of sight*”, meaning that, ideally, there needs to be an unhindered straight path between transmitter and receiver.

Antennas

We can regard an *antenna* (or *aerial*) as a device that either launches a wave into a medium, or extracts energy from a passing wave and converts it to electrical form. Perhaps surprisingly, antenna engineers don't distinguish between the two cases –it turns out that an antenna's characteristics are exactly the same whether you transmit or receive with it.

You have probably seen some different types of antennas, such as:

- An outdoor TV antenna, which looks like an array of metal rods.
- A single rod, as used on a mobile phone, or a car radio.
- A long wire, sometimes used for "short wave" reception.
- Large or small circular "dish" antennas, often used for satellite reception or microwave links.

There are in fact a large variety of different basic antenna designs, each working on slightly different principles, and having various advantages and disadvantages, but they share some common characteristics. The main property which interests us here is the ability of an antenna when transmitting to concentrate or "beam" the radiation in a particular direction, rather than just spraying it around equally in all directions[3]. In terms of a **receiving** antenna this corresponds to being more sensitive to waves arriving from a particular direction.

As I mentioned before, it doesn't really matter whether an antenna transmits or receives –its directional characteristics are the same. For convenience, we can think of antennas as transmitting only; it will be implicitly understood that they could receive as well.

We specify how directional an antenna is by comparing it to a hypothetical antenna which is precisely *omnidirectional*; that is, at a given distance from the antenna, the radiation intensity produced by it is the same, regardless of the direction[4]. The directional properties are usually measured at a large distance from an antenna; in this case, the radiation intensity is usually greatest in one primary direction and is somewhat less (perhaps close to zero) in other directions.

Two quantities which describe the "directionality" of an antenna are:

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[3] Of course, if the radiation is more concentrated in some directions, **less** must be radiated in other directions, since the **total** power, shared over all directions, must be the same.

[4] This is sometimes referred to by the dignified name of *isotropic radiator*.

- The *gain*, usually expressed in dB. At a large distance away in a particular direction, it is defined as

$$\text{Gain (dB)} = 10\log_{10}\left(\frac{\text{intensity produced by antenna}}{\text{intensity produced by ideal omnidirectional antenna}}\right)$$

Unless the direction is specified, the gain is usually taken to be the **maximum gain** (that is, in the direction of maximum intensity).

- The *beamwidth*, which describes how **sharply in angle** the radiation is beamed. It is the angle between the two directions where the antenna gain has fallen to half in power (-3 dB) compared to the maximum gain. This is perhaps more easily visualised than stated, and the graph below (a *polar* graph of the *radiation pattern*) shows how the gain varies with angle for an antenna with a beamwidth of about 70 degrees. Note that the main beam of an antenna can never be perfectly sharp (this is a legacy of diffraction), but must fall off smoothly to some degree.

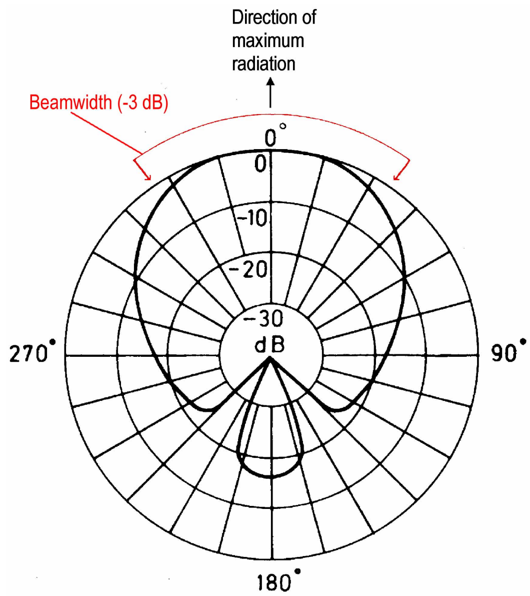

Figure 11-3. Polar graph showing the gain of an antenna with a beamwidth of about 70 degrees.

For a receiving antenna, a gain of more than 1 (i.e. > 0 dB) in a particular direction implies that signals from that direction are "boosted" by that much –while signals from other directions must be attenuated. This is why high-gain antennas, sometimes with gains of, say, 50 or 60 dB are used by deep-space tracking stations and radio astronomers to pick up weak signals before they are fed into radio receivers.

Since the intensity of an EM wave at some distance from a transmitting antenna depends on both the transmitter power **and** the antenna gain, a high-power transmitter connected to, say, an almost omnidirectional antenna might produce the same result in one direction as a low-power transmitter connected to a high-gain antenna; –that is, one whose radiation is strongly beamed in that direction. Of course, the high-gain antenna will need to be aimed correctly, and in other directions, won't do nearly as well as the omnidirectional antenna.

In general, the directional characteristics of an antenna depend on its **size**. The larger an antenna, the more directional it can be. You cannot build a very small, high gain antenna; the laws of physics dictate this. However, it's not just the physical size that matters, but the size **relative to the wavelength** of the radiation it's transmitting or receiving. An antenna which is physically much smaller than a wavelength is close to omnidirectional in most directions.

Although it can vary slightly depending on the exact antenna details, the beamwidth for a circular antenna (that is, usually a circular "dish" with the cross-sectional shape of a parabola) is given roughly by

$$\text{Beamwidth} \approx 75 \times \frac{\text{wavelength}}{\text{antenna diameter}} \quad \text{degrees}$$

while the (maximum) gain in dB is given by

$$\text{Gain} \approx 10\log_{10}\left(0.75 \times \left(\frac{\pi \times \text{diameter}}{\text{wavelength}}\right)^2\right) \text{ dB}$$

A crude but useful rule of thumb for any shape of antenna is that the beamwidth **in radians**[5] is very roughly equal to the inverse of the largest dimension of the antenna **expressed in wavelengths**. Thus an antenna which was 10 wavelengths across would be expected to have a beamwidth of about 0.1 radians, or approximately 6°.

Example 11.8: A ground station for a communications satellite operates an *uplink* (i.e. earth-to-satellite) transmitter at a frequency of about 14 GHz. It uses a circular dish antenna with a diameter of 25 metres.

[5] Recall that one radian is an angle of about 57°.

(a) Approximately what beamwidth would you expect the antenna to have?
(b) What would you expect its gain to be?

Answer: First we need to know the wavelength. At 14 GHz, the wavelength in air or vacuum will be $\lambda = c / f$, where $c = 3.00 \times 10^8$ m/s and $f = 14 \times 10^9$ Hz. This gives $\lambda = 0.021$ m.

(a) The beamwidth is thus approximately $75 \times 0.021 / 25 = 0.063$ degrees (or about 4 minutes of arc).

(b) The gain in dB will be about $10 \log_{10} (0.75 \times (\pi \times 25 / 0.021)^2) = 70$ dB

Example 11.9: A particular "brand X" TV antenna has a gain of 8.5 dB at the frequency of channel 10 (210 MHz). In the same location, a (hypothetical) omnidirectional antenna would have given a voltage of 5 mV at the input of the TV receiver connected to it. What voltage would you expect with "brand X" antenna connected?

Answer: This is just a calculation involving decibels. We don't need to use the frequency, as the gain of the antenna is known. The voltage will be higher by this amount, so that

$$8.5 = 20 \log_{10} \left(\frac{\text{voltage with brand X antenna}}{\text{voltage with omnidirectional antenna}} \right)$$

Rearranging, we find that

$$\text{voltage with brand X} = 5\ \text{mV} \times 10^{(8.5 / 20)} = 13.3\ \text{mV}$$

Example 11.10: Show that the antenna of a mobile phone operating at around 900 MHz will be close to omnidirectional.

Answer: At 900 MHz, the wavelength will be $\lambda = c / f$, where $c = 3.00 \times 10^8$ m/s and $f = 900 \times 10^6$ Hz. This gives $\lambda = 0.33$ m. Most mobile phone antennas are far shorter than this, typically only a few cm. Since the antenna size is only a small fraction of a wavelength, it should be omnidirectional.

Some antennas are specifically designed to work over only a narrow range of frequencies, perhaps within a few percent of the centre frequency, while other designs are "broadband" –that is, the usable bandwidth is a large fraction, perhaps one-half or more, of the centre frequency. TV antennas are usually broadband designs[6]. In general, the design of broadband antennas is considerably more difficult than that for narrowband antennas.

Antennas can also be designed to produce specially “shaped” or perhaps even multiple beams, in order to direct the radiation in a specific pattern. Examples of this type of antenna are found on modern communications satellites such as Aussat, where some beams are used to cover the Australian continent, while others serve more localised areas, such as Papua New Guinea. This degree of sophistication is only possible through modern computer-aided design and modelling.

Further Reading

EM radiation and health:

Australian Radiation Protection and Nuclear Safety Agency:
www.arpansa.gov.au/eme_pubs.htm

Stewart Fist:
http://www.electric-words.com/

[6] The Australian TV VHF (channels 0 to 11) and UHF (channels 28 to 69) bands cover the approximate frequency ranges of 45 to 220 MHz and 530 to 820 MHz respectively.

Chapter 12
INFRARED AND OPTICAL TRANSMISSION

The terms *infrared* (IR) and *optical* refer to electromagnetic waves with wavelengths between about 1mm and 300nm. Due to their much shorter wavelength, they are generated and detected in different ways to radio and microwaves. In addition, the losses they suffer during propagation are due to quite different mechanisms. Currently, wavelengths between about 650 nm and 1550 nm are commonly used for communications purposes (and would specifically be referred to as red visible light to *near infrared*). Although we can only see wavelengths shorter than about 700nm, it's not uncommon to refer to all these wavelengths as "light".

Two methods of transmission are common; radiation in a wide or narrow beam into free space, (for example, as used in TV remote controls), or guided in a "light pipe" consisting of an optical fibre. This chapter will concentrate mainly on optical fibres.

Sources of Radiation

Although many things produce EM radiation at optical or infrared wavelengths –for example, ordinary incandescent lamps –the ones that are used in communications are *semiconductor diodes*. These produce radiation when current (typically a few mA to a few hundred mA) is passed through a semiconductor *junction*. In doing so, they typically convert a few percent of the electrical power into radiation. There are basically two types: *light emitting diodes* and *laser diodes*.

Light emitting diodes

Often called *LEDs* (*"leds"* or *"ell-ee-dees"*), you know them as the little red, orange or green coloured lights you often see on the panels of radios, computers or electronic appliances. They can be designed to emit specific visible or infrared wavelengths, depending on the type of semiconductor material used. Special semiconductor materials such as *gallium arsenide* (GaAs) are typically used for infrared emitters, while *gallium phosphide* (GaP) and *gallium nitride* (GaN) are two compounds that can be used to construct red and blue LEDs.

The radiation from LEDs has two characteristics which can be drawbacks for some applications. First, it is spread over a fairly wide range of wavelength, typically a few percent of the central wavelength. Second, it is radiated in a rather broad beam, typically tens of degrees wide. However, because of their widespread use, LEDs tend to be fairly cheap (a few cents each for the most common visible light LEDs), and are ideal for short range, relatively low speed communication. LEDs are commonly used in communications applications such as:

- Remote controls for consumer appliances such as TVs, VCRs and air conditioners (at about λ = 950nm).
- Local data links over a few metres between computers and peripherals. Most notebook computers and PDAs (*personal digital assistants* – i.e. handheld computers) now come equipped with such an *IrDA* link (also at about 950nm).
- Sources of radiation for lower-speed optical fibre systems (most commonly at λ = 850nm –see later).

Laser diodes

Solid-state lasers or *laser diodes* are close relatives of LEDs, although their construction is a little more sophisticated. They are considerably more expensive, and must be driven with special circuitry, since they are easily destroyed. However, they have some unique properties which make them ideal for many applications, particularly in communications. First, their radiation is restricted to a somewhat smaller beam than LEDs (although considerably broader than that produced by conventional lasers). Second, they emit a very narrow range of wavelengths from a small area, which means that the radiation can be very efficiently focused into either a parallel or converging beam. Hand-held laser pointers work on this principle, containing basically a red laser diode and a small focusing lens. Typical laser diodes emit a few milliwatts of light power.

Laser diodes are used in a variety of practical applications, for example:

- CD players, where an IR laser beam (λ = 780 nm) is focused by a lens to a width of only 1.7 μm to read out individual bits of information.
- Surveying equipment, where the delay time of a narrow beam of laser light reflected from a distant target is used to measure distance.
- Optical speed radar guns used by police.
- Light sources for high-speed optical fibre systems, as we shall see shortly.

Aside: *How small can you focus a laser beam?*
In applications where it is important to have a very small spot of light (for example, in CD players and other optical data storage devices), smaller spot sizes can only be achieved with shorter wavelengths. This is dictated by the physical limits of diffraction, and the resulting spot is only a couple of wavelengths across. Although infrared laser diodes had been available for some time, visible laser diodes were only developed in 1988, well after the CD was invented. Currently, Digital Video Discs (DVDs) use red lasers with $\lambda = 650$nm wavelength to increase storage density over CDs ($\lambda = 780$nm), and presumably even shorter wavelength solid-state lasers will boost the information capacity of future storage devices (blue laser diodes are currently being commercialised).

Detectors

An optical *detector* converts a light signal into a voltage or current. The most common detectors used for visible and infrared radiation in communications applications are also semiconductor diodes. These are used in a different way to LEDs, and produce a (very) small current in proportion to the intensity of light falling on them. This current is converted to a voltage and amplified. They also work over specific ranges of wavelength, although somewhat wider than photo*emitters*.

Optical fibres

Fibre optics (which employs, of course, *optical fibres*) is one of the most important developments in modern communications. Optical fibres have a far greater information-carrying capacity than copper cables, as well as giving less signal loss. Optical fibres are now routinely used for many telecommunications and computer network links, particularly over long distances. Most telephone networks now use optical fibres for links between exchanges, and some countries intend to replace their whole network, right down to the individual consumer, with optical fibre within the next 20 years.

Optical fibres have a number of advantages over traditional cable or radio transmission methods:

- Extremely high bandwidth (and hence information-carrying capacity). It is possible to send data at rates of hundreds of gigabits per second (Gb/s) over some fibres.
- Immunity to interference and electrical noise. This is a big advantage in heavy industrial or dense suburban applications.

- High security, since it is extremely difficult to “eavesdrop” on an optical fibre. Eavesdropping on a copper cable is relatively simple!
- High degree of electrical safety, since optical fibres are insulators and hence there is no direct electrical connection for current to flow.

The basic idea of an optical fibre is very simple –it’s a pipe down which light (and remember we include both visible and IR wavelengths) is guided. The mirrored tube skylights you can buy for your home could be thought of as (crudely) similar. (In some applications bundles of optical fibres are used simply to pipe light to a place where illumination would otherwise be difficult.) Note that the light intensity does not fall off with distance along a fibre due the inverse square law, since no spreading occurs with distance. However, there are other losses along the way, so in this sense fibres behave rather like the electrical cables that we dealt with in chapter 10, with the attenuation in decibels being proportional to distance.

Information is most commonly carried on an optical fibre by simply turning the light source (a LED or laser diode) on and off, or, if you like, sending a series of light pulses along the fibre. This is a simple form of *amplitude modulation*, which we will meet soon.

Fibre construction and types

Optical fibres are very small in diameter, and are actually made of two concentric layers of transparent material (the *core* and *cladding*), each with different optical properties. These are then surrounded by an outer protective coating, as illustrated in the diagram below.

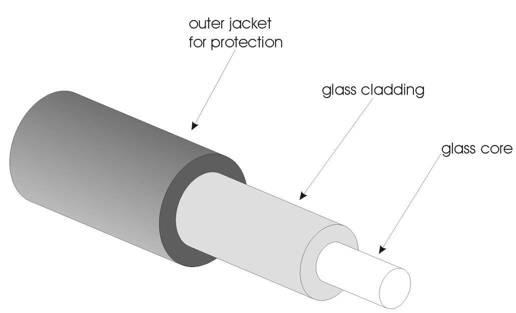

Figure 12-1 Basic construction of an optical fibre.

The outside diameter of the cladding layer is typically 125µm (one-eighth of a millimetre). The light is trapped and travels in the core, confined by the presence of the cladding layer. The boundary between core and cladding acts as a mirror, as shown below, due to a phenomenon known as *total internal reflection*.

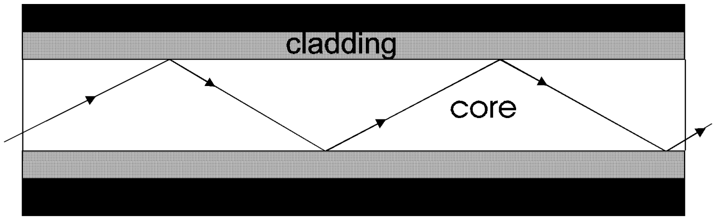

Fig 12-2 Light transmission is confined to the core of an optical fibre.

A little thought might convince you that, since the light can reflect off the boundary, there is not just one path that it can take on its way down the fibre. Very roughly speaking, each possible type of path is called a *mode*, and this can cause problems, since each type of path is a slightly different length, thus spreading the signal out slightly in time. The longer the fibre, the worse it gets. This effect is called *modal dispersion*. Fibres which allow multiple modes are referred to as *multimode fibres*.

There are three different types of fibre constructions, as shown in the diagram below.

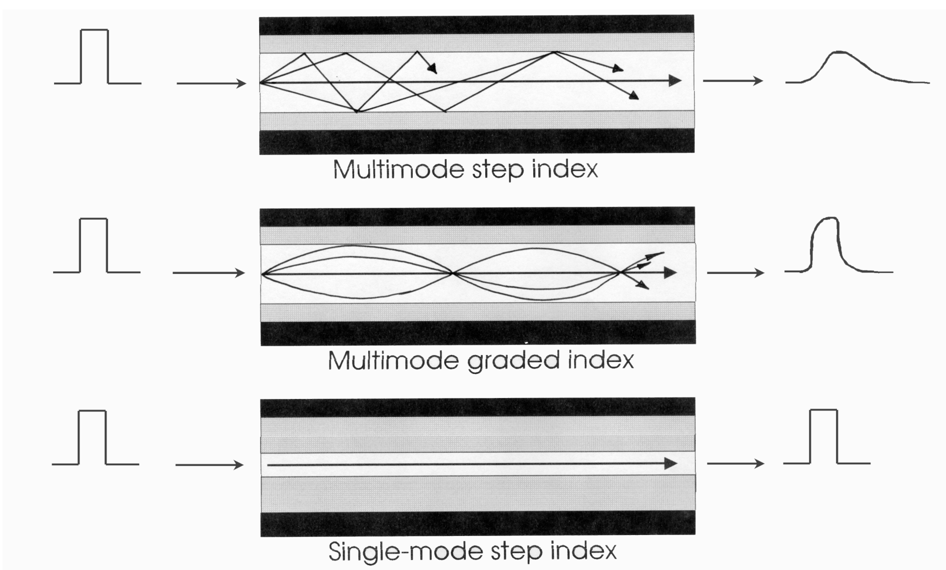

Figure 12-3 Different optical fibre types, showing the ways in which light propagates along them. The presence of many different modes of propagation leads to the “smearing” in time of light pulses.

These are:

- *Multimode step index fibre.* The simplest type, this has a relatively large core with a constant *refractive index* (a property of the glass which determines how fast the light travels), but has severe modal dispersion problems, leading to poor bandwidth. This type of fibre is rarely used.

- *Multimode graded index fibre.* Here, the refractive index of the core is designed to vary with distance from the axis in such a way that rays further from the axis travel faster, leading to a continuous "refocusing" effect, and reducing the modal dispersion. Fibres of this type typically have a core diameter of about 50μm, and LEDs are used as light sources.

- *Single-mode fibre.* In this type, the core has a constant refractive index, but an **extremely small diameter**. It turns out that in this case only one central "ray" can propagate down the fibre, thus completely eliminating modal dispersion. However, due to the small core diameter (about 10μm), getting light into and out of the fibre is much more difficult. Because of this and the need to use a narrow-band light source to take advantage of the low dispersion, single-mode fibres always use laser diodes as light sources. This type of fibre has by far the best performance, and is always used in long-distance applications.

Optical fibre bandwidth

Dispersion limits the rate at which information can be transmitted, since at some information rate successive light pulses will be "smeared" together beyond recovery. In addition, the effect increases in proportion to the length of the fibre. As a result, there is a direct relationship between the bandwidth[1] of a fibre and its length, given by

$$\text{Bandwidth (MHz)} \times \text{Distance (km)} = k$$

where the numerical value of k depends on the type of fibre, but is typically in the range 100 to 400 MHz-km for (graded index) multimode fibres. Thus if k=200 MHz-km for a particular type of fibre, then a 1 km

[1] Note that we define the bandwidth by considering signals which consist of variations in the light intensity sent along the fibre. Thus a 100 MHz signal would be one which varied the light intensity through 10^8 highs and 10^8 lows in 1 second. So the bandwidth of a fibre would be defined as the signal frequency at which the amplitude of the light variations at the output would have dropped by half, compared to very low signal frequencies.

length would have a bandwidth of 200 MHz, while a 10 km length would have a 20 MHz bandwidth, and so on.
For single-mode fibres, as normally used for longer distances and/or higher information rates, there is no modal dispersion, but other smaller dispersion effects ultimately limit the bandwidth attainable. As a result, single-mode fibres have bandwidths of the order of 100 GHz-km, as compared to the 1 GHz-km bandwidth in the best multimode systems.

For some short links it is possible to use somewhat cheaper plastic fibre (usually constructed from PMMA –"perspex"), and improvements are taking place in this area. An advantage here is that LEDs (near $\lambda = 650$nm) can be used, and information rates of at least 10 Gbits/sec have been achieved.

Attenuation in optical fibres

Optical fibres usually use high-purity silica glass with very low optical loss. The best fibre material is so clear that looking through several tens of km of such glass is equivalent only to seeing through a few inches of ordinary window glass!

The light loss through silica fibres depends on the wavelength of the light, as shown in the graph below. In very pure material the main loss is due to hydroxide ion impurities.

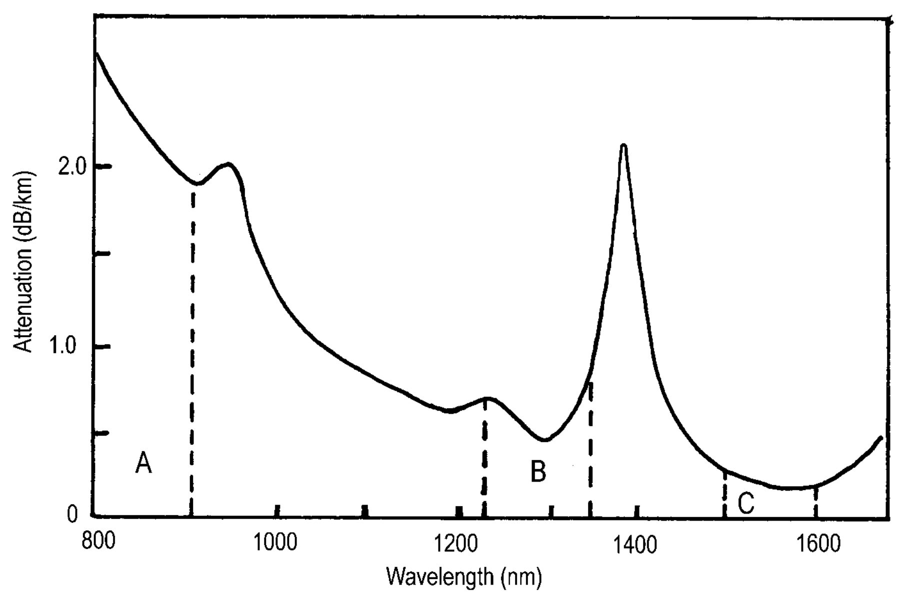

Figure 12-4 Attenuation in optical fibres as a function of wavelength. The three commonly used wavelength "windows" of relatively low attenuation are labelled A - C.

There are three commonly used wavelength ranges or “windows”. These are around 850nm, 1300nm and 1550nm (the lowest loss). The best available fibres have a loss of around 0.2 dB/km at 1550nm. However, the use of much longer wavelengths together with more advanced core materials should allow attenuations perhaps one hundred times lower to be achieved in the future.

Example 12.1: Using figure 12-4, estimate the attenuation of a 10 km length of silica glass optical fibre at a wavelength of 1300nm.

Answer: The graph of attenuation vs wavelength shows the loss at 1300nm to be approximately 0.5 dB/km. Since the loss is proportional to fibre length, the loss of a 10 km length will be 0.5 dB × 10 km = 5 dB.

Optical fibre cables

In practice, a number of individual fibres are commonly combined into a cable. The diagram below shows the typical cross-section of a complete optical fibre cable, such as might be used in a long-distance application. A number of individual fibres with individual protective tubing and carrying separate signals, as well as one or more spare fibres, surround a central carrier. This assembly is then surrounded by several more polyethylene, aluminium and Teflon layers to produce a structure which is high in mechanical strength.

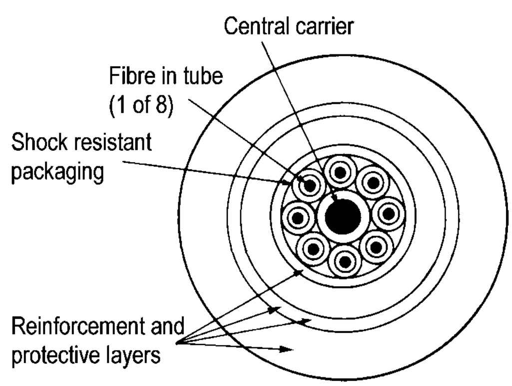

Figure 12-5 Typical construction of a multi-fibre cable.

It is also possible for light of different wavelengths to share the same fibre. Since each wavelength can carry separate information, this can lead to a vast increase in the already considerable capacity. This technique is referred to as *wavelength division multiplexing*.

Aside: *Satellites vs optical fibres for global communications***.**
How do optical fibres compare with satellites for global communications? Although for some applications they appear to be competing technologies, it seems likely that in the future optical fibres, because of their low cost and vast information capacity, will carry the vast majority of "high-bandwidth" signals between fixed points, and satellites will come into their own for mobile applications, where communication must be established quickly between two (possibly changing) points on earth. The (recently failed) Iridium satellite-based global mobile phone network and others which are planned for computer networking point to this sort of scenario.