1 GSW… Propagation for Mobile Comms

This chapter contains the minimum you'll need to know about radio propagation to understand the problems and issues faced by most modern mobile communications systems. Since almost all of these systems operate at carrier frequencies above 80 MHz, do not use high-gain antennas, operate over distances of up to a few kilometres and are not usually required to work more than 99.99% of the time, there are a lot of details about radio propagation you don't really need to know for this section[1].

What you will need to know: some basic information about electromagnetic waves and the radio spectrum; the qualitative effects of diffraction, reflections and atmospheric absorption; and the Doppler effect.

1.1 Electromagnetic Waves and the Radio Spectrum

In the late nineteenth century, James Clerk Maxwell formulated his famous equations that described the relationship between magnetic fields and electric fields[2]. Previously, experiments had shown that a changing electric field could produce a changing magnetic field and vice versa, but it was only when Maxwell produced his famous equations that something extraordinary became apparent.

Maxwell realised that a changing electric field produced a changing magnetic field around it, and that changing magnetic field produced a changing electric field around it, which in turn produced a changing magnetic field around it, which then produced a changing electric field around it… and so on. His equations allowed him to predict something remarkable: that the resultant pattern of magnetic and electric fields oscillating away into space travelled at enormous speed: 300 million meters per second. This is the fastest possible way to get energy from one place to another, and if you can control the transmission of this energy, you can transmit information.

As soon as this figure was derived, it was noted that this speed was, within experimental error, exactly the same speed as light travelled. (It wasn't proved until much later that light really was an electromagnetic wave, but it gave everyone a big clue that these waves really did exist.)

Ever since then people have been using these *electromagnetic waves* for communications, and that raises the inevitable questions: if I have a transmitter here, how far away can the receiver be, and still receive the signal? Attempting to answer that question leads first to the free-space path loss equation; but before that, a few notes about frequency and wavelength.

1.1.1 Frequency and Wavelength

A consequence of Maxwell's equations is that these *electromagnetic waves* (patterns of oscillating electric and magnetic fields taking energy through space) can have any frequency,

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[1] Although they can come up and give you a surprise occasionally (particularly the effects of refraction and ducting). There are more details about these, and some other interesting propagation effects in the relevant chapters in the section on Radio Propagation.

[2] If you're not sure what electric and magnetic fields are, try the chapter on WYNTKA Fields.

but once the frequency f is known, the wavelength in free space λ can be determined by the equation:

$$\lambda = \frac{c}{f} \tag{0.1}$$

where c is the speed of light. Different frequencies have different properties, and examples of EM-waves with frequencies from a few Hz to many hundreds of EHz (exaHertz = 10^{18} Hz) are known to exist.

(Oh – the wavelength is the distance between two adjacent maximum values of the electric field at one instant in time; the period is the time between two adjacent maximum values of the electric field passing one point in space, and the frequency is the inverse of the period, $T = 1 / f$, see figure Figure 1-1.

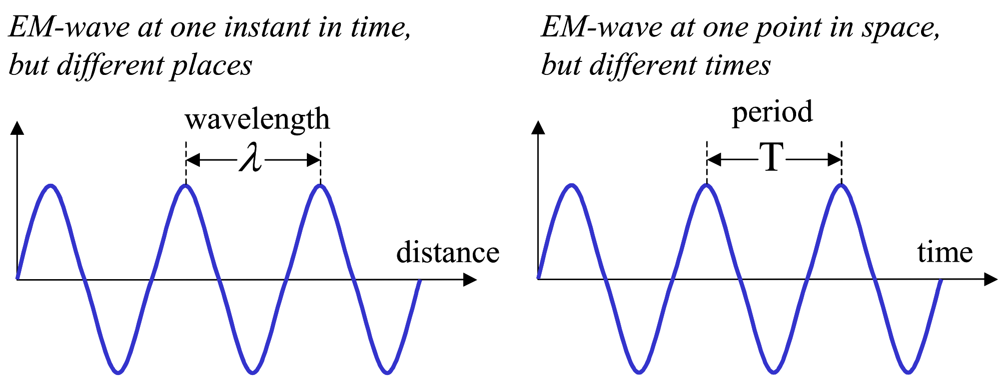

Figure 1-1 EM-Waves, Wavelengths and Periods

For our purposes here, we'll restrict ourselves to the range of frequencies between 100 MHz and 60 GHz. (That's a range of wavelengths between three metres and five millimetres.) Even then, we'll be mostly talking about a few small bands of frequencies within this range:

System	*Approximate Frequency*	*Approximate Wavelength*
GSM 900	900 MHz	33.3 centimetres
GSM 1800	1.8 GHz	16.7 centimetres
WCDMA (3G)	2.0 GHz	15.0 centimeters
Wi-Fi (802.11b/g/n)	2.4 GHz	12.5 centimetres
Bluetooth / ZigBee / WiBree	2.4 GHz	12.5 centimetres
WiMAX (in UK)	3.5 GHz	8.57 centimeters

(You might think it odd that Bluetooth, ZigBee, WiBree, and Wi-Fi all seem to use the same frequencies[3]. Doesn't that cause problems? Well, yes, it does. More about this later.)

[3] The reason they all use these frequencies (around 2.4 GHz) is that this spectrum is unlicensed: you don't have to pay the Government to use it. That makes systems using these frequencies very cheap to set up, and they are very
[continued on next page…]

1.1.2 Rays and Beams

Light is a form of EM-wave as well, although the frequencies that our eyes can see are much higher than those used for radio waves: visible light has frequencies around 500 THz (500,000 GHz). We're used to the idea that light travels in straight lines: if there is nothing directly between us and some object, we can see the object.

This isn't quite true. What actually happens is that the light we see coming from the object spreads out slightly into an ellipsoid beam, before converging again on our eye, as shown below[4].

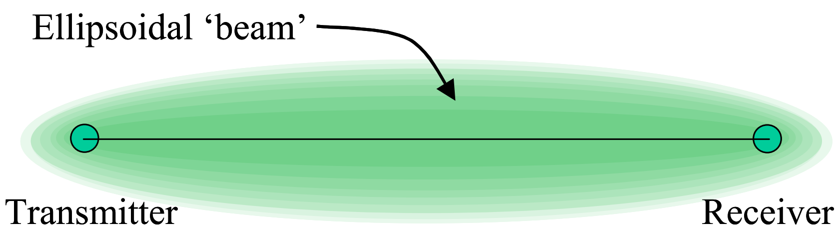

Figure 1-2 An Ellipsoidal Beam of Energy

As the frequency of the EM-wave decreases, the width of this beam increases; for example at 900 MHz, and over a path length of 1000 meters, most of the energy travels in a beam that's about nine meters wide at the half-way point[5]. At 3.5 GHz, this beam would be only 4.6 meters wide at the widest part (half-way between the transmitter and the receiver).

1.2 Antenna Gain and the Free Space Path Loss Equation

Consider an isotropic[6] antenna in the middle of an entirely empty 3-dimensional space, and then consider a sphere centred at that transmit antenna, with a radius of d. The surface area S of the sphere is:

$$S = 4\pi d^2 \qquad (0.2)$$

If the transmit power from the antenna is P_t, then the average amount of power emerging from each square meter on the surface area of this sphere must be:

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popular as a result. The disadvantage is that everyone else wants to use them to, so any system trying to work in this frequency band has to be able to cope with a lot of interference from other systems.

[4] This isn't quite true either. This 'beam' doesn't have a sharp cut-off at the edges, so that some points in space are inside the beam, and other points are outside it (I've tried to show this on the diagram with shading). It's just that the closer a point gets to the direct straight line between the object and your eye (or between the transmitter and the receiver in radio terms), the more energy will travel through that point. We talk about a 'beam' since we can usefully define the radius of this beam such that the majority of the received energy flows inside this beam; just not quite all of it.

[5] For those interested, this is the width of the first Fresnel ellipsoid at the mid-point. See the chapter on Diffraction for further details.

[6] An isotropic antenna sends the same amount of power in all possible directions.

$$P_d = \frac{P_t}{4\pi d^2} \tag{0.3}$$

We call this the *power density*, and measure it in watts per square meter (W/m^2). Since the antenna is isotropic, and the space is empty, the amount of power emerging from each square meter on the surface of this sphere must be the same. All we need to do to work out how much power is received by the receiver is to work out how 'big' the antenna at the receiver is, in other words how much of this power it intercepts.

1.2.1 Antenna Gain and Effective Aperture

The effective aperture of an antenna (measured in square meters) can be thought of as being the area of the incoming electromagnetic field whose power ends up in the receiver. Note this often has very little relationship with the actual physical size of the antenna itself[7].

So, the power received by a receiver in free space (i.e. with no obstacles anywhere between the transmitter and the receiver) is[8]:

$$P_r = P_d E_A = \frac{P_t E_A}{4\pi d^2} \tag{0.4}$$

where E_A is the effective aperture of the receiving antenna.

So far we've been assuming that the transmit antenna is an isotropic antenna, and one interesting thing about isotropic antennas is that they don't exist. You can't build one; it's a physical impossibility. All real antennas don't transmit the same amount of power in all directions: they transmit more energy in some directions than others.

The *gain* of an antenna is a function of direction, and is the ratio of the amount of power being transmitted in that direction to the average amount of power being transmitted in all directions. Or put another way: the gain of an antenna is the ratio of the power transmitted in one specified direction to the power that would be transmitted in that direction by an isotropic antenna (if you could build one).

By definition then, when a real transmit antenna is being used, the received power will increase by the gain of the transmit antenna in the direction of the receiver. That makes the total received power:

$$P_r = \frac{G_t P_t E_A}{4\pi d^2} \tag{0.5}$$

where G_t is the gain of the antenna at the transmitter in the direction of the receiver.

One last step: it's a useful fact that for any antenna:

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[7] For more about how antennas work, see the chapters on Antennas and Radio Propagation. You don't need to know how antennas work for this chapter.

[8] Actually, this is the maximum power that can be received by a receiver. To get this amount of power, the receiver has to be matched in impedance to the receive antenna. Again, more details in the section on Radio Propagation.

$$G = \frac{4\pi E_A}{\lambda^2} \tag{0.6}$$

where G is the gain of the antenna, E_A is its effective aperture, and λ is the wavelength of the radiation. We could specify the receive antenna not in terms of its effective aperture, but in terms of its gain G_r, and then write:

$$P_r = \frac{G_t G_r P_t}{\left(4\pi d / \lambda\right)^2} \tag{0.7}$$

This is the famous *free-space path loss equation*. It tells you how much power a receiver will receive, provided the receiver is matched and there are no obstacles anywhere between the transmitter and the receiver.

Note in particular that the received power is inversely-proportional to the square of the distance. Move twice as far away from the transmitter, and the amount of power received will go down by a factor of four. This is known as the *inverse-square law*. It's famous.

1.2.2 Power Density and Electric Field Strength

Another useful thing to know about electromagnetic fields in free space: there is a simple relationship between the power density and the electric field E (in Volts per metre) at any point:

$$P_d = \frac{\overline{E^2}}{Z_0} \tag{0.8}$$

where $\overline{E^2}$ is the mean value of the square of the electric field, and Z_0 is the impedance of free space, which is around 377 ohms. The important point about this relationship is that the mean power is proportional to the mean square of the electric field. So, if the power is inversely proportional to the square of the distance, the root-mean-square electric field strength is just inversely proportional to the distance:

$$\overline{E^2} = P_d Z_0 = \frac{G_t P_t Z_0}{4\pi d^2} \tag{0.9}$$

$$\sqrt{\overline{E^2}} = \frac{1}{d}\sqrt{\frac{G_t P_t Z_0}{4\pi}} \tag{0.10}$$

1.3 Diffraction

What if there are obstacles between the transmitter and the receiver? For most mobile systems, this is likely to be the case. (How often can you see the base station that your mobile phone is connecting to?) This doesn't mean you won't receive any signal at all (remember, energy doesn't travel only in the direct straight line, it spreads out in a wide ellipsoid, and not all of this ellipsoid is being blocked), however it does mean you'll receive less, since some of this ellipsoid is blocked.

However, if there is an obstacle between the receiver and the transmitter, then the amount of received power will go down[9]. This is known as *diffraction*.

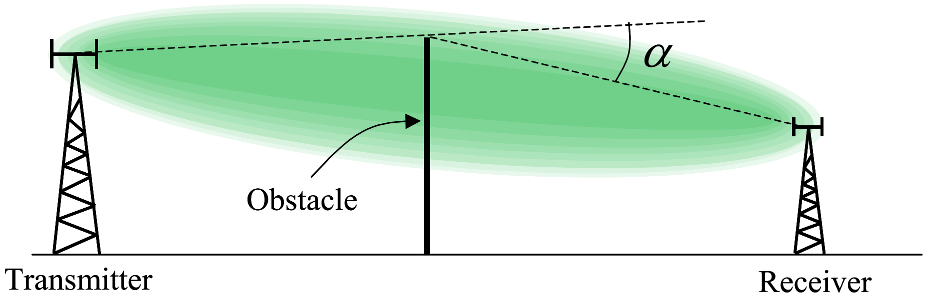

Figure 1-3 Diffraction over a Knife-Edge Obstacle

Calculating the diffraction loss is another complex subject[10], but all you need to know about diffraction for this section is that higher frequencies means higher diffraction losses (the ellipsoid in which most of the energy travels is thinner at higher frequencies); and the greater the diffraction angle (the angle through which the radio energy has to 'bend') the higher the diffraction loss also.

This means that lower frequencies are preferred: you get less diffraction loss that way. Unfortunately, there isn't much spectrum available at lower frequencies for mobile communications: it all got assigned to radio and television broadcasting before anyone knew how useful and popular mobile phones were going to be.

1.3.1 Diffraction over Multiple Obstacles

A very common problem in practice: what if there isn't just one obstacle, but there are several? One way to estimate the result of multiple-edge diffraction is to add up the effects of the diffraction loss from each obstacle. Other (much) more complex models exist, but they require detailed knowledge of the terrain: how big the obstacles are, what shape they are, their exact position and what they are made of. Even the most complex models are not very accurate, but the alternative is to go and take measurements everywhere, and that's very expensive.

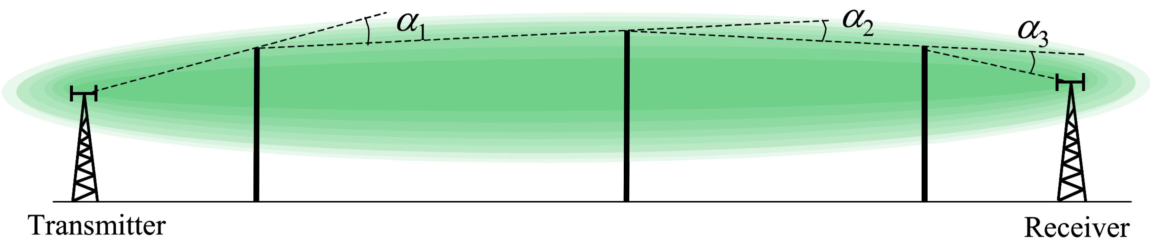

Figure 4 Diffraction over Multiple Obstacles

[9] Well, almost always go down. There are a few pathological situations in which it will go up, but they very rarely happen in practice. See the section on Radio Propagation for more details.

[10] See the chapter on Diffraction for more details.

1.4 Reflections

Just like light (another form of electromagnetic radiation, albeit with a much higher frequency), radio waves bounce off things. In general, this is quite a complex subject, so I'll restrict the discussion here to two cases of particular importance: both to do with cases where the EM-wave is travelling almost parallel to a smooth surface (known as *glancing incidence*). Note that the angle of incidence is always taken as being the angle between the incoming ray and the normal to the surface, so for glancing incidence, this angle is almost 90 degrees.

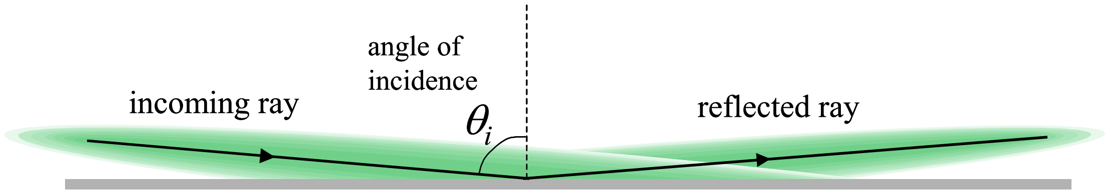

Figure 5 Reflection with Glancing Incidence

1.4.1 Specular Reflections at Glancing Incidence

The first important case is where the reflecting surface is perfectly smooth. In this case the surface provides a *specular* (i.e. mirror-like) reflection. For this section of the book, all you need to know about glancing incidence and specular reflections is that the reflection co-efficient (the ratio of the amplitude in the reflected ray to the amplitude in the incident ray) is minus one. The minus sign indicates that the reflected ray is 180 degrees out-of-phase with the incident ray.

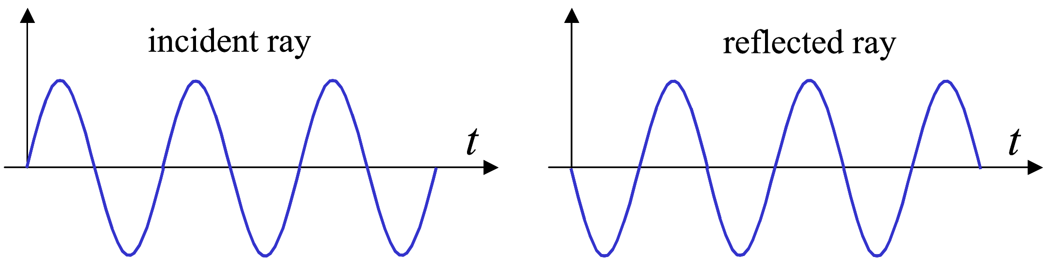

Figure 6 Incident and Reflected Rays 180 degrees Out of Phase

For all other angles of incidence the reflection co-efficient is greater than minus one (but less than one, of course: you can't have a reflection co-efficient of greater than one, that would mean the reflected ray had more energy than the incident ray.)

1.4.2 Non-Specular Reflections and the Rayleigh Criterion

If the surface the energy is reflecting from is very smooth, you get specular reflection. If the surface is very rough, you get what is known as *scattering*: the incident energy doesn't all bounce off in one direction, but it scatters and the incident energy ends up being split into lots of small rays bouncing off in all directions.

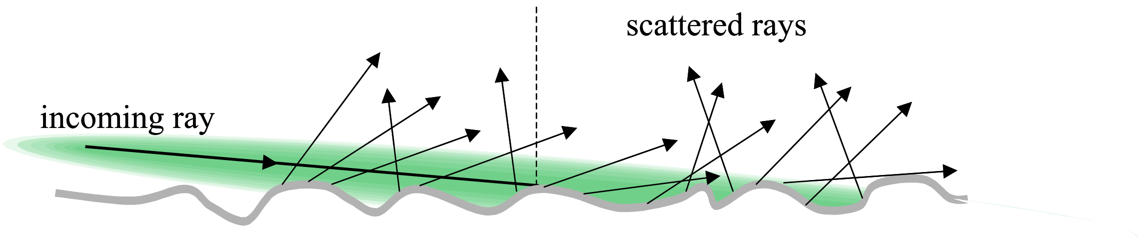

Figure 7 Scattering from Rough Surfaces

No real surface is perfectly smooth, so this raises the obvious question: how smooth does a surface have to be to produce specular reflections? This is the second important point about reflections. You don't need to know the details of the derivation, but the answer to this question is summed up in the Rayleigh criterion, which states that the reflection can be considered to be specular provided:

$$h < \frac{\lambda}{8\cos\theta} \tag{0.11}$$

where h is the root mean square (rms) height of the bumps on the surface, λ is the wavelength, and θ is the angle of incidence.

Note that at glancing incidence, $\cos(\theta)$ tends towards zero, which means h tends to infinity. In other words, it doesn't matter how rough the surface is, provided the angle of incidence is large enough, any surface will appear to be smooth, and provide a specular reflection. The other point to note is that for shorter wavelengths (and hence higher frequencies), the surface must be comparatively smoother to give a specular reflection.

It's possible for the same surface to give a specular reflection for lower frequencies, but a scattering reflection for higher frequencies.

1.4.3 Multipath

As soon as there are some objects to reflect EM waves, there is the possibility of multipath: two different rays from the same transmitter arriving at the same receiver at the same time. This can be a good or a bad thing, depending on how the system works, and the relative amplitudes and phases of the different rays.

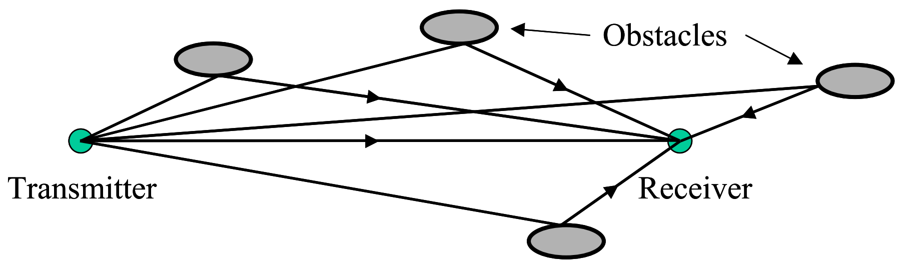

Figure 8 Multipath Propagation

To calculate the total amount of energy arriving at the receiver in these circumstances, you need to consider all the different rays, and it's not as simple as just adding up the energy. You have to take the phase of the reflections into account as well. For example, if two rays arrive in perfect phase (perhaps one has travelled an integer number of wavelengths further than the other), then the total electric field strength at the receiver is the sum of the electric field strengths in the two rays:

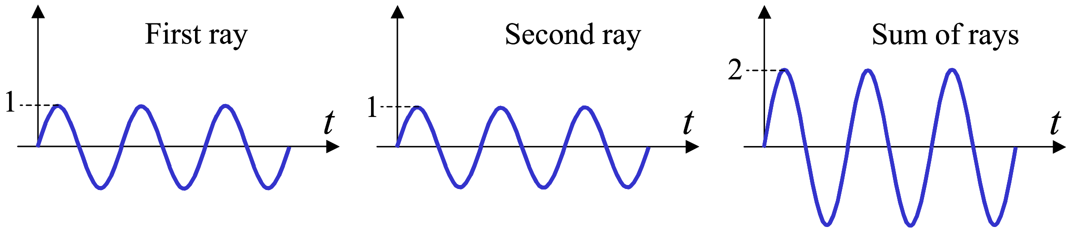

Figure 9 Two Rays Arriving In-Phase

In this case the amplitude of the received signal is twice as great as the amplitude in just one of the rays; and since power is proportional to the square of the amplitude, this means that the received power will be four times greater than the power that would be received if the second ray was not there.

Alternatively, if the two rays arrive exactly 180 degrees out of phase (perhaps one has travelled an integer number of wavelengths further than the other and bounced off a reflection, giving an additional 180 degree phase shift), then the two electric fields will cancel each other out, and the net result is nothing being received at all.

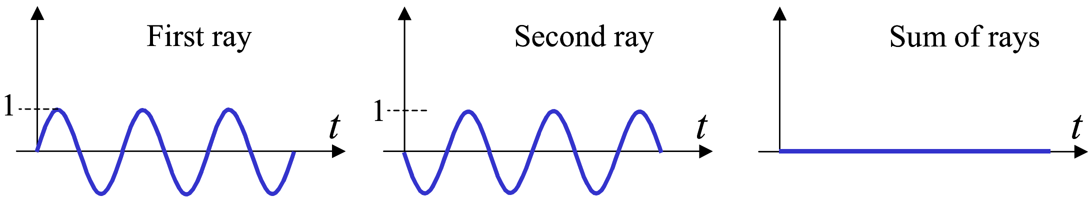

Figure 10 Two Rays Arriving Out of Phase

In the more usual situation for mobile communications, there are a lot more than two rays arriving (sometimes hundreds), and they won't all arrive with the same amplitude. In such cases we use vector techniques[11] to work out the amplitude of the electric field at the receiver.

1.5 Absorption in the Atmosphere

The atmosphere of the Earth is not free space[12]. This has several important consequences for mobile and personal communications systems, but the two most relevant ones can be illustrated in the following graph of typical attenuation of the air against frequency.

The first point to note is that wet air (mist, fog, clouds, rain, etc) has a higher attenuation than dry air, but the difference is only noticeable above 10 GHz. As a rule of thumb, if you're operating below 10 GHz you can forget about the effects of rain; if you're operating above 10 GHz you need to consider rain: during heavy rainstorms the most distant users of your network might not be able to receive a good signal.

[11] See the chapter on Vectors for more details about how this works.

[12] This is fortunate: if it was really free space it wouldn't have any air in it, and we'd all suffocate.

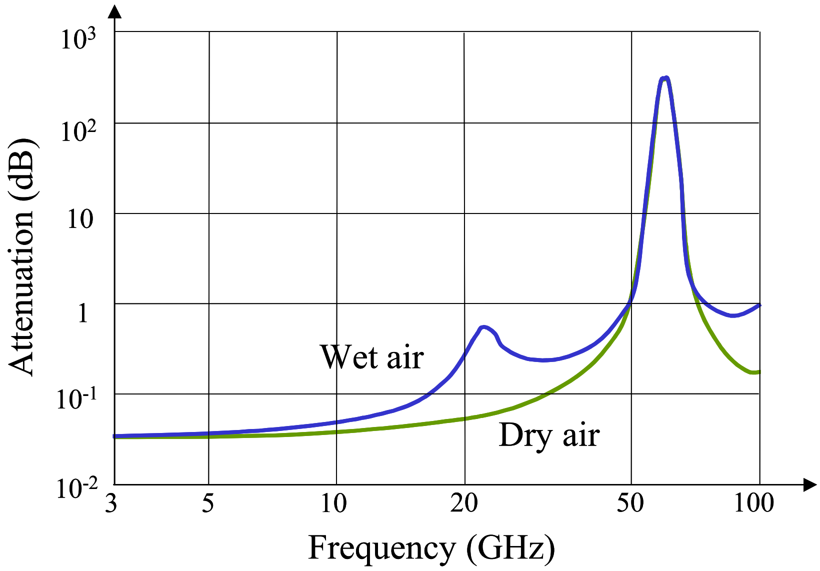

Figure 11 Attenuation in Wet and Dry Air

The second point to note is the huge peak in attenuation at 60 GHz. This is due to an oxygen absorption band: the energy in the EM-wave is being lost to vibrations in the oxygen molecules. This means that any transmission at 60 GHz doesn't go very far; which can be useful, when you've got two people very close together, both of whom want to use the same spectrum. This could be a very important part of the spectrum in the future; although currently the technology required to generate and receive signal at these frequencies is still very expensive.

1.6 The Doppler Effect

Listen to an ambulance or police car (or anything else with a siren) drive towards you at high speed, drive past you and then drive away from you and you'll hear the pitch of the siren change. You might even hear it on roads when cars without a siren pass by, and the note the engine makes drops in pitch as the car passes you and starts to move away. This is due to the Doppler effect: the frequency of the sound changes when the transmitter and receiver are moving relative to each other.

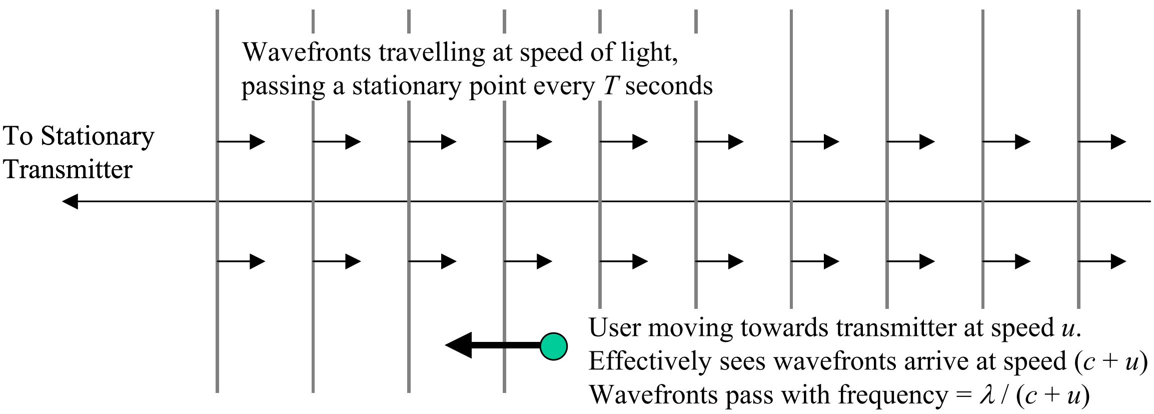

Figure 12 The Doppler Effect

The amount by which the frequency changes (Δf) is given by:

$$\Delta f = \frac{u\cos(\theta)}{\lambda} \quad (0.12)$$

where u is the relative speed (in meters per second) of the transmitter and the receiver, θ is the angle between the directions of motion of the two, and λ is the wavelength.

This formula has a simple derivation. First, consider for simplicity that the transmitter is stationary, and the receiver is moving. Then, resolve the motion of the receiver into two components, one directly towards the transmitter, and another at right-angles to this direction.

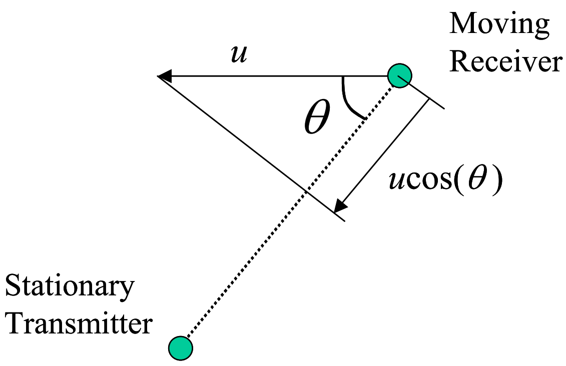

Figure 13 Resolving Receiver Motion

The peaks of the electric field in the EM-waves coming from the transmitter will be a distance λ apart (where λ is the wavelength: this is the definition of wavelength). The waves are travelling at the speed of light, c. The receiver is moving towards the transmitter with a resolved velocity of $u\cos(\theta)$. Therefore, the time between one peak value of electric field arriving at the receiver and the next peak value of electric field arriving will be:

$$\Delta t = \frac{\lambda}{c + u\cos(\theta)} \quad (0.13)$$

That means that entire cycles of the oscillation (from one peak value of electric field to the next peak value) appear at the receiver at the rate of 1 / Δt every second. That's just the definition of frequency: how many cycles arrive in one second. Therefore the received frequency f_r is:

$$\frac{1}{\Delta t} = f_r = \frac{c + u\cos(\theta)}{\lambda} \quad (0.14)$$

so the frequency shift (the difference between the received frequency f_r and the transmitted frequency f_t) is:

$$\Delta f = f_r - f_c = \frac{c + u\cos(\theta)}{\lambda} - \frac{c}{\lambda} = \frac{u\cos(\theta)}{\lambda} \quad (0.15)$$

Note this means that moving towards the stationary transmitter, and the received frequency is higher than the transmitted frequency. Move away, and the received frequency will be lower than the transmitter frequency. Move around the transmitter so you're always the same distance away, and the received frequency will be exactly equal to the transmitted frequency: in this case $\cos(\theta) = 0$.

1.7 Problems

1) Suppose I was driving at 100 km/hr straight towards a stationary radio transmitter broadcasting a carrier wave with a wavelength of 25 cm. What frequency is the radio transmitter transmitting at, and what frequency would I receive?

2) Many mobile communications system transmit in the downlink (from base station to mobile phone) on one frequency, and in the uplink (from mobile phone to base station) on a different frequency. The higher frequency is always chosen for the downlink. Why? (Hint: think about batteries and diffraction losses.)

3) A system transmits at 2.4 GHz over a distance of 200 meters, with the transmitter and the receiver both 2 meters above the ground. In-between the transmitter and receiver is a lake with ripples with an rms height of 5 cm. Is this going to give scattering, or a specular reflection?

4) 5 km away from a transmitter transmitting 10 Watts of power at 300 MHz from an antenna with a gain of 10 dB is a receiver with an antenna of gain 3 dB. Using the free-space propagation equation, calculate the maximum amount of energy that could be received.

Suppose a measurement was taken, and the real received energy turned out to be higher than this figure. How could this happen?

5) Over a period of a minute, a base station measures the received signal from a mobile phone and finds that the free-space path loss varies from 80 dB to 115 dB. The base station has an antenna of gain 8 dB, the mobile phone has an antenna of gain 2 dB. The frequency being used is 1800 MHz. What estimate can the base station make of the distance to the mobile phone? Is this likely to be an accurate estimate, and can you think of a better way the base station could work out how far away the mobile phone is?